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Risk Assessment of Falling Hazards in Earthquakes in the Groningen region: Appendices 1-4

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Arup bv
PO Box 57145
1040 BA
Amsterdam
The Netherlands

ARUP

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Appendix 1: The Falling Hazards Risk Model

1. Introduction

This is the first appendix to the Falling Hazards Risk Assessment report prepared by Tony Taig and Florence Pickup of TTAC Ltd based on research and analysis carried out for NAM and Arup during 2014 and 2015. It provides an expanded description of the Falling Hazards Risk Model and the evidence on which it is based.

At the heart of this risk model is the simple idea that the potential for harm outside buildings depends on the quantity of heavy material that falls through the air, and the area at risk into which it falls. Most seismic risk assessment involves definition of building damage states that relate either to the extent of structural damage or to loss of economic value. This study is different in that it uses volume of debris falling through the air outside buildings as the basis for definition of 'damage states' for non-structural building components. The model estimates the Community Risk (CR) to people in and around Groningen region buildings resulting from three particular exposure pathways:

- Passers-by exposed to debris falling outside buildings
- Building occupants running out into falling debris, and
- Debris falling through building roofs onto people inside.

The model has been developed in parallel with an internet-based survey of buildings in the Groningen region, carried out by a team of 20 undergraduate students and recent graduates during the summer of 2015. Both the model itself, and the surveyed building features on which the risk assessment is based, provide rough approximations rather than definitive assessments for individual buildings. The purpose of the model is to help prioritise areas for more detailed, on the ground assessment, and to support the development of general rules that can be applied in such prioritisation. It is NOT intended, and is not suitable, for making definitive decisions about individual buildings and building elements.

This Appendix provides

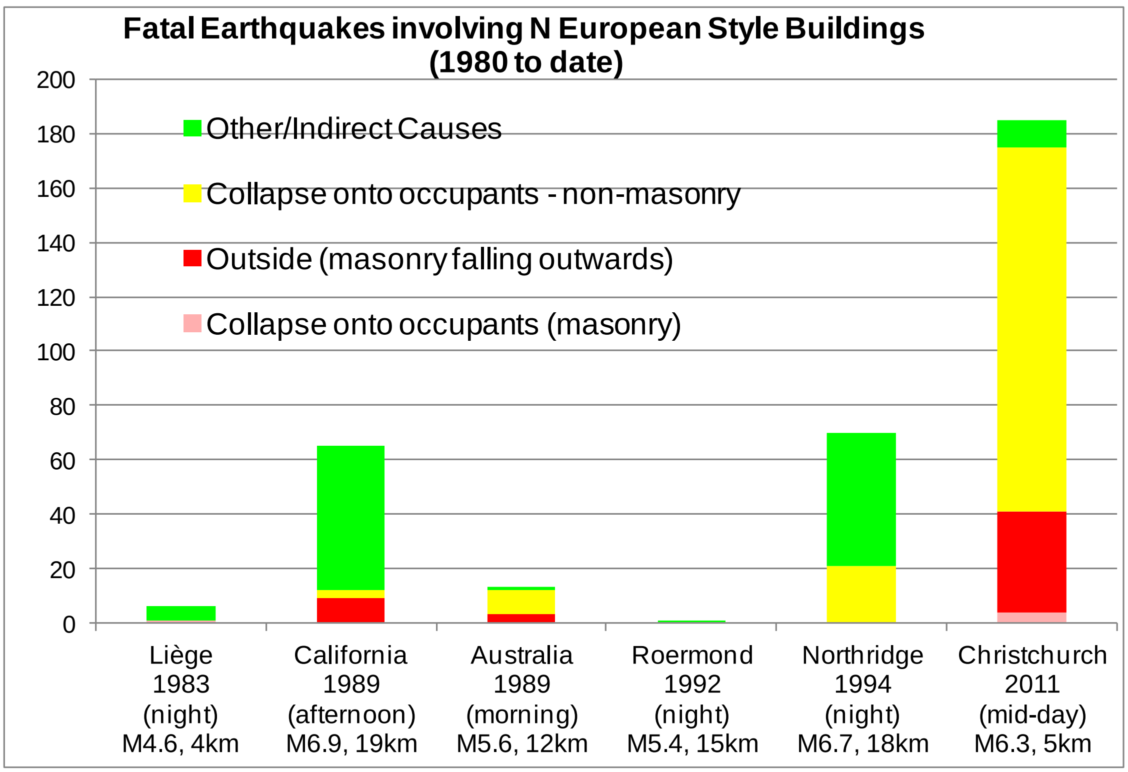
- Background on falling hazards and an overview of the risk model (Section 2)
- A step by step explanation of the model and how it works (Section 3), and
- Conclusions and suggestions for further development of the model (Section 4).

2. Background and Overview

In the absence of a risk model the importance of falling masonry outside buildings is difficult to assess. Widely used models such as HAZUS[1] generally tend to model casualties outside buildings as a simple multiple of casualties inside, linked to damage states which broadly describe the extent of structural damage or loss to a building.

A useful starting point in considering the seriousness of this issue is to review experience in previous earthquakes, particularly those in areas which, like the Groningen region, contain large populations of masonry buildings of a broadly North European style. Figure A1.1 shows the deaths from various causes that have occurred in all of the fatal earthquakes since 1980 in Northern Europe, North America, Australia and New Zealand (judged to be the most relevant in terms of the presence of large quantities of broadly North European style masonry).

Figure A1.1 Deaths in Earthquakes Since 1980



The largest single contributor to fatalities, shown in yellow in the chart, has been the collapse of a small number of large buildings onto their occupants (in particular two concrete buildings in Christchurch Feb 2011, one in Newcastle NSW in 1989 and one timber framed building in Northridge in 1994). The next largest contributors taken together are the "Other/indirect causes" (which include road deaths, fires, heart attacks and personal injuries – frail elderly people falling and never recovering). The issue of falling masonry outside buildings was raised in the aftermath of all these earthquakes, but did not have lethal effects in any of them other than Newcastle and Christchurch, as the earthquakes occurred at night when the streets were quiet so few people were

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[1] Department of Homeland Security Emergency Preparedness and Response Directorate, FEMA, "Multi-hazard Loss Estimation Methodology Earthquake Model HAZUS®MH MR4 Technical Manual, US FEMA, 2003

exposed to risk. Reports on the Roermond, Liège and Northridge earthquakes all commented that, had the event occurred when the streets were busy, numerous deaths would have been expected outside buildings.

Recognition of this hazard has led to the inclusion of special consideration for falling non-structural elements of buildings in the seismic building codes of earthquake-prone regions such as Japan, California and New Zealand[2].

The Christchurch earthquake of 22 February 2011 was the only earthquake in this set where large volumes of masonry debris were generated outside buildings at a time when the streets were busy. 41 people were killed by falling masonry, 36 of them outside and 5 inside the buildings from which the debris originated (three of whom were removing the organ from a church badly damaged in the previous earthquake).

Elsewhere in Christchurch, in the residential Port Hills suburbs to the south of the city, a quite different hazard was experienced as large volumes of rock and boulders detached from hillsides and cliffs. Several houses at cliff tops fell with the cliff and over 100 boulders of diameter 1m or more rolled down slopes and penetrated houses. Five people were killed by rock falls, none of them in the houses penetrated by boulders, largely because those houses were empty at the time.

GNS Science, New Zealand, developed a model of risk for boulder roll and cliff collapse onto people, houses, roads and footpaths, in which Tony Taig was heavily involved as reviewer and co-developer[3]. The risk model has been extensively debated in New Zealand and has been peer reviewed by experts in the US and Australia as well as NZ. The model was used by the central Government of New Zealand and by Christchurch City Council to inform decisions on which houses were safe to re-occupy and which should be the subject of a government offer of purchase. The risk model developed for falling hazards adopts the approach of this GNS model, with the major steps as illustrated in Figure A1.2.

[2] See for example "Seismic Evaluation and Retrofit of Existing Buildings", US Standard ASCE/SEI 41-13, American Society of Civil Engineers, 2014, and "Reducing the Risks of Non-Structural Earthquake Damage – A Practical Guide", US FEMA E-74, December 2012.

[3] C Massey, M McSaveney et al "Canterbury Earthquakes 2010/11 Port hills Slope Stability: Life Safety Risk from Rockfalls (Boulder Rolls) in the Port Hills (2012)", GNS Science report 2012/123 (plus companion report GNS 2012/124 on cliff collapse)

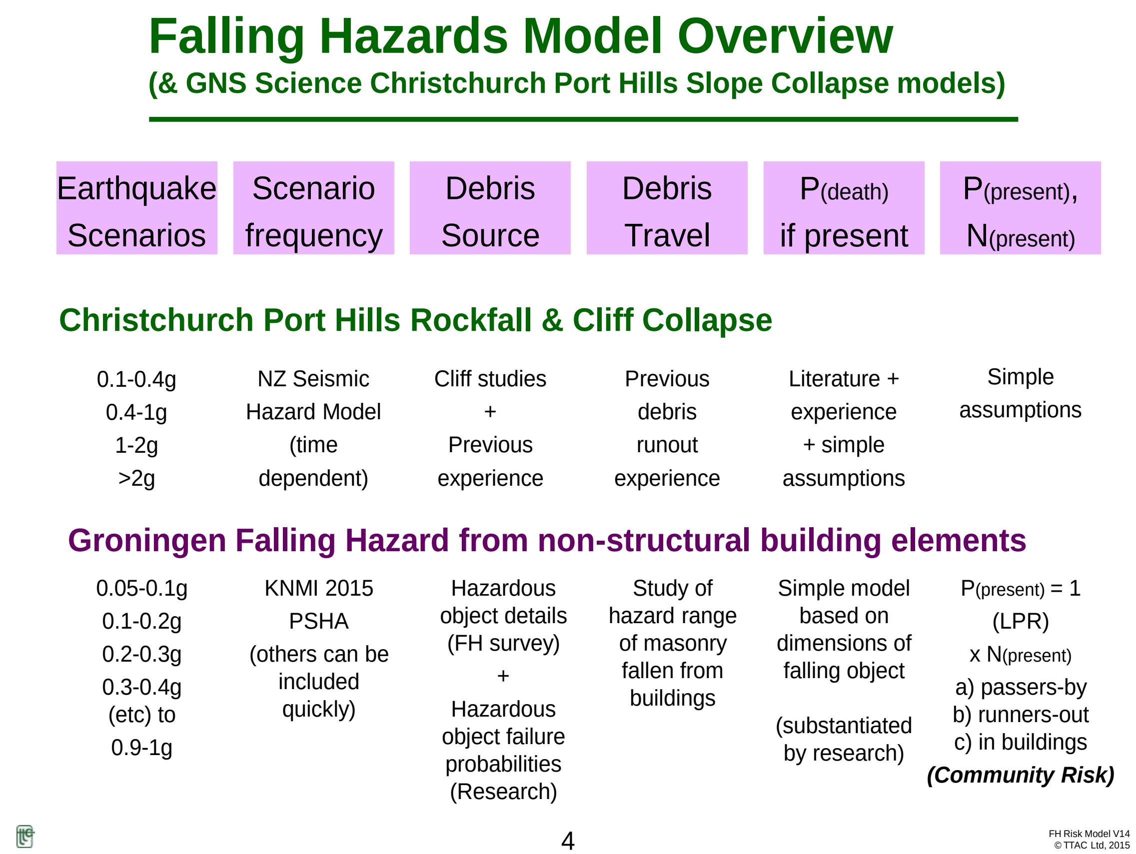


Figure A1.2 Rock fall and Falling Hazard Risk Modelling Approaches

The first step is to define a set of earthquake scenarios to represent the totality of all possible earthquakes. This is done in both models by defining bands of shaking (defined in terms of peak ground acceleration, PGA) which are mutually exclusive and collectively exhaustive.

The frequency of each shaking band is estimated with the aid of a probabilistic seismic hazard assessment (PSHA) model which provides, for a given location, information on the frequency with which a given ground motion is expected to be exceeded. The frequency of occurrence of earthquakes within the band is then simply equal to the exceedence frequency for the bottom end of the band, minus that for the top end. The consequences of earthquakes in each band are then estimated by taking an earthquake scenario (typically with shaking in the mid-point of the band) to represent all earthquakes within that band. Clearly this involves a good deal of approximation, as earthquakes within a range of PGA could have widely different characteristics (other than PGA) which could be important for building damage.

Estimation of earthquake consequences begins by characterising what debris will be detached, with what probability, from a given non-structural building component, in a given earthquake. There are two main steps in doing this for a specific building

a. identifying and characterising the potential falling hazards on a particular building, and

b. estimating the likelihood of defined failures (in particular corresponding to defined debris generation) in the event of a given earthquake.

The first of these is addressed in this study via the Falling Hazards survey described in the main report and Appendix 7. The second involves an empirical approach to estimate both the probability that a given building element will fail, and, should it do so, the likelihood of different portions of its volume falling to the ground as debris. Note that “failure” throughout this study is taken to mean “failure in such a way as to generate at least some debris falling through the air”. We are not interested in cracking or minor damage, though these may have significant potential for economic damage and distress – our concern is purely with failures that might harm people.

Having estimated the debris generated, typically as a set of different debris volume scenarios and associated probabilities of occurrence, we then need to consider where that debris will travel and the area at risk from it. This is addressed in Appendix 7 based on both theoretical calculations of the range of travel for objects sliding or toppling from roofs, and on a study of injuries sustained by people in public places as a result of masonry falling from buildings.

The impact of falling masonry on people, and the likelihood of death in the event of a given impact, is then evaluated. Appendix 8 describes a review of literature on the lethality of objects striking the body, and observations and conclusions from our study of injuries sustained by people as a result of falling masonry. The conclusion is that for a simple model such as this, the probability of death can be treated as one if a substantial item of masonry (bigger than a single brick) strikes the head, and zero otherwise. It is recognised that this introduces an element of conservatism (over-statement of risk) for smaller falling objects.

The steps described so far enable the individual risk to be calculated for an imaginary person who is present full-time in the at-risk area. This is known in the Netherlands as plaatsgebonden risico or Local Personal Risk (LPR) and is well established as a risk metric used in the regulation of hazards such as those from dangerous chemicals. Separate at-risk areas are considered in relation to objects that could impact on people passing by outside the building, people running out of it in an earthquake, and people inside it in respect of objects falling through the roof.

The final step is to combine Local Personal Risk with information on how many people are exposed to risk in order to calculate Community Risk, the risk metric of primary concern. This will depend on many factors such as the weather, time of day, whether passers-by walk close enough to the building be exposed to risk and how busy or otherwise the area outside the building is. A particular issue in relation to hazardous objects which could fall above doorways is the widely observed general propensity of people to rush out into the street when a significant earthquake happens. For this study our aim is to estimate the year-round average number of people likely to be present – no attempt is made to estimate the likelihood of different scenarios involving more or fewer people being present.

The approach taken in the model, and the evidence on which it is based, is discussed in the following section.

3. The Risk Model, Step by Step

3.1 Definition of Earthquake Scenarios

Earthquake scenarios are defined in terms of bands of peak ground acceleration (PGA) as follows:

- 0.05 to 0.1g
- 0.1 to 0.2g
- 0.2 to 0.3g
  and so on in increments of 0.1g up to
- Greater than 0.9g.

PGA was used as the basis for definition of the scenarios because

a. it is the most widely used and calculated (and thus most readily available) measure of ground shaking, and

b. our research in New Zealand has found that it demonstrates a good, rough and ready correlation with the failure performance of non-structural building elements (see discussion of Christchurch URM performance and Canterbury chimneys performance in Appendix 2).

It is recognised that this is a simplistic metric which does not fully reflect the many aspects of ground motions that can be significant in terms of damage to buildings. It is considered appropriate for the simple empirical model discussed here.

In the early stages of developing the model the choice of bands was discussed with Matthew Free of Arup and Robin Spence of CAR. It was agreed that bands of width 0.1g were about the most appropriate as they provided reasonable correspondence at the lower levels of shaking to MMI or EMS intensities 5, 6 and 7 which are widely used in reporting building damage in relation to ground motion.

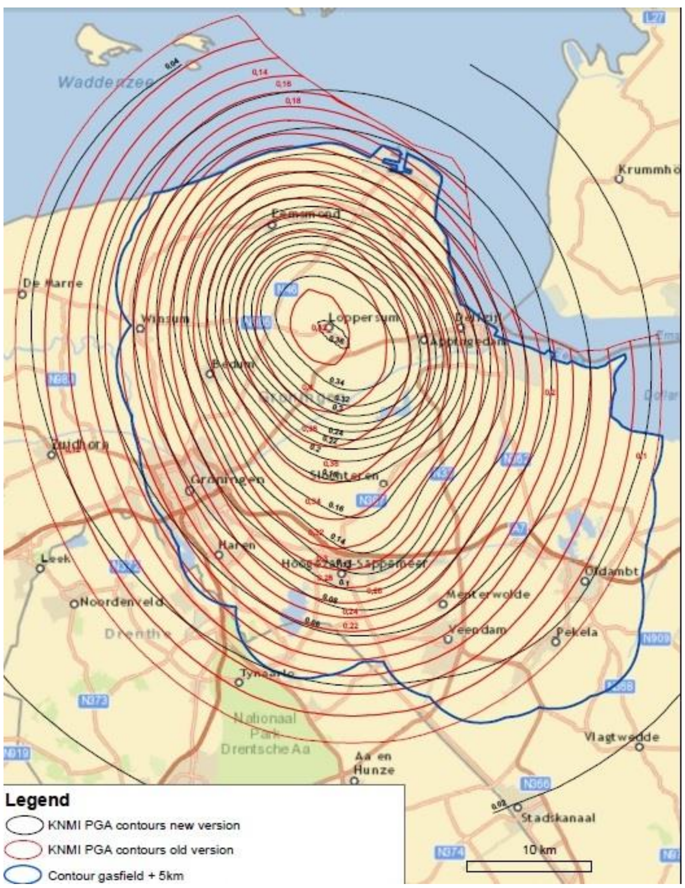
The bottom band has to be truncated at the bottom at a value well above zero, otherwise its frequency could become very large as a result of including frequent tiny earthquakes with insignificant shaking. 0.05g was chosen as a reasonable lower limit at which any significant debris might be detached from buildings. It is notable that the strongest ground motion in the Groningen region to date, the Huizinge earthquake of August 2012, involved measured PGA just above this level in Gaarst and Middelstum, and that no fallen debris of any sort was reported. Though only a single incident, this helps build confidence that significant debris falls are not being ignored by failing to consider ground shaking at levels less than 0.05g PGA.

3.2 Seismic Hazard – Earthquake Frequency

In the course of this work we have set up risk models using both the models available at the time of the 2013 NAM Winningsplan (KNMI and NAM versions, for different time periods) and, more recently, using the recently developed updated model of KNMI[4]. The model is currently configured for implementation across the Groningen region to provide a user option to select either the KNMI 2013 model (which is the basis of the current draft NEN-NPR 9998 norm) or the more recent KNMI 2015 model.

The more recent model takes into account the significant change in slope of the graph of earthquake frequency vs time since gas production was reduced in 2013/14. Where the 2013 model projected an exponential increase in earthquake frequency going forward, the latest model makes less pessimistic assumptions. Changes have also been made in the boundaries of the areas within which earthquakes are assumed to occur, the likelihood of earthquakes having a given magnitude (in particular truncation of magnitude at different maximum levels is now considered) and in ground motion prediction.

Figure A1.3 KNMI 2013 and 2015 Seismicity



The effect of these changes has been to reduce the expected frequency of earthquakes, and in particular to reduce the geographic range over which substantial ground shaking might be

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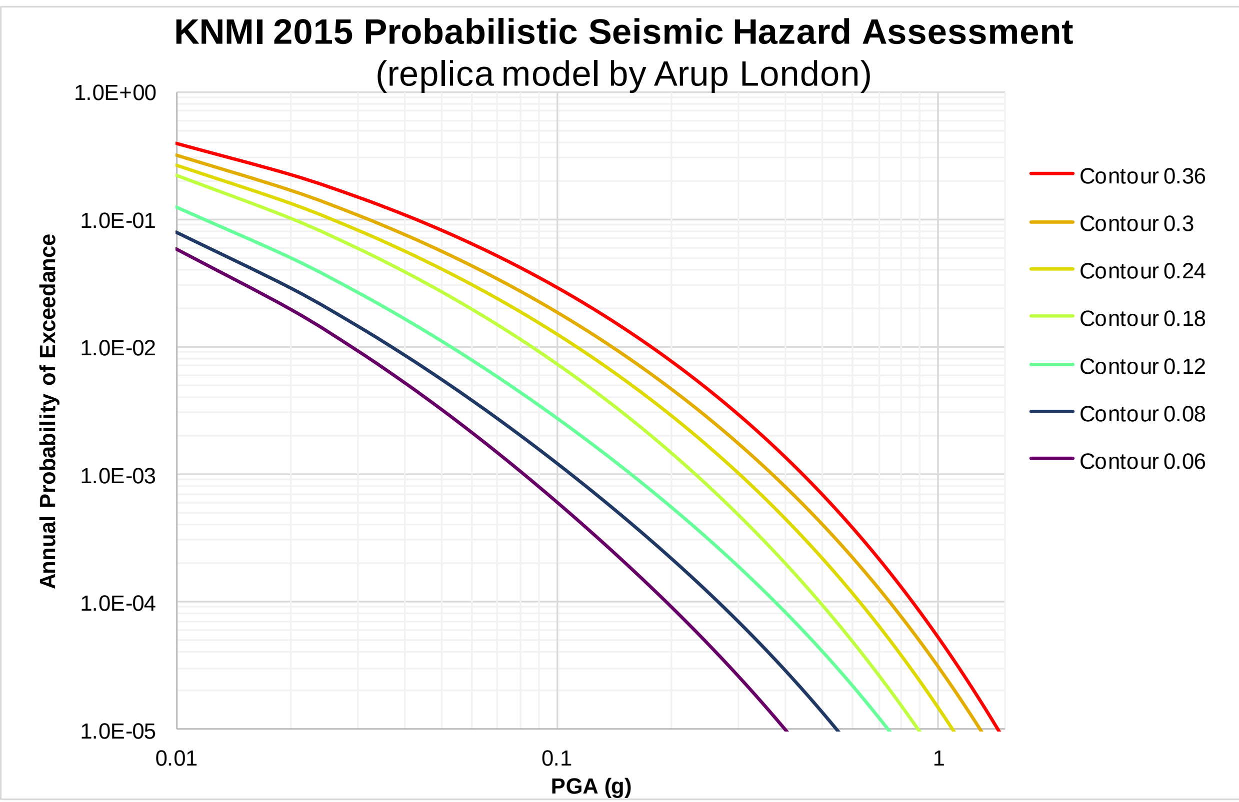
[4] B Dost & J Spetzler, "Probabilistic Seismic Hazard Analysis for Induced Earthquakes in Groningen; Update 2015, KNMI Netherlands, October 2015

expected to occur. Figure A1.3 shows the contours of PGA (based on the 1 in 475 year exceedence frequency which is widely used in standard setting) for both the 2013 and 2015 models.

PSHA results from KNMI could not be obtained on the timescale of this study for locations across the Groningen region. Arup therefore carried out a PSHA to replicate the results of the 2015 KNMI study[5]. This mirrors the KNMI results almost exactly, and has been used by Arup to generate frequency of exceedence curves for locations at different contours on the map in Figure A1.3.

Selected such curves as calculated by Arup are shown in Figure A1.4, while a comparison of the curve at the 0.36g contour for the 2013 and 2015 models is shown in Figure A1.5. Figure A1.6 then shows the resulting frequencies of shaking in the different seismicity bands used in this study, as predicted by the two models for Loppersum and the city of Groningen respectively.

Figure A1.4 Exceedence Frequency (Arup replica of KNMI 2015 model)



[5] Personal Communication, M Free, Arup London, October 2015

Figure A1.5 Comparison of Exceedence Frequency, KNMI 2013 & 2015 Models

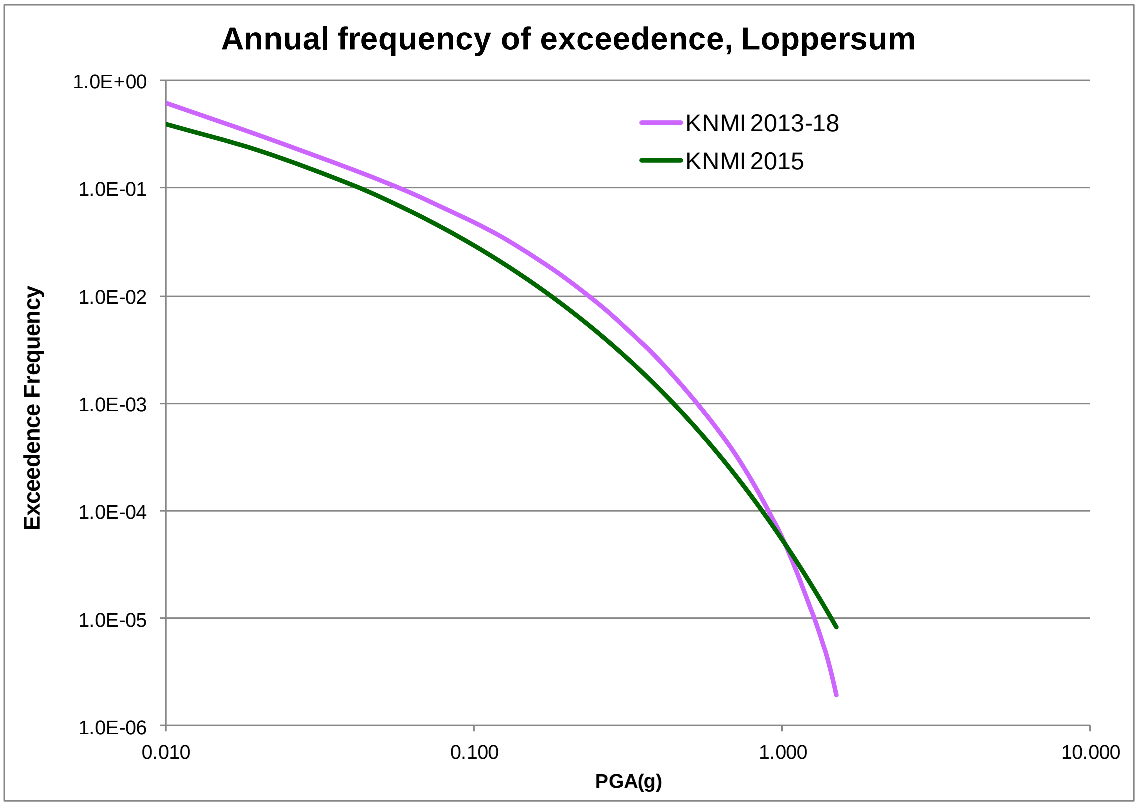


Figure A1.6 Predicted Frequency of Earthquakes in Seismicity Bands

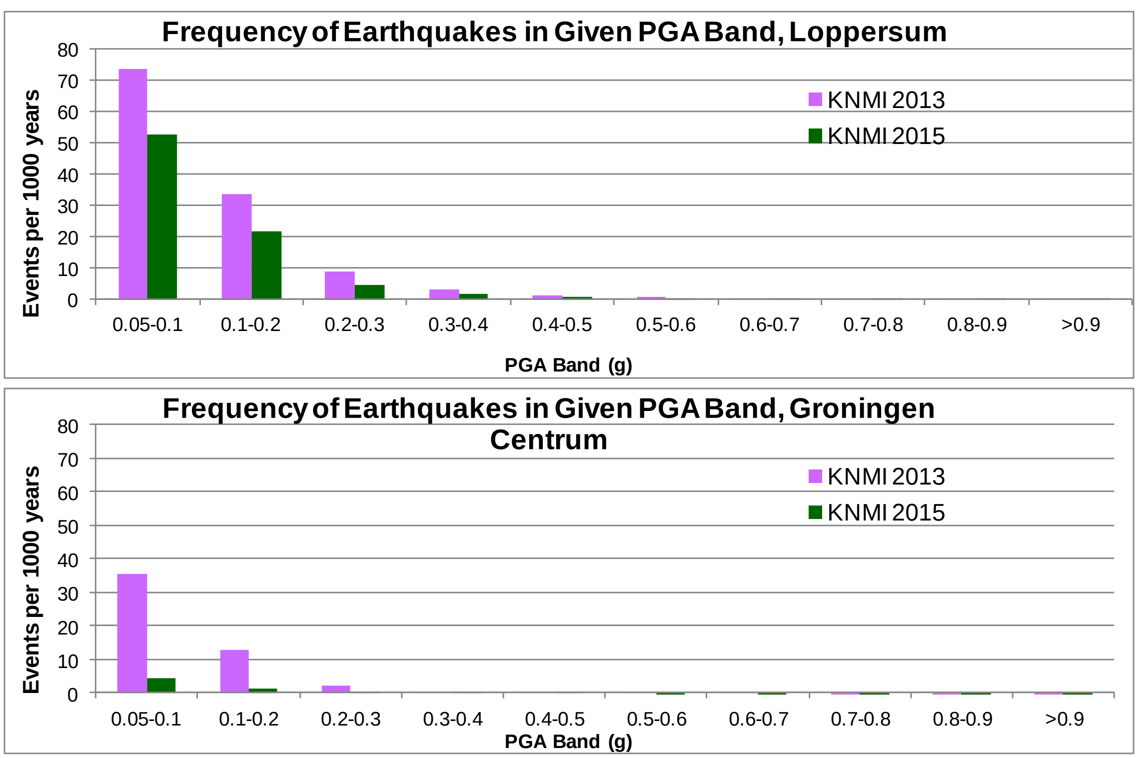


Figure A1.5 shows a modest reduction in predicted frequencies for a given PGA contour, which translates into a reduction in predicted shaking for Loppersum across most of the PGA range, as shown in Figure A1.6. Figure A1.6 also shows, though, the much greater impact of the new KNMI model in reducing the frequency of earthquakes further out from the centre of the gas field. The frequencies of events in the city of Groningen are reduced proportionately far more than those of events in the areas of highest seismicity around Loppersum.

The Arup replica of the KNMI model is used throughout this study as the source of seismicity information linked to a given PGA contour on the KNMI 2015 map. The assumption here is that the shape of the exceedence frequency curve is the same all the way around the contour. The PGAs used here do not account for soil conditions, on which greatly improved information has recently become available for the region. A natural future development of the model would be to take soil conditions into account; the effect would be to increase damage in low shaking bands (as observed in several of the earthquakes described in Appendix 2) but to dampen surface motion and reduce damage for higher shaking bands.

In applying the KNMI 2013 model, an exceedence frequency curve could be obtained only for the area of highest seismicity. For all other areas, exceedence frequencies were estimated by creating a new curve with the PGA scaled by the ratio of (PGA at contour of interest) divided by 0.42 (the PGA at the area of highest seismicity).

Finally, it may be helpful to bear in mind the following in considering what follows about the performance of building elements at different levels of shaking. According to the 2015 model, events in different shaking bands have about the following frequencies in the areas of highest seismicity (as per the dark bars in the upper chart of Figure A1.6):

- 0.05 to 0.1g band   About once in 20 years
- 0.1 to 0.2g band   About once in 50 years
- 0.2 to 0.3g band   About once in 200 years
- 0.3 to 0,4g band   About once in 600 years
- Anything >0.4g   About once in 750 years.

3.3 Debris Generation from Non-Structural Building Elements

There are two aspects to this: first the determination of what non-structural elements are present, and second the estimation of the probability with which they will give rise to given debris volumes under different levels of shaking. The first is established via the Falling Hazards Survey as described in the main report and Appendix 7. We explain here the basis on which we have estimated failure extents and probabilities, dealing in turn with

- The information sources used (Section 3.3.1)
- Previous review studies of chimney and parapet performance (Section 3.3.2), and
- Research and re-analysis of damage data from specific earthquakes (Section 3.3.3).

More information on the earthquake sources studied is provided in Appendix 2, and on the judgments formed in light of that information to propose probabilities of failure for application in the Groningen region in Appendix 3.

3.3.1 Information sources

Our first source was to investigate reviews already carried out of non-structural building element performance across a wide range of earthquakes. We were able to find three significant such sources, which are listed in the upper part of Table A1.1.

We then trawled through reports and data on earthquakes considered of greater relevance for Groningen, in that they involved large populations of broadly Northern European masonry buildings and, wherever possible, earthquakes of shorter duration such as are expected. The earthquakes on which we have primarily relied for information are listed in the lower part of Table A1.1.

Table A1.1 Primary Information Sources on Building Element Performance

Previous Review Studies across Multiple Earthquakes								
Study	**Year**	**Failure Info on**	**Magnitude**		**Shaking**		**Positives**	**Negatives**
Dowrick, GNS NZ		Chimneys	Mostly >6		MMI 6-8+		Many quakes & buildings	B G L R
FEMA, US	2010	Chimneys	Mostly >5		Mostly 0.2 to 1g PGA			
FEMA, US	2010	Parapets						
Re-analysis of data for Earthquakes involving N European style masonry:								
Location	**Year**	**Failure Info on**	**Mag**	**EMS (max)**	**PGA (Max)**	**Depth (km)**	**Positives**	**Negatives**
Liege Belgium	1983	Chimneys +	4.9	7		4	**B R S** D*	G D*
Newcastle NSW	1989	Parapets, Walls	5.6	8		11	B D	L G R
Bishops Castle UK	1990	Chimneys	5.1	6		14	B R D	G L
Roermond NL	1992	Chimneys +	5.4	6/7		17	B R	D L G
Northridge USA	1994	Walls +	6.7	9	>1g	18	G U	B L R
Melton Mowbray UK	2001	Chimneys	4.1	5		11	B R	G L
Dudley UK	2002	Chimneys	4.7	5		14	B R	G L
Folkestone UK	2007	Chimneys	4.2	6		5	**B R S D**	G
Gisborne NZ	2007	Parapets	6.6	8	0.28g	33	D G R	L C
Market Rasen UK	2008	Chimneys	5.2	5		19	B R	G L
Kalgoorlie Australia	2010	Chimneys, Parapets	5	6		2	**D R S**	G
Christchurch NZ	2010	Walls +	7.1	10	0.3g	10	D G R	L
Canterbury NZ	2010	Chimneys	7.1	10	0.3g	10	D G R	L
Christchurch NZ	2011	Parapets, Walls	6.3	10	>1g	5	D G R U	L C
Lorca Spain	2011	Parapets, Walls	5.1	8	0.37g	1	G R S	D

Key to Positives/Negatives:

B Building stock relevance (positive if broadly similar, negative if significant differences from North European practice

C Confounding factors – interpretation made difficult by damage inflicted in previous earthquakes

D Damage information quality (positive if good, negative if poor)

G Ground motion measurements available at sites of damage

L/S Long/Short duration – short duration is of greater relevance to the earthquakes anticipated above the Groningen gas field

R Relevant shaking levels – we are particularly interested in moderate earthquakes; data is of more interest if it covers shaking in the range 0-0.5g than >0.5g

U Upgrade effectiveness can be deduced from some of the damage data.

In any exercise attempting to infer building or building element fragility from previous earthquakes there are inherent difficulties in inferring performance for the buildings and earthquakes of interest from that of different buildings in different earthquakes. In many cases of considerable interest in terms of the buildings exposed and the damage to them, there is no direct measurement of ground motion available from close to the buildings involved (indicated by the large number of ‘G’s in the right hand column of Table A1.1). In cases where ground motion measurements were available, either the buildings may have been significantly different from those in the Groningen region, or the earthquakes may have been of a different character (in particular deep, tectonic, high magnitude earthquakes tend to produce longer duration shaking and more damage than would be expected from the shallow, moderate magnitude earthquakes anticipated in Groningen).

The reported relationship between building damage and ground motion after earthquakes tends to be established in one of three main ways:

a. By studies of building damage close to sites of known, directly measured ground motion at equivalent levels of PGA

b. By studies of building damage in areas where the intensity of ground motion was not directly measured but can be estimated independently of building damage, for example from reports of felt shaking or using ground motion prediction equations, or

c. By studies in which the intensity of shaking is estimated by examining building damage.

Many macro seismic studies after earthquakes are of type (c). In such cases the apparent correlation between damage and shaking is highly unreliable – the relationship derives from the assumption underpinning the analysis rather than from any actual observations. Clearly studies of type (a) provide the most reliable information. Several of the earthquakes in Table A1.1 fall into this category (in particular the Christchurch NZ earthquakes of 2010/11 and the Lorca earthquake in Spain, as well as several of the US earthquakes referenced in Section 3.3.2).

Generally, though, such information is available only in seismically active areas, and so for most of the earthquakes of greater interest closer to the Netherlands we are reliant on studies of type (b) above, where levels of ground motion have to be estimated in the absence of direct measurements. Where the ground motions are known to be significantly different from those expected in the Groningen region (e.g. in the Christchurch and Roermond earthquakes) this is taken into account in making inferences about the performance to be expected from building elements in the Groningen region in comparison with that observed in other earthquakes.

The approximate correspondence between PGA and MMI (modified Mercalli intensity), based on the standard USGS system linked to their Shake Maps, is shown in Table A1.2. The other widely used intensity scale (the European EMS intensity) maps onto PGA in a very similar way.

Table A1.2 PGA and Intensity Levels

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<0.1*	*0.5*	*2.4*	*6.7*	*13*	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	*11*	*22*	*43*	*83*	*>160*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

The general assumption throughout this study is that the match between our shaking bands and reported MMI or EMS intensities is roughly as follows:

- 0.05-0.1g Intensity 5 (V)
- 0.1-0.2g Intensity 6 (VI)
- 0.2-0.3g Intensity 7 (VII)
- 0.3-0.4g Intensity 7/8
- 0.4-0.5g Intensity 8.

Above these levels the intensity scale values cover quite wide ranges of PGA. As will be seen below, it is less important to understand non-structural element performance in detail at higher levels of shaking, as we can be reasonably confident that in most cases a high proportion of building elements such as chimneys, parapets and gables will fail if exposed to significant shaking at PGA greater than 0.5g, and bearing walls may also fail out of plane

Some types of building element such as chimneys and parapets lend themselves to relatively simple types of analytical approach to determining ground motions that could cause failure via different modes. Having reviewed some such analyses (see sections 3.3.2 and 3.3.3) we considered the uncertainties involved to be so large that we preferred to use experience in previous earthquakes as our primary guide to what might be expected in Groningen. We have to some extent incorporated analytical insights for chimneys and parapets, in that these formed part of the development of the fragility functions for chimneys and parapets by the US FEMA, which we included in our consideration of appropriate values for Groningen.

Not shown in Table A1.1, because no failure (as defined here – involving some portion falling to the ground) of any building elements occurred, are two very important, much more local earthquakes, in Huizinge in 2012 and Roswinkel in 1997. For both earthquakes, ground motion measurements are available from close to the site, and considerable efforts were made to establish damage that occurred to buildings in them. We have included both areas in our Falling Hazards survey in order to establish the populations of exposed building elements (as discussed in Section 3.3.3).

3.3.2 Previous review studies

The first such study of which we are aware was carried out by David Dowrick[6] of GNS Science, New Zealand as part of a wider initiative to establish reliable means by which to estimate the intensity of ground shaking in earthquakes. He collected information from various locations after several different (all tectonic) earthquakes. Ground motion was characterised in terms of shaking intensity on the Modified Mercalli scale, and data was used only for cases where independent estimation of intensity was available (i.e. data where building damage was used as a means of estimating intensity of shaking was excluded). His results are summarised in Table A1.3 (reproduced from the paper referenced above).

Table A1.3 Dowrick Correlation of Chimney Damage with Intensity

Intensity	Number of Intensity Cases	Total number of chimneys per case		Proportion of chimneys which fell		
		Min.	Max.	Min.	Mean	Max.
MM8	15	50	6,600	0.12	0.55	1.0
MM7	11	600	6,500	0.02	0.08	0.20
MM6	30	50	30,000	0	0.005	0.030

Note: * "Fall" means that at least the portion of the chimney above the roof-line falls (i.e. breaks off completely).

A second study carried out by Dowrick and others[7] provided a useful clarification of the relationship between "chimneys damaged" (often reported in NZ and other earthquakes) and "chimneys that had actually fallen" via a study of areas exposed to different shaking intensities following the 1968 Inangahua earthquake. The relationship is reproduced in Figure A1.7, and provides a useful rough guide to interpreting reports of "chimney damage" where the extent of such damage is not specified ("fallen" chimneys correspond to about a third to a half of those damaged at lower intensity levels, and to the majority of those damaged at higher intensity levels).

[6] D Dowrick, "The Modified Mercalli Earthquake Intensity Scale – Revisions arising from recent studies of New Zealand earthquakes", Bulletin of the NZ National Society for Earthquake Engineering, Vol 29 No. 2, June 1996
[7] D Dowrick et al, "The Modified Mercalli Intensity Scale – Revisions arising from New Zealand Experience", Bulletin of the NZ Society for Earthquake Engineering, Vol 41 No. 3, Sept 2008

The strengths of the Dowrick information include coverage of a large number of locations and buildings, and the use only of data where estimates of intensity derived independently from building damage reports were available. The limitations in the context of this study include

- ground motions are only loosely characterised,
- the building stock is significantly different from that in the Netherlands (largely wooden houses with masonry chimneys),
- no distinction is drawn between chimneys of different geometry, age etc, and
- the earthquakes are all relatively large magnitude, tectonic events involving long shaking durations (typically of order 10-20 seconds or more).

Figure A1.7 Dowrick et al Chimneys “Damaged” vs “Fallen”

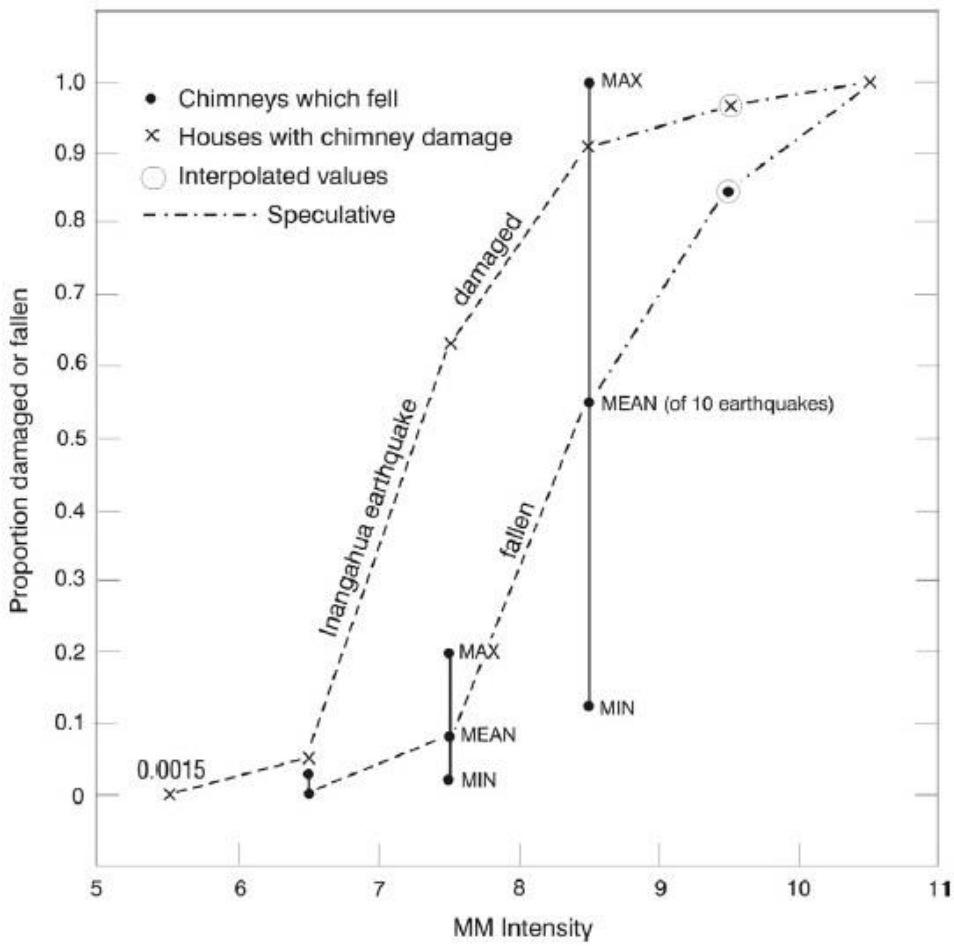


Figure 2. Proportions of brittle chimneys (1) damaged, and (2) fallen, as functions of Modified Mercalli intensity, in New Zealand earthquakes.

When we were already well advanced in this study we became aware of a pair of US FEMA reports reviewing chimney[8] and parapet[9] performance in US earthquakes, and proposing fragility functions (graphs relating probability of damage to ground motion measured in PGA or other parameters). These reports are extremely interesting in that they start by defining damage states and reviewing empirical data (observations on performance in US earthquakes), then discuss and use analytical models to predict failure rates via various mechanisms (toppling, cracking and sliding). They then propose fragility functions for chimneys and parapets generally, based on a combination of empirical data and insights from analytical calculations.

The damage states defined for chimneys are shown in Figure A1.8 (reproduced from the FEMA report referred to above).

Figure A1.8 FEMA Chimney Damage States (reproduced from FEMA P-58/BD-3.9.7)

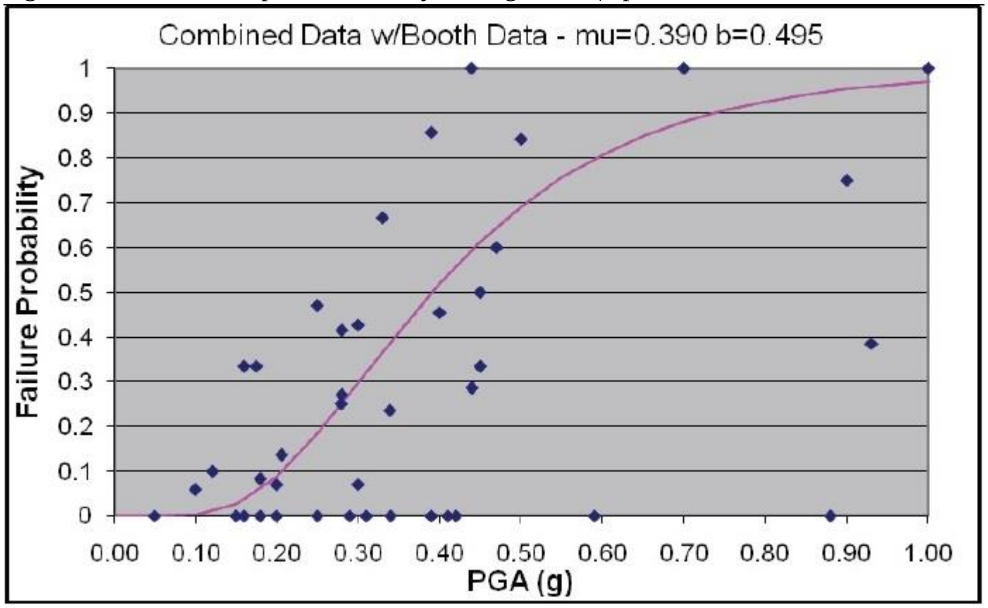
DS1	DS2
Cracking with offset > 1/16”	Toppling of all or portion
	

As we are interested only in failures involving falling of some debris to the ground, it is DS2 (toppling of all or a portion) of chimneys that is of primary interest to this study.

The empirical data (from the San Fernando 1971, San Simeon 1971, Northridge 1994, Nisqually 2001 earthquakes) on chimneys is reproduced from the FEMA report in Figure A1.9.

[8] J Osteraas & H Krawinkler, “Fragility of Masonry Chimneys”, FEMA P-58/BD-3.9.7, 2010 (background document to FEMA P-58 guide to Seismic Performance Assessment of Buildings, 2012)
[9] J Osteraas & H Krawinkler, “Fragility of Masonry Parapets”, FEMA P-58/BD-3.9.8, 2010 (background document to FEMA P-58 guide to Seismic Performance Assessment of Buildings, 2012)

Figure A1.9 FEMA Empirical Chimney Damage Data (reproduced from FEMA P-58/BD-3.9.7)



The immediate observation from Figure A1.9 is that there is very wide variability in the proportion of chimneys that fail at a given shaking level. This is unsurprising as the studies from which the Figure is derived involved different methods, and in particular were examining different populations of buildings without discriminating between the different attributes of chimneys (or of the more detailed ground motion spectra of earthquakes) that might be expected to account for large differences.

The proposed fragility functions for chimneys are shown in Figure A1.10. The failure probability of interest to us is the lower (toppling).

Figure A1.10 FEMA Proposed URM Chimney Fragility Curves (reproduced from FEMA P-58/BD-3.9.7)

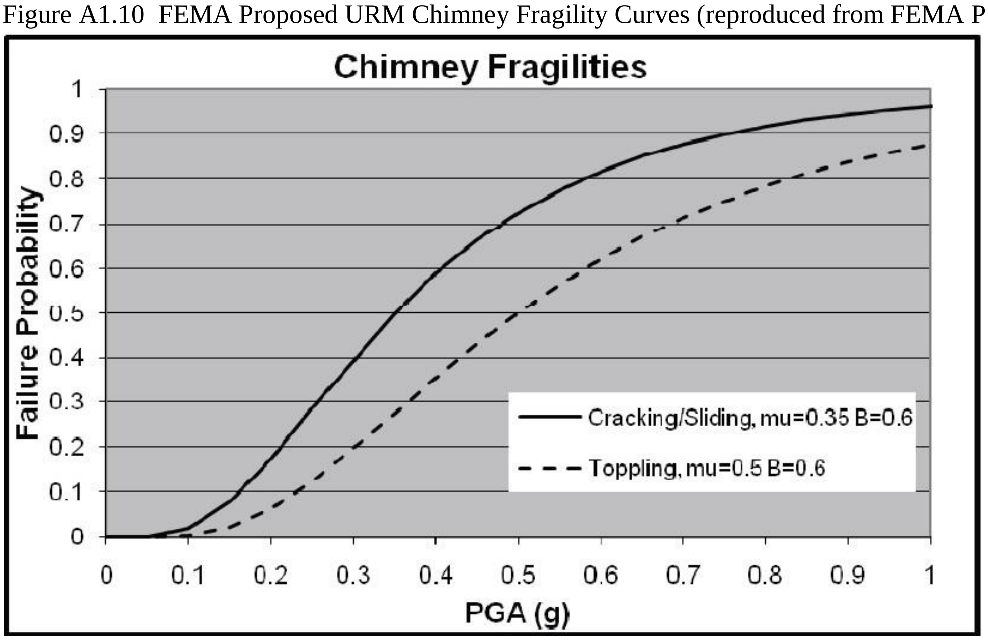


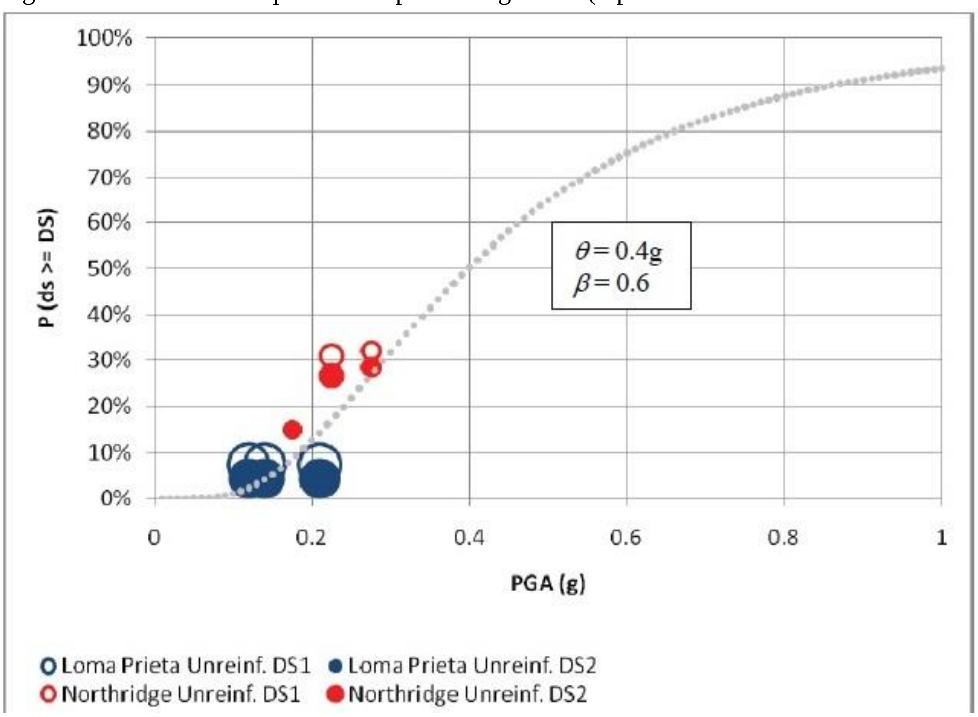
Figure A1.11 provides a counterpart to Figure A1.8 for parapets, showing damage states similarly defined to distinguish between failures in which debris does or does not fall.

Figure A1.11 FEMA Parapet Damage States (reproduced from FEMA P-58/BD-3.9.8)

DS1	DS2
Cracking with offset > 1/16"	Toppling of all or portion
	

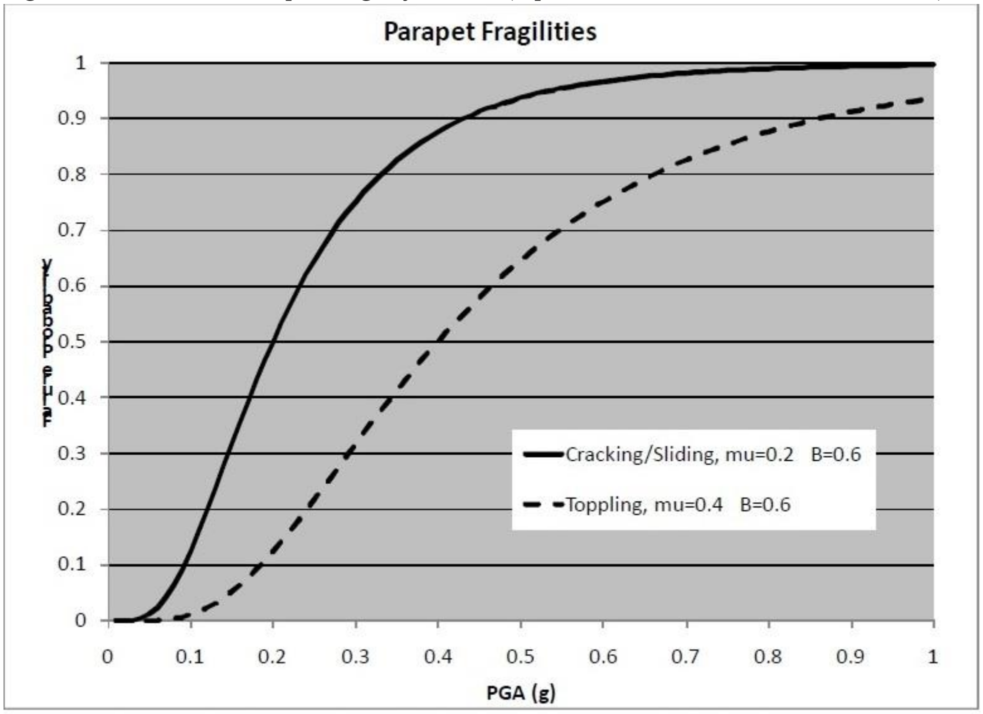
Figure A1.12 provides an overview of the empirical data on parapet failure available for the FEMA study.

Figure A1.12 FEMA Empirical Parapet Damage Data (reproduced from FEMA P-58/BD-3.9.8)



The empirical data is limited to just 566 parapets shaken in two earthquakes (Loma Prieta 1989 and Northridge 1994). The corresponding fragility curves derived after consideration of analytical approaches as well as the empirical data are shown in Figure A1.13.

Figure A1.13 FEMA Parapet Fragility Curves (reproduced from FEMA P-58/BD-3.9.8)



As for chimneys, it is the lower (toppling) curve that is of interest for this study. Comparison of Figure A1.13 with Figure A1.10 suggests that parapets are significantly more fragile (more likely to fail) at low levels of shaking than are chimneys, by about a factor of two for shaking below about 0.3g.

The strengths of these FEMA studies are that they combine data from several earthquake studies and many building elements (note – many more for chimneys than for parapets), and that they bring together empirical data with insights from an analytical approach. Their limitations for our use are that they relate primarily to relatively long duration, large magnitude tectonic earthquakes, the building stock may be significantly different from that in the Groningen region, and for parapets the empirical evidence base is very limited. As in the Dowrick review, no attempt is made to distinguish between the performance of building elements of different ages, shapes, dimensions or condition.

Both the Dowrick and the FEMA studies very usefully distinguish between damage states in which some part of the building elements falls and those in which it does not. A summary of probabilities of failure (meaning "with some portion falling") from Dowrick and the FEMA sources is provided in Table A1.4.

Table A1.4 Summary Failure Probabilities from Dowrick & FEMA Reports

Shaking Band	Chimneys (Dowrick, NZ)	Chimneys (FEMA, USA)	Parapets (FEMA, USA)
0.05-0.1g	no data	0-0.2%	0-1%
0.1-0.2g	0-3%	0.2-6%	1-10%
0.2-0.3g	2-20%	6-20%	10-30%
0.3-0.4g	12-100%	20-36%	30-50%
0.4-0.5g	12-100%	36-51%	50-65%
>0.5g	12-100%	>51%	>65%

Note: the FEMA fragility curves are presented as a single line; the range shown correspond to the values at the lower and upper ends of each band

3.3.3 Re-analysis of earthquake damage data

Appendix 2 provides an overview of what we have learnt from re-analysis of earthquakes in

- the Rhine Valley graben (in particular the Liège and Roermond earthquakes)
- other parts of Europe
- North America, and
- Australia and New Zealand.

Further information is provided in companion reports providing more detailed information on many of these earthquakes, and in some cases of our own research studies. Our aim throughout has been to strengthen our understanding of building element failure in terms of ***how much debris falls to the ground***, particularly at relatively low shaking levels as these are poorly represented in the review sources discussed in Section 3.3.2, and could be of high significance in the low to medium intensity earthquakes anticipated in the Groningen region. Appendix 2 provides an example of the type of analysis carried out, showing how photographic evidence from low intensity UK earthquakes has been collated and classified (App 2 Section 3.2).

In this section of the report we summarise what we have learnt from this research and analysis about chimneys, parapets and gables in turn, then discuss what the more local earthquakes at Huizinge and Roswinkel can tell us, before proposing probabilities of failure for use in Version 1 of the Falling Hazards risk model

3.3.3.1 Insights into building element performance

Tables A1.5, A1.6 and A1.7 provide an overview of the earthquake data which have informed our judgment of failure probabilities for the V1 risk model, for chimneys, parapets and gables respectively. More information on the actual failure data is provided in Appendix 3.

Table A1.5 Overview of Data on Chimney Performance in Earthquakes

Earthquake	Size of sample			Shaking bands of relevance									
	N buildings	N chimneys	N damaged	0.05-0.1g	0.1-0.2g	0.2-0.3g	0.3-0.4g	0.4-0.5g	0.5-0.6g	0.6-0.7g	0.7-0.8g	0.8-0.9g	>0.9g
Liège 1983 (1)	~65000	??	~8000										
Folkestone 2007	707	~700	12										
Other UK (2)	V large	V large	10's										
Roermond (3)	~20000	~20000	100's										
Kalgoorlie (4)	400	138	5										
Canterbury (5)	1358	1248	510										

(1) Numbers of undamaged chimneys not available. No data on chimney characteristics. Detailed data available in principle from Belgian Fonds de Calamités

(2) Isolated exampes of chimney damage from among very large populations of buildings

(3) Numbers refer approximately to Roermond + Heisinge, the worst damage village in N Germany. No detailed damage studies available.

(4) Several 1000's buildings were surveyed from detailed photographs. These 400 buildings were then selected for on the ground, detailed damage studies (including info on % chimney volume that toppled)

(5) All buildings/chimneys within 300m of strong motion stations. Total chimneys approx 1800; 1248 could be matched to the earthquake that caused most damage. Info on dimensions/age of every chimney collected

Important observations on chimney performance (see also Appendices 2 & 3) include:

1. At low shaking levels, failure (meaning "falling of some debris to the ground") is confined to older chimneys on buildings built before about 1920.

2. The failure mechanism of older chimneys at low shaking corresponds more to the shaking loose of bricks than to the snapping of chimneys, which is the primary failure mechanism for newer chimneys.

3. For older chimneys the proportion of chimney volume falling is generally small at low shaking. For newer chimneys, failure is much less likely at low shaking but if they do fail they are more likely to snap, with the fall of a larger proportion of their volume.

4. There is considerable uncertainty in failure probabilities for older chimneys at low shaking levels. On the one hand low intensity earthquakes in the UK demonstrate failure probabilities in our lowest shaking band (0.05-0.1g) of less than 0.1%. On the other, the short duration earthquakes at Liege and Kalgoorlie provide examples of well over 1% of chimneys failing at such shaking levels, as does our study of chimney performance in the (much longer duration) Canterbury earthquakes. Our view is that the performance to be expected in Groningen should be nearer to that of the UK buildings than to that in the worst-hit parts of Liège (where a combination of poor condition buildings, soft soils and

hilly topography created a 'perfect storm' of exacerbating factors) and in Canterbury (where shaking was prolonged in a M7 earthquake).

5. As shaking increases, so the uncertainty in fragility and differences between chimneys reduces. A majority of masonry chimneys should be expected to collapse under shaking in excess of 0.4g.

Table A1.6 Overview of Data on Parapet Performance in Earthquakes

Earthquake	Size of sample			Shaking bands of relevance									
	N buildings	N* parapets	N damaged	0.05-0.1g	0.1-0.2g	0.2-0.3g	0.3-0.4g	0.4-0.5g	0.5-0.6g	0.6-0.7g	0.7-0.8g	0.8-0.9g	>0.9g
Liège 1983(1)	~65000	??	10's??										
Newcastle 1989(2)	359	156	18										
Northridge 1994(3)	Large	100's	10's										
Gisborne 2007(4)	55	101	19										
Kalgoorlie 2010(5)	400	284	19										
Darfield 2010(6)	618	494	34										
Christchurch 2011(7)	627	485	327										
Lorca 2011(8)	7000	??	~100's										

** Parapet numbers include all facades of buildings known to have had a parapet*

(1) Numbers of parapets and damaged parapets not known. Detailed data available in principle from Belgian Fonds de Calamités on every aspect of damage to about 9000 buildings that claimed from the fund.

(2) Based on TTAC re-analysis of EEFIT photo dataset archived by CAR

(3) Further information is available (see refs in FEMA report) but not able to access to date. Of particular interest as includes before/after upgrading to meet LA County ordnances

(4) Detailed study of parapet damage vs dimensions, heights, orientation, support etc but no info on what fell. Some plain parapets fell inward. Interpretation complicated as this was 3rd quake of similar shaking in 20 years.

(4) Several 1000's buildings were surveyed from detailed photographs. These 400 buildings were then selected for on the ground, detailed damage studies (including info on % parapet volume that toppled)

(6) Based on TTAC analysis of Geoscience Austtralia photo dataset. Though shaking deep & prolonged, unlike the 22/2/11 event the buildings had NOT been badly damaged by previous earthquakes

(7) This N parapets figure is almost certainly N(buildings with parapets) rather than total on all facades. Massive parapet damage accounted for several deaths outside buildings. Pre-damaged in 4/9/10 earthquake.

(8) No detailed building damage survey available. Numerous photos of whole streets inundated by parapet debris from both sides. Many were masonry parapets on concrete buildings. 9 deaths attributed largely to parapet debris.

Our observations on parapet performance in many ways mirror those on chimneys:

- At very low shaking failure is primarily confined to older parapets
- Newer and older parapets converge and uncertainty reduces as shaking increases
- Probabilities of failure are broadly similar to those of chimneys.

Observations specific to parapets include

- Older as well as newer parapets appear more inclined than chimneys, if they do fail, to lose a substantial proportion of their volume as falling debris.
- Plain parapets can fall inward as well as outward (ref Gisborne, App 2 – no known examples of parapets falling inward through roofs), but parapets with any sort of ornamentation on the outer face tend always to fall outwards.

Table A1.7 Overview of Data on Gable Performance in Earthquakes

Earthquake	**Size of sample**			**Shaking bands of relevance**									
	N buildings	**N*** gables	**N** damaged	**0.05-0.1g**	**0.1-0.2g**	**0.2-0.3g**	**0.3-0.4g**	**0.4-0.5g**	**0.5-0.6g**	**0.6-0.7g**	**0.7-0.8g**	**0.8-0.9g**	**>0.9g**
Liège 1983(1)	~9000	??	10's??										
Newcastle 1989(2)	359	47	12										
Roermond 1992(3)	~20000	??	10's										
Northridge 1994(4)	Large	??	10's+										
Darfield 2010(5)	618	188	25										
Christchurch 2011(6)	627	163	105										

** Gable numbers correspond to the number of facades of buildings identifiable as gable walls*

(1) Numbers of gables and damaged gables not known. Detailed data available in principle from Belgian Fonds de Calamités on every aspect of damage to about 9000 buildings that claimed from the fund.

(2) Based on TTAC re-analysis of EEFIT photo dataset archived by CAR

(3) Numbers refer approximately to Roermond + Heisinge, the worst damage village in N Germany. No detailed damage studies available.

(4) Further information is available (see refs in FEMA report) but not able to access to date. Of particular interest as includes before/after upgrading to meet LA County ordnances

(5) Based on TTAC analysis of Geoscience Austtralia photo dataset (see App. 2). Though shaking deep & prolonged, unlike the 22/2/11 event the buildings had NOT been badly damaged by previous earthquakes

(6) This N gables figure is almost certainly N(buildings with gables) rather than total on all facades. Massive parapet damage accounted for several deaths outside buildings. Pre-damaged in 4/9/10 earthquake.

At lower shaking levels, gable failure appears much less common than chimney and parapet failure. As for chimneys and parapets, it appears to be primarily an issue for older buildings at low shaking levels, and generally to involve detachment of small numbers of bricks at shaking levels below about 0.2g. As shaking increases the gap between new and old, and the gap between gables and chimneys/parapets, appear to shrink. Above about 0.5g gables appear to be nearly as vulnerable to falling, and to losing a large part of their volume, as are parapets and chimneys.

3.3.3.2 Benchmarking against Huizinge and Roswinkel

The two largest earthquakes to have occurred in recent times in and near the Groningen region were at Huizinge in 2012 (above the Slochteren gas field) and at Roswinkel in 1997 (above a smaller field to the south). Neither involved any recorded building elements falling; a CCTV camera captured images of bottles toppling from a shop shelf in the Huizinge event. Both areas were surveyed (see Section 4) to establish how many potential falling hazards were present. Table A1.8 shows the results for Huizinge and Table A1.9 those for Roswinkel[10].

Table A1.8 Falling Hazard Exposed Population – Huizinge

Location	Chimneys		Gables		Parapets	
	Pre-1920	1920 onward	Pre-1920	1920 onward	Pre-1920	1920 onward
Garsthuizen	2	14	6	18	0	0
Middelstum	106	272	17	144	13	2
TOTAL	**108**	**286**	**23**	**162**	**13**	**2**

In terms of their combination of number present and fragility, if anything had failed in either event it would have been expected to be chimneys. At Huizinge, there were 108 pre-1920 chimneys exposed, which gives us reasonable confidence that the associated probability of chimney failure could not have been much higher than 1%. This is consistent with our view that the higher probabilities of failure at 0.05-0.1g shaking experienced in the worst-hit suburbs of Liège and in the M7 Darfield earthquake Canterbury NZ are unlikely to apply in Groningen. But there were insufficient chimneys exposed to inform us as to what a reasonable estimate of failure probability for this shaking band should be in the Groningen region, particularly bearing in mind that the maximum measured PGA was around 0.06g, so quite close to the bottom end of our lowest shaking band.

Table A1.9 Falling Hazard Exposed Population – Roswinkel

Location	Chimneys		Gables	
	Pre-1920	1920 onward	Pre-1920	1920 onward
EMS 5 Area	44	487	71	415
EMS 6 Area	4	5	0	28
TOTAL	**48**	**492**	**71**	**443**

Roswinkel is particularly interesting as it involved a relatively high measured PGA of 0.3g, which in the earthquakes we examined had typically been sufficient to collapse several 10's of % of older, and a good percentage of newer, chimneys. The simple fact that the isoseismal map for such a high measured PGA had contours of only EMS 5 and EMS 6 shows that the intensity

[10] Note that, in line with the recording policy for the survey, hazardous objects were only recorded if they were above a doorway or public space, or were located at height above the roof of an occupied building. The figures in Tables 8 & 9 thus tend to understate the population of chimneys, parapets and gables.

experienced, by people and buildings, was well below that which would be expected from a simple PGA/Intensity relationship such as that shown in Table A1.2 above.

With 48 pre-1920 chimneys in all, there can be reasonable statistical confidence that the "true" failure probability of chimneys in the event was no more than a few %. This provides good support for the hypothesis that very short duration, low magnitude earthquakes may be considerably less damaging to buildings and non-structural building elements than the associated maximum PGA would suggest. But this is just a single data point – we find it an extremely interesting and relevant one, but do not feel we can allow it altogether to outweigh the very large volume of evidence from other earthquakes to suggest that chimney and parapet failures can reach very significant levels under shaking of order 0.2 or 0.3g.

3.3.3.3 Fragility assumptions adopted in V1 model

Taking all these considerations into account, we have adopted in the V1 model the fragility assumptions which are shown in full in Appendix 3. Table A1.10 provides an overview of our proposed failure probabilities in comparison with those proposed by Dowrick and FEMA for chimneys.

Table A1.10 Proposed Chimney Failure Probabilities: This Study vs Previous Reviews

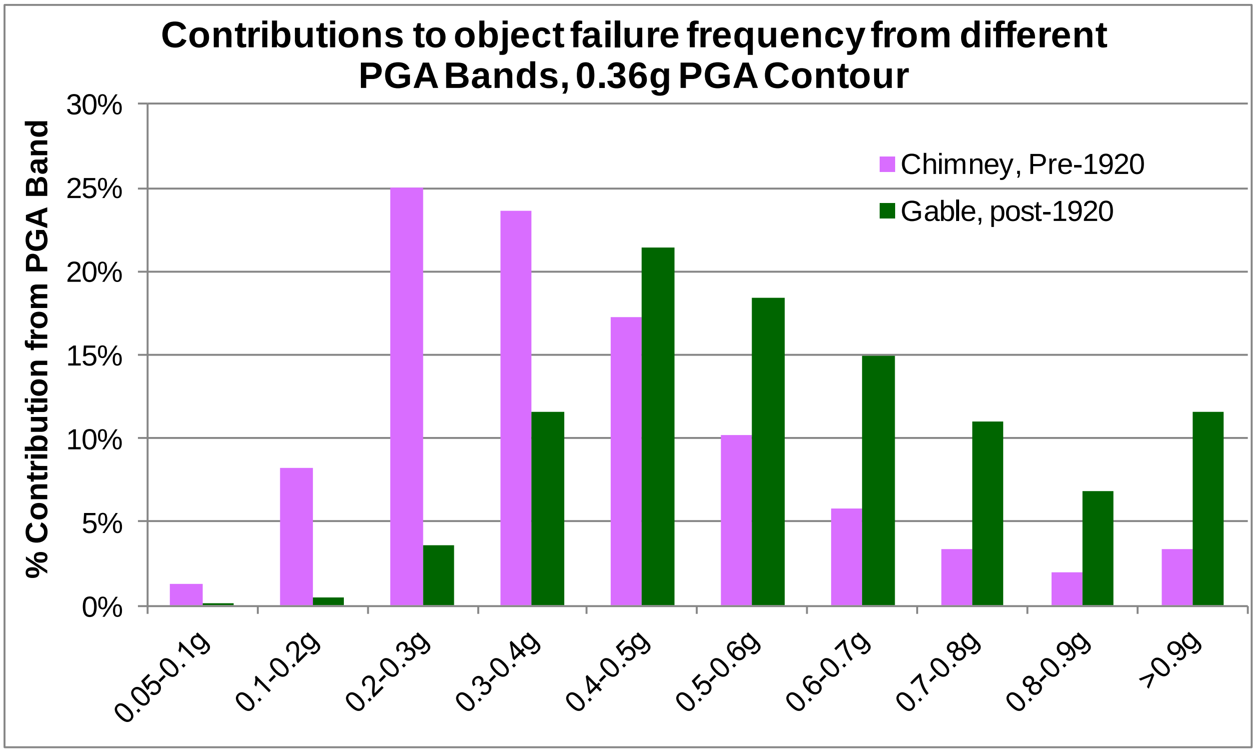
Shaking Band	Chimneys (Dowrick, NZ)	Chimneys (FEMA, USA)	Parapets (FEMA, USA)	Chimneys pre-1920 (this study)	Chimneys post-1920 (this study)
0.05-0.1g	no data	0-0.2%	0-1%	0.1-3%	0.01-0.3%
0.1-0.2g	0-3%	0.2-6%	1-10%	0.5-20%	0.1-3%
0.2-0.3g	2-20%	6-20%	10-30%	6-35%	1-15%
0.3-0.4g	12-100%	20-36%	30-50%	20-60%	5-45%
0.4-0.5g	12-100%	36-51%	50-65%	36-80%	15-60%
>0.5g	12-100%	>51%	>65%	50-90%	30-70%

Note: the FEMA fragility curves are presented as a single line; the range shown correspond to the values at the lower and upper ends of each band

We can now combine the estimates of fragility in Appendix 3 with the seismicity estimates discussed above to estimate the frequency of failure of chimneys, parapets and gables, and the contribution to it of different bands of shaking. Figure A1.14 shows this breakdown for an old chimney (the most fragile) and a newer gable (the least fragile of the objects for which we have empirical data). The calculations for both are based on the KNMI 2015 seismic hazard assessment, as replicated by Arup.

Figure A1.14 is extremely interesting as it suggests that, even for the most fragile object in our set (an old chimney), the contribution to risk from shaking in the lowest two PGA bands of the set of shaking scenarios we consider is quite small – less than 10% between them. This means that the results of the model are unlikely to be particularly sensitive to fragility assumptions for these lowest bands of shaking, which is where uncertainty in fragility is greatest. For a less fragile object such as a modern gable, this relative insensitivity to fragility uncertainty extends up to about 0.3g.

Figure A1.14 Contributions to Falling Object Failure Risk from Shaking Bands



Note*: the upward kink for the right-most PGA band in Figure A1.14 arises because the frequency of earthquakes exceeding 0.9g shaking is estimated to be higher than that of the 0.8-0.9g PGA band by the PSHA which generated the underlying seismicity data.*

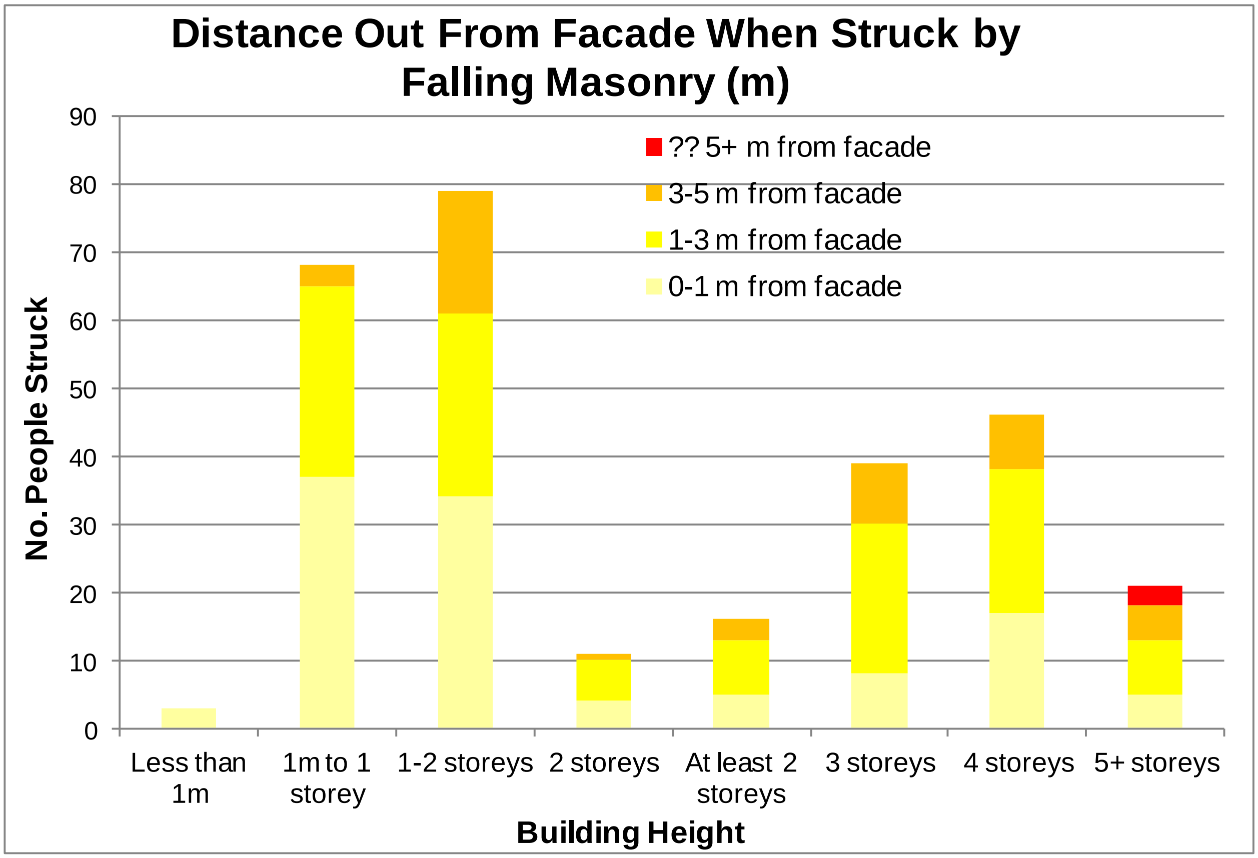
3.4 Debris Travel and Hazard Range

People outside a building are clearly at risk if they are close to the building, but at some point on moving away from it will become out of range of falling masonry or other objects. We have estimated the range outward from a building facade for which people are at risk via two studies. In the first we collected a database of examples of incidents in which people had been injured, or narrowly escaped injury, when masonry fell into public places. In the second we carried out simple analytical calculations of the distances that an object sliding off or toppling from a roof could travel for given roof and object parameters, and then applied these to 5000 buildings in the Groningen area for which Rapid Visual Screening (RVS) results were available providing information on gutter heights and roof slopes. These studies are described in greater detail in Appendix 8; a brief description of the findings is provided below.

Our study of real incidents included about 240 incidents in which people were struck by masonry falling from buildings, as a result of storms, poor building maintenance, earthquakes, items dropped by construction workers and other causes. For each of these incidents the scale of the object falling, the height from which it fell and the distance from the building facade of the injured person was established. Other information was also collected on where on the body the victim was struck and their ultimate health outcome (this is referred to again in Section 3.5 when estimating the probability of death in the event of being struck by falling debris).

Figure A1.15 shows how far out from building walls people were standing when they were struck by debris falling from buildings.

Figure A1.15 Distance from Facade of People Struck by Falling Masonry



Note – the small number of incidents involving "height < 1m" all involved low walls collapsing outdoors. Sadly one of the three incidents proved fatal for a toddler playing in the area.

With the exception of a single incident (in red on the right hand side of the chart, involving three people in a car struck when a large industrial building collapsed), we could confidently determine that the people struck were within 5m of the building facade. In that single incident we suspected, but were not confident, that the car was within 5m of the facade.

Our conclusion from Figure A1.15 is that a large proportion of masonry debris falling from buildings, of all heights, is concentrated within 3m of the building wall. In a modest minority of cases, the hazard range could extend up to 5m. If it happens at all, travel beyond 5m for objects falling from buildings is extremely rare[11].

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[11] We note that travel beyond 5m may be more credible in cases where, for example, a tall, strong wall topples out of plane. Several people were killed in the Christchurch earthquake of 22/2/2011 at a distance of several metres from building facades by walls collapsing in this way. We have focused on objects falling from buildings so, although our database includes some such examples (including the only cases of injury that might possibly have occurred more

Our calculations of debris sliding and toppling from roofs gave us confidence that this conclusion could safely be extended to buildings in the Groningen region.

The falling hazard model thus makes the following assumptions in assessing the risk outside buildings from falling masonry and other objects:

1. The risk is minimal (assumed zero) at distances greater than 5m from the building facade.
2. If there is publicly accessible space (e.g. a pavement, or the entrance to or space around the walls of a building with public access) within 5m of the building wall, then anyone walking past or into/out of the building is assumed to be at risk from falling debris.
3. The risk to which they are exposed is estimated on the basis that debris falls randomly within a 3m strip in front of the building facade.

These assumptions lead to a modest degree of overestimation of risk for people walking past buildings. But the community risk to passers-by is greatest in areas of very heavy footfall, in particular shopping centres, where passers-by are generally walking on pavements within 2-3m of building facades. Thus the assumptions are most accurate where the community risk for passers-by is greatest.

The implication of these assumptions is that for passers-by the area at risk from falling masonry is taken to be a strip of 3m width running for the length of the building facade.

For people running out of doorways our general assumption is that people fleeing a building are likely to run away from the facade within about 1m either side of a straight line heading directly away from the doorway. The area at risk from hazardous objects falling above doorways is thus taken as $10m^2$. This is considered an appropriate value for most residential buildings. It is probably less accurate for larger buildings where doorways may be larger and patterns of use different from those for houses.

3.5 Consequence of Debris Impact on People

The effects of masonry debris impacts on people are discussed in Appendix 8. In addition to the study of actual incidents of people being struck by falling masonry, described above, we carried out a review of the literature relating to the injury impacts of objects impacting the human body. This literature is substantial, covering contexts including

- Road traffic accidents
- Impact of blast fragments
- Design of non-lethal weapons for crowd control
- Design of protective helmets (from sporting to military purposes)
- Causes and treatment of blunt trauma injuries generally

---

than 5m from a building wall) we did not actively explore such incidents. Our conclusions thus may not be as applicable to whole wall failures as they are to objects falling from buildings.

- Workplace accidents, and most recently
- Risk of impact of small remotely-controlled aircraft on people.

We developed a quite complex model relating the probability of death to the mass of a masonry object and the height from which it fell. For large objects (more than 2-3 bricks in mass), the probability of death was very high if struck on the head from virtually any realistic height. After discussion with NAM and Arup we simplified the model drastically to revert to a very simple concept:

> ***If a masonry objects strikes a person on the head, it kills them; if it does not strike them on the head then it does not kill them.***

Taken in isolation, this would clearly provide pessimistic estimates of lethality probability, particularly for smaller objects falling from lower heights. However, this inaccuracy is greatly reduced by combining the assumption above with the following assumptions as to the at-risk area swept out by objects as they fall:

> ***The area swept out by the object as it falls through the air corresponds to the product of***
>
> - ***The longest dimension of the whole object (height, width or depth)***
> - ***The next longest dimension of the whole object, and***
> - ***The percentage of the object volume falling for a given damage state.***

The effect of these assumptions is that for higher damage states, when most of the object is falling, the at-risk area is based on the falling orientation that maximises risk. For lower damage states, though, the effect is to make the swept-out area considerably smaller than the maximum possible. This effect can be illustrated with an example. Consider a chimney of dimensions 1m high x 0.5m wide x 0.5m deep, failing (a) in damage state 5, in which 70-100% of the object falls, or 85% on average, or (b) in damage state 1, in which 1-3% of the object falls, or 1% on average.

for case (a): The area swept out is 1m x 0.5m x 0.85

for case (b): The area swept out is 1m x 0.5m x 0.02.

For case (a) this orientation provides close to the maximum possible area put at risk by the chimney fragment as it falls through the air. For case (b), though, we are effectively assuming that a thin slice of the chimney is falling edge-on. The real situation in case (b) is more likely that 2 or 3 individual bricks are falling. Our assumption for case (b) corresponds to an orientation which makes the area swept out considerably smaller than the average possible (if the thin slice fell differently it could sweep out an area 0.5mx0.5m rather than 0.5mx0.02m as we have effectively assumed), but which is more realistic in terms of the real potential of the falling object to kill someone (which would be much lower if falling in a face-on rather than an edge-on orientation).

In order to test the validity of this simplified model for use in risk assessment, calculations were carried out (as described in Appendix 8) using the more complex model to estimate probabilities of lethality for a chimney of average dimensions for the Groningen region, failing in each of the five damage states considered, for all possible falling orientations. The "best" model calculations are the averages over all possible falling orientations, calculated on two different bases:

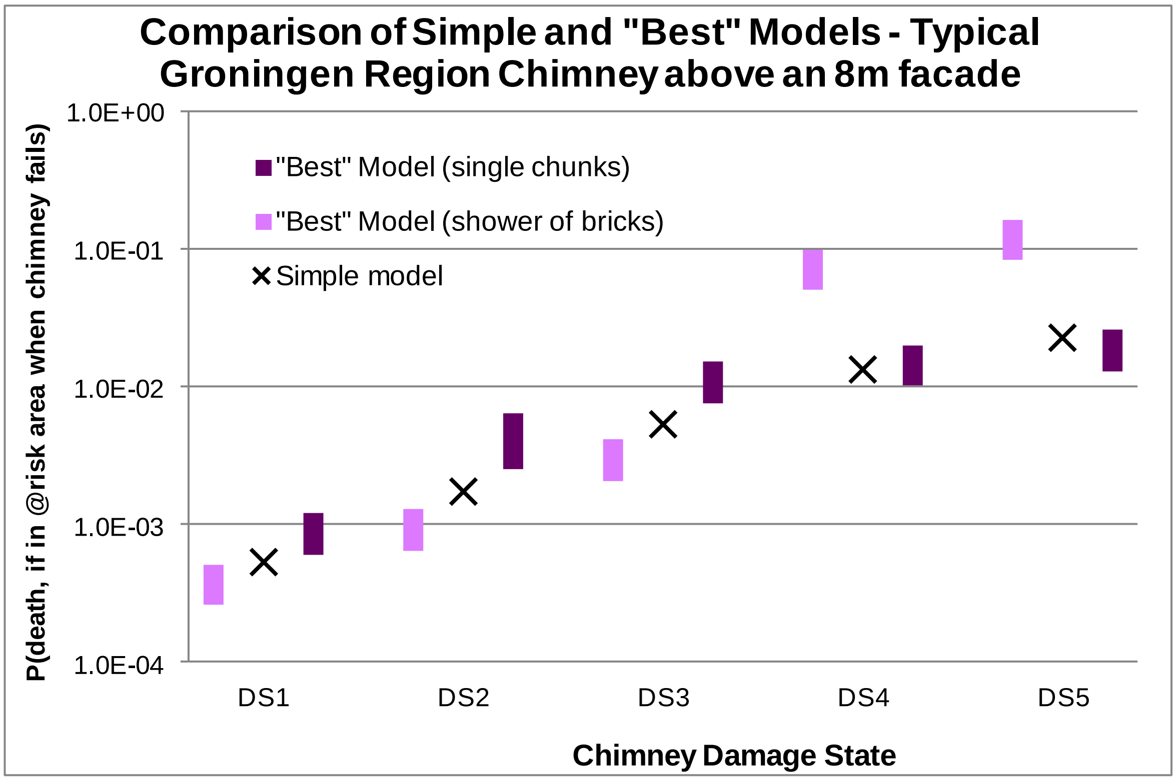
a. that the falling material falls as a single "chunk", and

b. that the falling material falls as a "shower" of individual standard sized bricks.

The true probability of failure would be somewhere in-between that calculated on bases (a) and (b) – closer to (a) for high damage states in which the failure mode corresponds to snapping off of a large proportion of the object, and closer to (b) for lower damage states for which the failure mode corresponds to a few individual bricks detaching from the object and falling.

The results are shown in Figure A1.16.

Figure A1.16 Lethality Estimates – Simplified vs Full Model



For every damage state, the probability of death for a person present calculated using the simplified model is in-between that calculated by the more complex model using "single chunk" and "shower of bricks" assumptions. The simplified model has the additional attractive feature that the results are

- closer to those of the "single chunk" assumption for high damage states (which in reality are likely to correspond to a large part of the object snapping and falling in a coherent mass), but
- closer to the "shower of bricks" assumption for low damage states (which in reality are likely to correspond to a few individual bricks detaching from the object and falling).

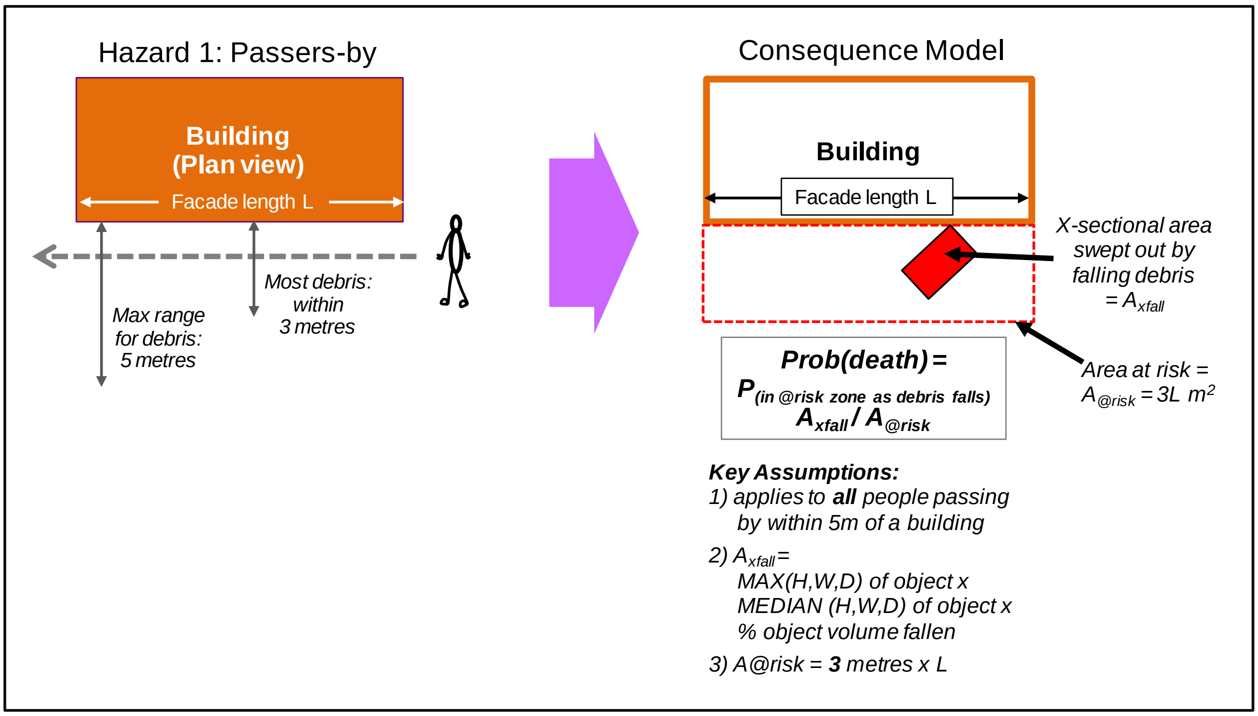
Our conclusion is that the simplified model, combining simple assumptions as to both lethality and orientation of objects as they fall, provides a sound basis for risk assessment.

Having established a simple way to estimate probability of death from a given impact, we can now use this to derive appropriate models of lethality for the three risk exposure routes considered in the model:

- People walking past the building facade (at-risk area = facade length x 3m)
- People running out of doorways (at-risk area assumed = $10m^2$)
- Objects falling through roofs into buildings (at-risk area = building floor area).

Figure A1.17 illustrates the situation of a person walking past a building facade, and how their probability of death is estimated.

Figure A1.17 Consequence Model for People Walking Past a Building



Based on our simple model of lethality, the probability of death of the person while in the at-risk area is simply the ratio of the area A_{xfall} swept out by the falling object to the area at risk. The area A_{xfall} is calculated from the dimensions of the object measured in the falling hazards survey and the percentage of the object falling for a given damage state, assuming the worst possible orientation of fall for the whole object. To each dimension is added the radius of an average human head (taken as 10cm) to allow for the fact that the object will strike the head if the centre of the head is within one radius of the object edge. Thus

$$A_{xfall} = [\text{Max(H,W,D of object)} + r_{head}] \times [\text{Median(H,W,D of object)} + r_{head}]$$

x [proportion of object fallen for a given damage state]

The area $A_{xfall,whole}$ is calculated for the whole of the object, and a corresponding swept out area for each object damage state k is then calculated as

$$A_{xfall,k} = A_{xfall,whole} \times \alpha_k ,$$

where α_k is the proportion (percentage) of the object falling for damage state k, as summarised in Table A1.11 below. The proportion falling is taken as the mid-point of the range encompassed by each damage state. The damage states were defined so as to provide a suiTable A1.range of values for a simple risk assessment, while being reasonably easy to estimate for given building components via analysis of photographs of earthquake damaged buildings.

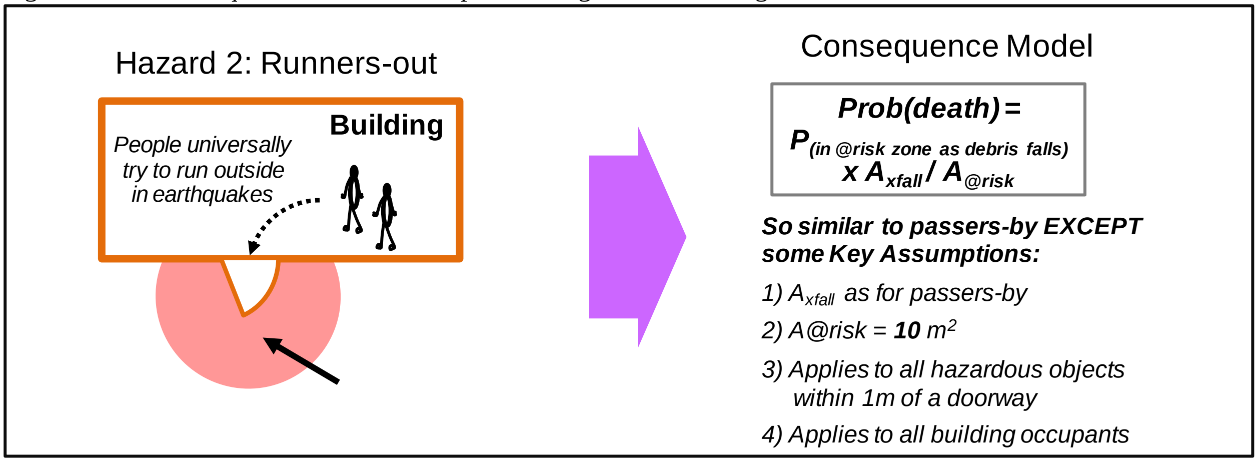
Table A1.11 Damage States and Proportions Falling

DS==>	**1-3%**	**3-10%**	**10-30%**	**30-70%**	**>70%**
α	0.02	0.065	0.2	0.5	0.85

The assumption here is that the object falls, whatever its damage state, as a single "chunk" of debris. In an earlier version of the model an alternative option was provided in which the object could be assumed to fall, instead, as a pile of individual bricks. This reduced the probability of death for each impact, but increased the number of impacting objects and generally made a modest increase in calculated probabilities of death. After discussion with NAM, this model was dropped as it added complexity while making only a modest difference to estimated lethality. Any over-optimism (under-estimation of risk) in treating objects as a single piece of debris is considered to be more than compensated for by the pessimism (over-estimation of risk) in assuming that whole objects always fall in the worst possible configuration, and that any proportion of an object falling is lethal if it strikes the head.

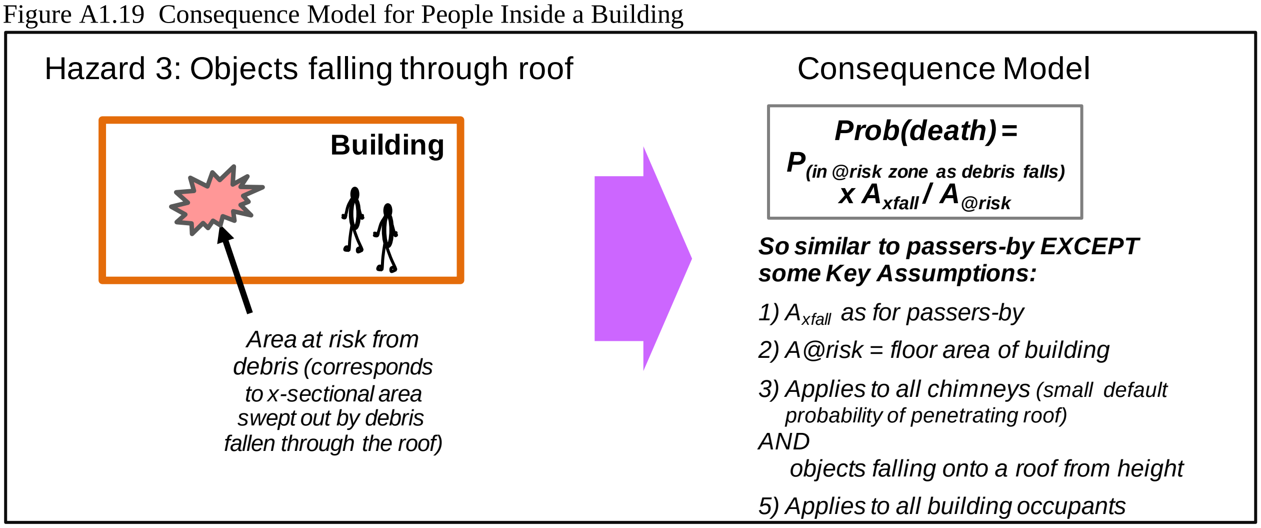
The area swept out is calculated for each object damage state and is then used similarly in estimating the probability of death for people running out of a building and for those inside a building when an object falls through the roof, as illustrated in Figures 18 and 19.

Figure A1.18 Consequence Model for People Running from a Building



Note in Figure A1.18 the assumption is made that everyone in the building has the same chance of death if they are within the at-risk area. The chance that people inside will actually be in that at-risk area is addressed in the following section.

Figure A1.19 Consequence Model for People Inside a Building



Note in Figure A1.19 that there are two cases in which objects are considered capable of falling through roofs into buildings:

1. Every chimney is assumed to have a modest chance (currently assumed to be 3%) of falling through the roof on which it sits. This assumption is based on observations in earthquakes (notably Liège 1983, Christchurch 2010 and Market Rasen 2008) in which people were killed or injured by chimneys falling through the roof on which they stood, and on an aerial video of Liège taken the morning after the earthquake, in which two out of 56 roofs can be seen with large holes where a chimney has fallen through. For smaller objects, ceilings/floors should provide considerable protection, and probabilities of death for someone whose head is in the path of the object are assumed as follows:

   1 for DS5 (>70% falling), 0.7 for DS4 (30-70% falling),
   0.5 for DS3 (10-30% falling), 0.1 for DS2 (3-10% falling),
   zero for DS1 (1-3% falling).

2. Where an object of any kind is located at height above a roof such that, if it fell, it could impact that roof at speed, it is assumed that the whole falling object penetrates the roof and travels through any intermediate floors until it reaches the ground. For the purpose of this study, this assumption has been applied to any object of which some part can fall 2m or more onto a roof. This applies particularly to chimneys and gables that can fall onto other occupied building areas, and is recognised as providing a cautious basis for the assessment (i.e. as tending to overestimate, rather than to underestimate, risk.

3.6 Occupancy of At-Risk Areas

In order to calculate Community Risk from falling hazards we need to estimate the average number of people in the at-risk area for the different exposure routes to risk, which are considered in turn below.

3.6.1 Passers-by in front of building facade

Each person who walks past a building makes a small contribution to the total average number of people occupying the at-risk area over a defined time period, equal to the time spent in the at-risk area divided by the time period of interest. So, if a person spends 10 seconds in the at-risk area, their contribution to average number present over a time of one hour would be 10/3600.

To calculate the total average number at risk we thus need to

- pick a time period (we use an average week, as this is the basis on which commercial footfall data is often available)
- estimate how many people walk past the building facade in that time period
- estimate for how long each is at risk per walk past the facade, so that we can then
- calculate the average number present as shown below.

Step 1 Total "people seconds" in front of building in one week

= No. of people M walking past per week

x T seconds spent by each in the at-risk area in front of facade.

Step 2 T (seconds spent by each person in the at-risk area per walk past)

= Facade length L (m) / Walking speed V (m/s)

Step 3 Average number N of people present in the at-risk area

= (Total people seconds of presence) / (seconds in one week)

= M x L / (V x seconds in one week)

We can also express the occupancy in terms of the number present per linear metre of the facade by dividing out the facade length L, so that

Step 4 Average N present per linear metre = M / (V x seconds in one week)

or, with walking speed W expressed in kilometres per hour

Average N/m = M / [W x (1000/3600) x (7 x 24 x 3600)]

= **M / (W x 168000).**

The number of people walking past a building during a given period is known as the footfall, and is widely measured in shopping areas in developed countries as it is a vital statistic in planning the location of shops. Conventionally, footfall is estimated via regular surveys in which people stand with ‘clicker’ counters in defined locations for given periods of time. Footfall for whole days/weeks/months/years is then extrapolated based on knowledge of shopping habits collected across different shopping areas of similar types. Increasingly, electronic automated counters are being installed in towns and cities all over the developed world.

At present, footfall data in the Groningen region is commercially available only for the central areas of Groningen city. We purchased this data and have used it for all the buildings in Groningen Centrum for which the providers (Locatus NL) had made estimates. They (Locatus) use a proprietary app to interpolate footfall outside shops all around a shopping area from measurements taken at selected points.

In other areas, we have used footfall data estimated by the surveyors in the Falling Hazards survey on a rating scale from 1 to 10. The surveyors were asked to estimate the footfall rating based on what they judged would be the average “busy-ness” of the street outside buildings, rather than on how many people they could see in Street View photos, and were provided with photographs of street scenes corresponding to different footfall ratings at busy times.

The corresponding footfall ratings, numbers of passers-by per week and assumed walking speeds are shown in Table A1.12. The lower four rows of the Table A1.show measured footfall for selected streets in Groningen Centrum, taken from the Locatus data supplied, along with translations into the N per metre measure.

Table A1.12 Footfall and Occupancy Assumptions – Passers-By

Footfall Category	Footfall (typical), M/week	Walk Speed kph	Ave N per m length along direction of travel	Notes
1	20	3.5	3.40E-05	Isolated; only residents/postman
2	100	3.5	1.70E-04	e.g. End of quiet cul-de-sac
3	320	3.5	5.44E-04	Typical residential streets
4	1000	3.5	1.70E-03	
5	2150	3.5	3.66E-03	Village/small town centre
6	4600	3.5	7.82E-03	Larger town centres, city suburb shopping areas
7	10000	3	1.98E-02	
8	21500	3	4.27E-02	Busy town centres/city suburbs
9	46500	2.5	1.11E-01	City shopping areas
10	100000	2.5	2.38E-01	Busiest city shopping areas
Groningen Max	175300	2.5	4.17E-01	Busiest section of Herestraat
Groningen 90%ile	123600	2.5	2.94E-01	Waagstraat
Groningen 50%ile	40450	2.5	9.63E-02	Zwanestraat
Groningen 10%ile	15300	3	3.04E-02	Steentilstraat

In checking the survey results, it became clear that footfall had been one of the more difficult items for surveyors to assess, and that there was considerably variability in the estimates produced. A small team of 4 surveyors was thus selected for more training in footfall estimation, informed by the Locatus information and reports. They carried out a street by street review of all the footfall estimates made by their colleagues for the approximately 100,000 buildings in the highest priority Gemeenten surveyed (see Section 4), taking into account the presence of identifiable "footfall magnets" in the area such as shops, schools, stations and major community buildings.

Checking of the survey and risk assessment results revealed a further issue with the potential to understate Community Risk around some "public use" buildings such as churches, hospitals and schools, where people using the building but not people walking past in the street might be put at risk. This related to inappropriate allocation of a "Low" rating for footfall around the facades of such buildings in some cases. A final check of such "Low" footfall ratings for off-street building facades was thus undertaken prior to finalising the survey and risk assessment findings.

After discussion with Locatus, a further initiative was undertaken to develop improved estimates of footfall in shopping areas outside Groningen Centrum. Locatus provided advice on typical visitor numbers per week to shopping areas, based on the number, type and floor area of the shops they contained. This data was purchased and was used by Rakesh Lakeja of Shell to develop a simple footfall model for shopping areas, which was calibrated against the Groningen Centrum data. [Note – insufficient time was available to map the shops in the Locatus data set onto the building database used by Arup and NAM to incorporate this data – this provides an opportunity for refinement of the model in subsequent versions].

3.6.2 People running from buildings

NAM has already estimated the number of people present, on average, in each building in the Groningen region. From this number, we can estimate the number in the at-risk area in front of a doorway while debris is falling using by considering in turn:

a. The proportion of those occupants who, on average, are awake and able to flee

b. The proportion of such occupants who would attempt to flee in an earthquake, and

c. The proportion of fleeing occupants who would be in the at-risk area in front of a doorway at the same time as debris was falling.

To many people it is surprising that this is being considered as an issue in the Groningen region, as the earthquakes there are expected to be of very short duration (a few seconds maximum). The instinctive expectation is thus that “Surely there will not be time for people to run outside before the shaking is over and any debris has finished falling?” In other words, the proportion in category (c) above might intuitively be expected to be extremely small or even zero.

Experience in other earthquakes, though, suggests otherwise. In particular, in the Liège earthquake of 1983, 30 people were injured , mostly by falling debris while running out of buildings (though reports of injuries vary and include some lower estimates). This earthquake was shallow (4km) and of relatively low magnitude (4.6) and short duration (less than 5 seconds), and took place in the middle of the night (00:40 am). In the worst affected suburbs of St Nicolas and Flémalle, just over 15,000 buildings suffered damage to over 3,000 chimneys. Across the whole of Liège and the surrounding villages/suburbs, nearly 8,000 chimneys were damaged. Not all of those chimneys will have generated falling debris, but in addition to the chimneys (and the smaller number of large building element failures such as parapets, gables and whole walls), it is reasonable to expect that many buildings will have shed small items of debris such as pieces of broken glass or roof tiles.

We can use this information to make some **very rough** estimates of the probability of running out of buildings so as to coincide with falling debris. To make an estimate of the minimum plausible value of the probability that people running out coincided with debris falling, suppose

15000 houses in all generated falling debris outside doorways (approx 2x the number with damaged chimneys, of which many will not have been above doorways).

Then about

30000 people would be expected to have been present in buildings that generated debris (assuming 2 people at home per house on average)

Now suppose

10% of those people were awake and able to run outside, should they have wished to, and

70% of those able to do so attempted to run outside (assuming this to be a behaviour the majority of people would adopt).

Then roughly

2000 people (70% of 10% of 30,000) can be estimated to have tried to flee, of whom

30 were injured in total, of which let us suppose

20 involved being struck by falling debris[12].

This provides us with a minimum value of 1% for the proportion of people running out whose timing coincided with debris falling. If we assume some or all of

a. fewer houses generated debris falling above doorways (this could easily have been 3 times lower than the assumption above), or
b. that fewer people were awake and in a fit state to be able to run outside (again, this could easily have been 3x lower), or
c. that fewer people attempted to run outside (again, could easily have been 3x lower),

then our estimate of the probability of running out coinciding with debris falling could rise considerably, to 10% or more.

Before using this very flimsy evidence in the model, it is important to consider how it can be that so short duration an earthquake allowed so many people to get outside quickly enough to be struck by falling debris. There are several plausible explanations, including

a. Non-structural building elements may not fail instantly; there might be a few seconds delay

[12] Reports consistently describe the injuries as involving "being struck by falling debris".

b. There could be a further few seconds delay as objects travel down roofs and fall to the floor

c. Those injured may have been a sub-set of building occupants who were awake, alert and close to doors when the shaking happened.

In our view, the experience of the Liège earthquake demonstrates the significant plausibility of a small percentage of people running out of houses during a short duration earthquake being present in the at-risk area outside doorways at the same time as debris (if any) is falling.

In the current model we have used a probability of 5% that people who attempt to run out will coincide with any debris that is falling above a doorway. **This is an assumption which is consistent with the Liege experience but is NOT directly determined from data.**

We consider a value of 1% to be on the low side, while 10% would be on the high side for this parameter. Preliminary calculations indicate that this is an important uncertainty in our analysis, and place it high on our list of issues that we would like to investigate further.

On this basis, we calculate the proportion of building occupants in the at-risk area as follows:

50% of average occupants are assumed awake/able to respond to short duration shaking of whom

70% attempt to run outside when significant shaking occurs

of whom

5% coincide with any debris that is falling above the doorway.

Multiplying these proportions together gives a proportion of 1.75% of the occupants of buildings who are assumed to be in the at-risk area outside doorways. Again we wish to emphasise that **these are assumptions which are consistent with the Liege experience but are NOT directly determined from data.**

This proportion is applied for every hazardous object identified in the Falling Hazards survey which is within 1m (laterally) of a doorway. For houses we consider this to be a reasonable assumption. For larger buildings in public spaces it could be considerably inaccurate. Consider, for example, a school or hospital containing hundreds or even thousands of people:

a. There are likely to be multiple exits; it is impossible that everyone in the building simultaneously runs out of every exit (which is effectively what the model assumes)

b. If there is one main exit towards which people converge, then
- people further away will take some time to get there, and
- there is likely to be congestion inside the exit.
Both factors will tend to reduce the number who can get outside and the density of people once outside.

c. 1.75% of 1000 people (17.5) could not credibly fit in an at-risk area of about $10m^2$ outside a typical domestic sized doorway. On the other hand

d. Some buildings have larger doorways, and in some cases large ornamental features above them, which might increase the area at risk and potentially also the population of people at risk, and

e. It is not uncommon for people to meet into people on approaching a building and stop for a chat outside, which will tend to increase occupancy outside doorways[13].

Our preliminary calculations suggest that, with these assumptions, people fleeing buildings account for a substantially larger proportion of higher risk objects than do people passing by in the street. The assumptions made here are thus of considerable importance for the model. To date most of our research and analysis has focused on understanding the fragility of non-structural building elements; in moving forward we consider this focus probably needs now to shift onto the relatively very simple assumptions used in the model about the lethality of falling objects and, in particular, the occupancy of at-risk spaces.

3.6.3 Building occupants at risk from objects falling through roof

Our model here is simpler than that for building occupants running outside. We assume that the whole of the interior of a building is at-risk, and that there is no modification of the risk by the building structure. The population in the at-risk space is just the average number of building occupants, which we read into our model from NAM's latest exposure database.

By doing this we are effectively ignoring the presence of the building roof and upper floors in mitigating (or exacerbating) risk for those beneath. This clearly involves an element of pessimism, in that no protection from debris trapped on the roof or failing to penetrate upper floors is allowed for. For lighter weight falling objects, and/or for stronger (e.g. reinforced concrete) roofs and floors, this could clearly be a very pessimistic assumption, and for chimneys in general falling through the roof of their own building (other than those 2m or more above the roof) this is taken into account via reduced probabilities of death as discussed above.

On the other hand, we have witnessed at first hand the damage caused to timber-framed houses in the Port Hills area of Christchurch by boulders falling through roofs. The appearance in some cases is as though a bomb has hit the affected room – with large fragments of the building and contents having been thrown violently around as the result of the impact. Further research into both the protective and the exacerbating effects of boulders falling through houses is currently in progress in relation to these buildings. For the present we make the simple assumption that any protective effects (from a lightweight building structure) are offset by exacerbating effects (from secondary debris produced by the initial impact). This is a conservative (pessimistic) assumption for the relatively low speed falling objects anticipated above most roofs.

We are comfortable with this assumption for this first version of the model, but anticipate reviewing it once a first round of risk assessment has been completed for the buildings where there is a real hazard of objects falling onto their roof from height. While the numbers of objects appear to be relatively modest – typically a few per cent of all hazardous objects are so situated – our initial risk assessment results suggest that they account for a disproportionate share of higher Community Risk objects. Checking of the Survey results revealed that a significant proportion of

[13] See for example students sitting on the steps outside the main University building in Groningen, or shoppers pausing for a chat outside the supermarket in Loppersum, in the current Street View photographs of the buildings.

such objects had been missed in the initial survey. Given their potential importance for risk, a final pass through the Survey files was made to ensure they had been consistently identified and characterised.

Another opportunity for improvement in this part of the model is that the Survey did not collect information on which building was at risk from an object falling through its roof. Each object elevated 2m or more above a roof is identified by an F or an N in the “direction of fall” towards which it could fall through either its own building’s roof (F) or a neighbouring building’s roof (N). In the latter case, though, the building involved is not identified. The simplifying assumption made in all such cases in the current version of the model is that the floor plan area and internal population of the “target building” are in every case the same as that of the “source building”. By adding a small number of fields to the model it would be possible to identify more specifically which was the “target building” in each case. There are just over 4,000 such objects identified, which could be re-surveyed to collect the additional data with a few weeks of effort.

3.7 Calculation of Risk Parameters

Local Personal Risk is not considered a particularly useful metric of risk for falling hazards outside buildings as the general nature of this hazard is one of relatively frequent objects falling (the same can be said of storms and other sources of falling objects than earthquakes) into spaces which are relatively lightly occupied in comparison with the hazard of buildings collapsing onto their occupants. However, it provides a useful calculational mid-point in the calculation of Community Risk so is described as the first step in our model process. Object-related Community Risk (OCR) is our preferred metric for prioritisation of buildings for upgrade and is described next. Finally, we describe the calculation of Object-related individual risk (OIR[14]), the metric which Commissie Meijdam has proposed should be used in comparing falling hazard risk with individual risk norms.

3.7.1 Local personal risk (LPR)

The contribution LPR_{ijk} to local personal risk from earthquakes in band i for an object of type j (see Table 16 below for a list of object types) damaged to damage state k is given by

$$LPR_{ijk} = f_i \cdot P1_{ij} \cdot P2_{ijk} \cdot Pd_{jk} \qquad [1]$$

where

f_i is the frequency of earthquakes in shaking band i

$P1_{ij}$ is the probability of failure of object j, given shaking in band i

$P2_{ijk}$ is the probability of object j reaching damage state k, given failure in shaking band i, and

Pd_{jk} is the probability of death for a person randomly distributed within the at-risk space beneath, given failure of object j to damage state k.

[14] Referred to in the Commissie Meijdam advice as OIA – objectgebonden inidividueel aardbevingsrisico

The overall Local Personal Risk (LPR) is calculated for an individual hazardous object by summing over all shaking bands and damage states, for each of the three exposure routes.

Given our simple assumption that the probability of death is simply the ratio of the area swept out by falling debris as it falls through the air, we can rewrite (with $A_{xfall,whole}$ and $A_{at\ risk}$ defined as in Section 3.5 above)

$$Pd_{jk} = \alpha_k \cdot (A_{xfall,whole}/A_{at\ risk})$$

This is extremely useful in implementing the risk model for large populations of buildings, as the only terms in equation [1] that are specific to individual buildings and hazardous objects are the two areas (that swept out by the whole of the falling object, and that of the at-risk space beneath it). When summing over shaking bands and damage states the equation for LPR for a given object of type j can thus be written as

$$LPR_j = (A_{xfall,whole}/A_{at\ risk}) \cdot \sum_{i,k} f_i \cdot P1_{ij} \cdot P2_{ijk} \cdot \alpha_k \qquad [2]$$

The sum on the right is the LPR calculated for a falling object whose whole volume would exactly fill the at-risk space beneath it.

In the implementation of the model, the sum on the right is calculated for each object type at each contour of PGA on the KNMI map (in 0.02g contour intervals) and is referred to as the **Standardised LPR**. The Standardised LPR is the LPR that would be created by an object just big enough to cover the whole of the at-risk area below if the whole object fell.

The LPR for a specific object and building is then calculated simply as

LPR_{jmn}	=	$A_{xfall,whole}$	(specific to individual hazardous object)
	x	S_{jm}	(specific to object type and PGA contour on map)
	÷	$A_{at\ risk,n}$	(specific to the building and the exposure pathway)

where

S_{jm} is the Standardised LPR (the sum on the right of equation [2] above for objects of type j on PGA contour m), and

$A_{at\ risk,n}$ is the at-risk area for object j and exposure route n.

This enables LPR to be calculated efficiently for 1000's of hazardous objects within a spreadsheet, for each of the three exposure pathways (passers-by, runners-out and people indoors) considered in the model.

In the implementation of the current model the LPR is then multiplied by reduction factors if there are visible restraints present (e.g. on chimneys or parapets), or if a gable wall has visible ties. The LPR is multiplied by an incremental factor if the object has features (e.g. a substantial metal railing on top of a brick balcony, or a series of similar balconies above it on an apartment block) that would not necessarily dramatically change the area swept out as the object would fell but would tend to increase it. Finally, a condition factor is used to increase LPR for objects which were identifiably in bad condition for the age of the building (as identified on Street View – this was used by exception only, in cases where there was serious visible leaning or damage involving missing bricks/mortar).

The modification factors to LPR currently assumed in the model in order to provide an approximate indication of the magnitude of effects associated with these building features are as follows:

- x 0.5 for a gable with visible ties
- x 0.33 for a parapet or chimney with visible metal restraints
- x 1.2 for objects whose swept area may be extended by surrounding materials/objects, and
- x10 for an object in visibly seriously bad condition on Street View.

The effect of these parameters is modest in relation to the uncertainties in the model; the intent is to provide a modest differential between objects with and without such features when prioritising for on-the-ground inspection, which should be able to make better informed judgments about relative fragility based in particular on the observable condition of buildings and objects.

3.7.2 Object-related Community risk (OCR)

Object-related Community risk (OCR) for each exposure pathway n and objects j is the product of LPR and number of people at risk for that object and pathway:

$$CR_{jn} = LPR_{jn} \cdot N_n$$

where N_n is the average number of people present in the at risk area for exposure route n and other nomenclature as above.

The OCR for a specific hazardous object is the sum of that calculated for each exposure route.

(Note that, if LPR were to be calculated for an object for all exposure routes, there would be a little more complexity as the passers-by exposure route affects different people from the building occupants who are affected by objects falling through the roof or running outside into falling debris).

3.7.3 Object-related Individual risk (OIR)

OIR is calculated from LPR for each exposure pathway as the product of LPR for that pathway and the proportion P_t of time spent in the at-risk area for a representative building user:

$$OIR_j = LPR_j \cdot P_t$$

It is not as yet fully clear how OIR should be summed over exposure routes since it is an individual risk metric, and while a representative individual can readily be defined for the “running out of doors” and “object through roof” pathways (a representative building occupant), people passing by or spending time in the vicinity of the outside of the building may be different individuals.

Appendix 4 explains our proposal for dealing with this issue by defining the representative individual to be a building user, and basing occupancy of the space outside a building on pessimistic assumptions which are likely to overstate risk exposure for a large majority of people and objects/buildings. The proposed occupancy levels (values of Pt) are related to the primary use of buildings as shown in Table A1.13:

Table A1.13 Occupancy Assumptions for OIR Calculation

Building Use	**Occupancy (realistic representative individual)**	**Occupancy (for OIR comparison with norms)**
Residential (dwellings)	70%	100%
Healthcare/care homes	100%	100%
Workplaces (shops, schools, offices, industrial etc)	20%	100%
Gathering places (churches etc)	5%	5%
Outside buildings within 5m of facades	1%	1%
'Notverblijfsobjecten' (sheds, garages, other CC0 buildings)	0%	0%

The model is set up to provide outputs of both the realistic OIR for a representative individual (based on typical upper level occupancies as in the centre column of the table above) and the OIR recommended for comparison with individual risk norms (where Commission Meijdam recommended that buildings in regular use by large numbers of people for a substantial proportion of their time – such as schools and workplaces generally – should be treated as being occupied for 100% of the time). In risk assessment throughout this study, the occupancies on the right of Table A1.13 (i.e. those corresponding to the basis on which Commissie Meijdam proposed that OIR should be compared with risk norms) are used.

4. Conclusions and Development Suggestions

4.1 Conclusions

1. A quantitative model has been developed to estimate the risk from falling building elements onto people as a result of man-made earthquakes in the Groningen region.
2. The model and supporting building data have been designed to be suitable for
   a) screening communities to prioritise them for the essential 'on the ground' inspections that need to precede any final decisions on upgrades, and
   b) for informing the development of practical rules to decide when such upgrading is warranted.
3. The model is not suitable for making definitive assessments on individual buildings.
4. Much of the model development has taken place with a mind-set that the fragility of building elements such as chimneys, parapets and gables was likely to be the most critical issue in risk estimation. Now that the model is taking shape it appears that this may not be the case, and that some of the assumptions concerning lethality of falling objects and occupancy of the space beneath them may be equally critical for risk estimation.

4.2 Suggestions for Further Development

Further development of the model is suggested to address the following opportunities for improvement:

a. specific local features of hazardous objects, buildings and their use which can significantly affect risk exposure

b. introduction into the model of the shopping area footfall model developed but not yet incorporated

c. collection of data on specific buildings at risk from objects falling from height onto roofs

d. procurement and analysis of further information on non-structural building element performance in earthquakes, both

   i. to build confidence in estimates of performance of the chimneys, parapets and gables already covered in this report, and in particular

   ii. to enable more confident predictions of performance to be made for the numerous dormers, canopies, balconies and other types of non-structural elements which adorn many of the buildings in the Groningen region, and

e. investigation of the impact of soil type on estimated falling hazard risk levels.

[end of Appendix 1]

Appendix 2: Performance of Falling Hazard Objects in Earthquakes

1.Introduction

This appendix provides a description of the performance of non-structural building elements in earthquakes. It has been prepared by Tony Taig and Florence Pickup of TTAC Ltd as part of the Falling Hazards Risk Assessment developed for Arup and NAM, based on research carried out during 2014 and 2015.

Earthquakes are grouped geographically as follows, starting with those nearest to the Groningen region:

- The Rhine valley (Belgium, Netherlands, Germany, Section 2)
- Other European earthquakes (Section 3)
- North America (Section 4), and
- Australia and New Zealand (Section 5)

Quantitative data from the individual earthquakes, where available, is presented in Appendix 3 along with the reasoning used to arrive at failure probabilities and damage state distributions for the V1 Falling Hazards Risk Model. Several companion papers discuss individual earthquakes in more detail. In this Appendix we concentrate on explaining the qualitative observations on earthquakes and on providing information for those earthquakes which are NOT the subject of companion papers.

2 Rhine Valley Earthquakes

The Upper and Lower Rhine Graben have a long history of earthquakes with magnitude up to M_L 6 or higher[1], with typically three or four events of M_L 4 or greater per decade. In the past year (17 May 2014) a shallow (5km) magnitude 4.2 M_L event near Darmstadt caused damage to about 80 buildings, including several examples of falling roof tiles and collapsed chimneys[2]. A stronger, deeper earthquake near Alsdorf in 2002[3] (M_L 5, 13 km depth) caused shaking at EMS VI over an area well over 100km^2 and EMS V of about 2,000 km^2.

We would have liked to have collated information on the relatively isolated examples of building damage for these earthquakes and related it to the building stock present, but found damage information difficult to locate. We have therefore focused instead on a number of low magnitude, relatively low intensity earthquakes in the UK for which we were able to obtain useable photographs of building damage. To provide an illustration of our approach to re-analysis of photographic evidence these are presented in more detail in Appendix 2. Among the North Rhine valley earthquakes we have focused on the two major events for which substantial building damage data was collected: at Liege in 1983 and Roermond in 1992. Both earthquakes involved substantial areas of towns and villages being subject to large quantities of debris falling into the streets, but both occurred in the middle of the night when the streets were quiet so that casualties outside buildings were limited largely to minor injuries from falling glass, tiles and masonry.

2.1 Liège 1983

This was a low magnitude (M_L 4.9) but shallow (4km) earthquake, which occurred in a hilly area where soil conditions were diverse and there was a long history of subsidence associated with coal mining. In the worst affected areas (the centre of Liège and in particular the suburbs of Saint Nicolas and Flémalle) many of the buildings were URM, over 100 years old, and either previously damaged by subsidence or otherwise in run-down and dilapidated condition.

Building damage to older URM buildings was extensive. There were numerous examples of collapsed parapets, bricks falling from gable ends, and large sections of walls failing out of plane. One elderly woman was killed in her bed by a chimney collapsing through the roof

A comprehensive survey of 9,000 buildings in the worst affected suburbs was carried out based on claims submitted for compensation by building owners[4]. This included details of damage to chimneys, parapets, gables and other walls. Unfortunately, this dataset has now effectively been lost (it exists only in paper records which are in such poor condition that they cannot be accessed for health reasons).

For this study we were fortunate to be provided with two sets of data by people who were involved in building surveys and subsequent analysis of the earthquake:

a. Thierry Camelbeeck of the Royal Observatory of Belgium provided us with a spreadsheet detailing building damage (classified using damage levels 1-5, and including a special category of D2/3 used specifically to define chimney damage) within 100x100m grid squares in Saint Nicolas and Flémalle, and within about 25 other communities around the Liège area. This had been reconstructed from the original comprehensive building dataset before the paper records degenerated to their current point, and had been used in support of a relatively re-appraisal of the intensity map of the earthquake[6].

b. Prof Emeritus André Plumier of the University of Liege provided us with a number of still photographs and, of particular interest, a film shot the day after the earthquake and including aerial pictures of about 70 houses in the worst-affected areas, from which the extent of damage to chimneys could clearly be seen.

This data is analysed in greater depth in a companion report[6]. The available data do not segment buildings by age but do provide substantial information on the variability of percentages failed across geographical areas. We have taken these variations to be indicative of variations in age and condition, but they may also reflect differences in local soil conditions and topography.

The key conclusions from our analysis are

1. Damage of all types was concentrated in older, poor condition URM buildings; damage to buildings in good condition was slight.
2. Proportions of chimneys damaged ranged from
    a. about 80% in the worst affected area of St Nicolas (EMS VII shaking), to
    b. 2-15% in other areas subjected to VI-VII intensity shaking, and
    c. <1% up to about 10% in areas subjected to intensity V shaking.

3. Where chimneys were damaged, substantial proportions of cases involved a large part of the chimney detaching and falling to the ground. In particular
   a. In areas of the highest shaking tens of % of chimney volume typically detached from the chimney (from 20 to 100%)
   b. Detached material in most cases slid down roofs and fell into the street within 1-2m of the building, but
   c. Shallower roofs in several cases retained significant proportions of chimney debris on the roof, and
   d. In at least 2 cases out of a sample of 41 damaged chimneys (i.e. about 5%) the chimney fell through the roof and into the house.
4. There is no direct data from which to assess parapet failure. We estimate based on photographs and Prof Plumier's advice that failure proportions of parapets ranged up to about 10% in the worst affected areas, and that when parapets did fail the volume of masonry falling was substantial, typically 10's of % of the parapet volume.
5. Around 1% of houses in the worst affected area (Saint Nicolas) sustained Level 4 damage, and about 0.2% Level 5. Based on photographs of the occasional cases of large scale out of plane wall failures we assume that this corresponds to up to 1% large scale out of plane wall failure for "worst condition" older URM buildings. Smaller failures of order 1m^2 or less wall failure, particularly of gables, were more prevalent and we estimate might have occurred in 5-10% of poor condition older buildings subjected to intensity VII shaking.

2.2 Roermond 1992

This was a larger magnitude (5.4 M_L) and deeper (about 15km) earthquake than that at Liège. The maximum shaking intensity of VII (EMS/MSK scales) was experienced locally in Roermond itself and in a cluster of villages and towns around Heinsberg in North Germany. The earthquake took place at 03:20, so although large quantities of debris fell into the streets in Roermond and some of the North German communities, the streets at the time were very quiet and no-one was killed by falling debris.

One death was attributed to the earthquake (due to the heart failure of an elderly lady in Bonn), while about 45 people were injured, largely by falling debris encountered as they ran out of buildings (though a significant proportion of the hospital admissions in Roermond in particular also related to heart conditions exacerbated by the earthquake).

An EEFIT survey was carried out a week after the earthquake, and surveyed 4 areas of Roermond itself, 9 other Netherlands and 27 North German communities (not including Heinsberg itself)[7]. This study segmented buildings into three age bands: pre-1920, 1920-1960 and post-1960. Damage states 1-5 were allocated, with damage definitions based on extent of cracking in walls for levels 1-3 (with 3 also including "wall material dislodged"), while level 4 corresponded to partial destruction (loss of whole walls for URM buildings) and level 5 to complete collapse. Apart from the wall damage descriptions mentioned, there was no particular association of failure of non-structural building elements with particular damage states.

The EEFIT data is re-analysed, grouped into areas corresponding broadly to different levels of shaking, in our companion paper on the Roermond earthquake[8]. Out of just under 4,000 houses in the surveyed areas in total, none were damaged to levels 4 or 5, just 5 to level 3, 96 to level 2 and 594 to level 1. The survey authors provided us with their photographs taken during the survey and discussed it with us; they emphasised the strong association between damage and building condition and, as the survey made clear, that well built and maintained URM buildings had performed very well throughout the survey area, including in the highest intensity shaking areas. The EEFIT quantitative data shows very clearly the association of building damage with older buildings, with a factor of >10 reduction in proportions of buildings damaged between Pre-1920 and newer buildings.

The EEFIT survey proposed, based on the extent of observed building damage, that the “true” intensity of shaking was about one level (on the MKS scale – similar to EMS and MMI) lower than that stated in the “official” macro seismic survey. This view was supported by a later re-appraisal by Camelbeeck et al[1]. The true extent of damage to non-structural building components has proved difficult to determine. Press reports suggest large areas of Roermond, Heinsberg and other communities being deluged in fallen debris, whereas the EEFIT report provides a more moderate picture of damage. What does seem clear is that chimneys were by far the most commonly damaged non-structural element (with modest numbers of parapet, gable and other wall failures in parallel), that newer and good condition buildings performed well, and that shaking and damage was distributed over quite a wide area (possibly in part because of a thick layer of energy-absorbing sediments in the Roer Valley graben in the region of Roermond[10].

Our conclusions from the analysis of EEFIT and other available data in the companion paper are:

1. The proportion of pre-1920 houses suffering significant falls of chimney or roof tile debris ranged from about 1% for the less badly affected (notionally MSK V shaking) to about 10% for the worse affected (notionally MSK VI or VII) communities. The difference may owe as much to differences in building condition as it does to differences in shaking.
2. The proportions of 1920-1960 houses suffering such chimney/roof damage were about a factor of 10 lower than the proportions of pre-1920 houses, and the proportions of post-1960 houses suffering such damage were lower again.
3. Where they occurred, chimney failures largely involved partial collapse or detachment of bricks and pots from chimneys, rather than whole chimneys snapping at their base.
4. Failure of gables and parapets appears to have been around an order of magnitude (factor of 10) less prevalent than that of chimneys.
5. Churches sustained particular damage, with large masonry items falling both inside and outside churches over many 10’s of km distant from the epicentral area.

There is an important and frustrating uncertainty as to the prevalence of falling debris associated with this earthquake. Press reports of injuries to people, damage to cars and debris in the streets all suggest that falling debris was widespread within many communities, whereas the EEFIT report suggests that damage involving serious falling hazards was more limited.

3 Other European Earthquakes

For the most part we have not examined southern European earthquakes because of the significant differences in building construction in comparison with Northern Europe. An exception is made for the Lorca earthquake in Spain in 2011, which is of particular interest because a) it involved a relatively modest magnitude (5.1M_W) shallow earthquake and b) it provided a wealth of information on non-structural component failure (which was responsible for the 9 deaths in the earthquake). We have also examined a group of low magnitude earthquakes in the UK which illustrate the potential for low probability, low masonry volume failures to occur at relatively low shaking intensities.

3.1 Lorca 2011

The major earthquake (MW 5.1, measured PGA 0.37g) occurred at 16:47 local time, one hour and 42 minutes after a slightly less powerful (MW 4.2, PGA 0.28g) earthquake shook the city. Damage in the second (major) earthquake may have been exacerbated by damage caused in the earlier earthquake. But in human terms damage was greatly reduced because the one large, multi-storey reinforced concrete building which suffered a “pancake collapse” (attributed to the use of short columns in the design) was evacuated after the first earthquake. 9 deaths occurred, attributed to impacts of debris from falling parapets and non-structural wall panels.

We have not been able to obtain detailed building survey data for the Lorca earthquake. The quick field report[9] provides clear illustrations of the lethal non-structural debris that fell into the streets. A Spanish joint institutes’ report on the earthquake[10] provides valuable information on the types of damage which occurred and on the relationship between damage and building construction, and between damage and soil type. With the exception of the major concrete building collapse mentioned above, the main types of damage, which affected both traditional masonry and more modern concrete buildings (many of which used masonry infill panels or had masonry parapets), were (all figures reproduced from reference 10):

- Collapsed parapets, which in several cases inundated narrow streets with debris (Figure A2.1)
- Out of plane failure of non-load-bearing masonry walls (Figure A2.2) and
- Shear failure and out of plane collapse of masonry infill panels (Figure A2.3)

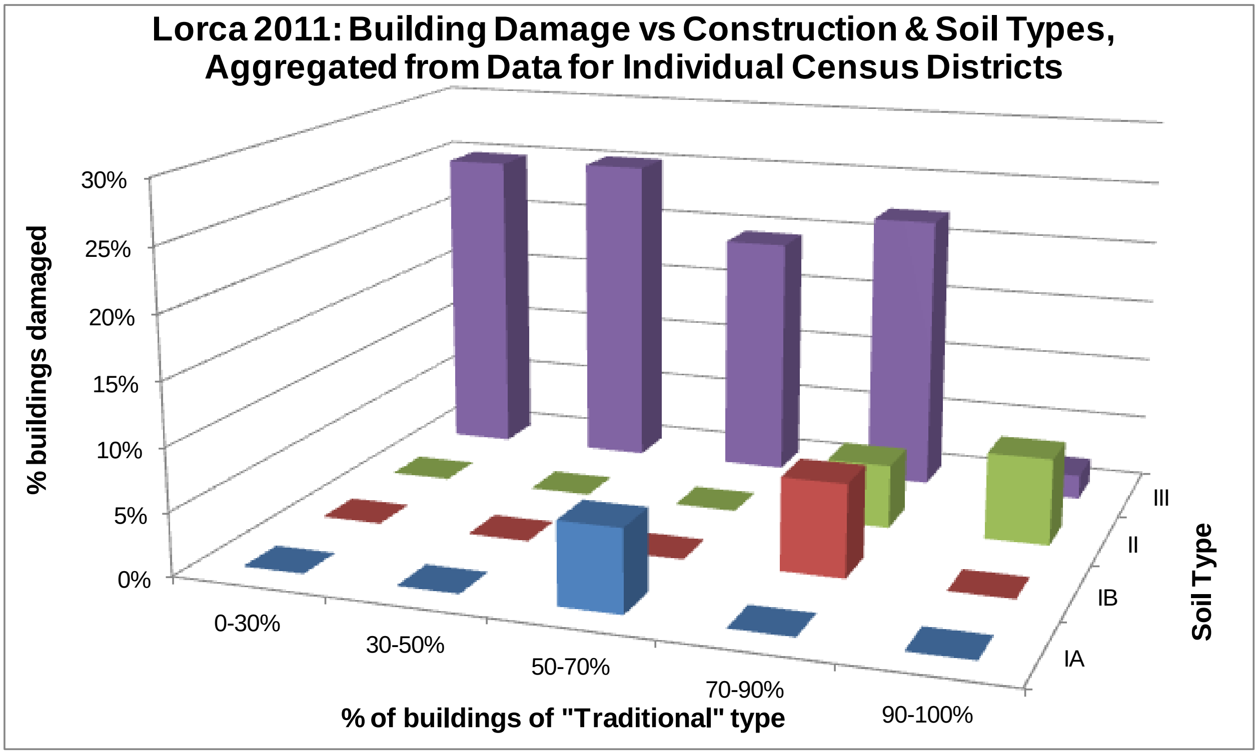
Figure A2.1 Parapet Collapse and Debris in Streets

Figure A2.2 Out of Plane Masonry Wall Failure (Lorca Station)

Figure A2.3 Shear Failure and Out of Plane Collapse of Infill Panels

The Spanish institutes' analysis shows a strong correlation between damage and soil type, with damage heavily concentrated in the Type III (soft soil) areas. Their data is collated and presented graphically in Figure A2 4.

Figure A2.4 Building Damage vs Soil Type and Construction[10]



There does not appear to have been a particularly strong correlation between the mix of "traditional" and "modern" buildings and damage, though it is noticeable from Figure A2 4 that only the census districts with higher percentages of traditional buildings sustained damage other than in the soil type III areas. It is also notable that in the areas where numerous parapets failed, there appeared to be little distinction (based both on photographs and on the back row of bars in Figure A2 4) in parapet performance between traditional and more modern buildings.

Consideration of photographs of debris in streets and of the distribution of soil types with damage leads us to suspect that some of the areas with the greatest damage and debris may have experienced stronger shaking than that recorded at the one seismic monitoring station in the vicinity.

Interpretation of the significance of the Lorca observations for the Groningen region is complicated by these soil/ground motion factors and by differences in building type (for example, infill masonry panels in modern concrete buildings are relatively unusual in much of the Groningen region), as well as by the possibility that significant proportions of walls and parapets may have been significantly cracked in the earthquake that immediately preceded the major event. Moreover, we do not have detailed building by building survey data on parapet and wall performance.

And finally, there was general awareness throughout Spain of the significant possibility of earthquakes for several decades prior to this event, and building codes had evolved over time to provide progressively more stringent design measures for new buildings. The design earthquake for Lorca, though, involved ground accelerations 2-3x lower than were experienced in May 2011, and it was clear that a large proportion of both older and newer buildings did not incorporate features providing effective restraint of parapets and wall panels.

Quantitative estimation of HRBE performance relevant to Groningen region is thus very difficult. We do, though, have numerous photographs taken immediately after the earthquake of streets in which buildings on one side or the other clearly possessed parapets for most if not all of the length of the streets. There are numerous photographs of such streets in which debris is prolific in patches along the street, but where there are larger areas not covered in debris. There are smaller numbers of other photographs in which virtually the whole street is inundated with debris from one side or the other, particularly in the Calle Galicia de Lorca area where several people were killed by falling debris. Our judgment from examination of photographs is that somewhere between 20 and 50% of parapets collapsed, possibly more in the worst affected areas.

As mentioned above, our interest in performance of masonry infill panels is less than that in failure of plane masonry walls. We have insufficient data from which to estimate the proportion of buildings with masonry walls which experienced substantial out of plane failures, but in the worst affected areas this was clearly of order several % of relevant buildings or higher.

Important qualitative conclusions from the Lorca earthquake include

1. Relatively modest magnitude earthquakes can give rise to high local ground accelerations and substantial building damage.
2. Shaking experienced by individual buildings depends critically on local factors such as soil.
3. Failures of masonry parapets appeared to occur with little regard for the construction of the building on which they were standing.
4. The combination of (tall buildings with parapets) and (narrow streets) is particularly dangerous.

3.2 Low Magnitude UK Earthquakes

We were fortunate to be provided with access to photographs of building damage (largely to chimneys) in the Folkestone earthquake of 2007 and the Bishop’s Castle earthquake of 1990 by Matthew Free of Arup and Andrew Coburn (via CAR) respectively. These provided valuable information not only on the proportions of specific building types that failed but also on the extent and fate of masonry debris detached from chimneys.

We complemented these with reviews of damage in a number of other relatively modest magnitude and intensity earthquakes in the UK in recent years in which building damage had been reported in BGS (British Geological Survey) annual reports and in the media.

We provide below our analysis of

a. the numbers of buildings suffering specific damage (largely to chimneys), and
b. the proportion of building element volume falling to the ground as debris.

The earthquakes covered and primary information sources used are:

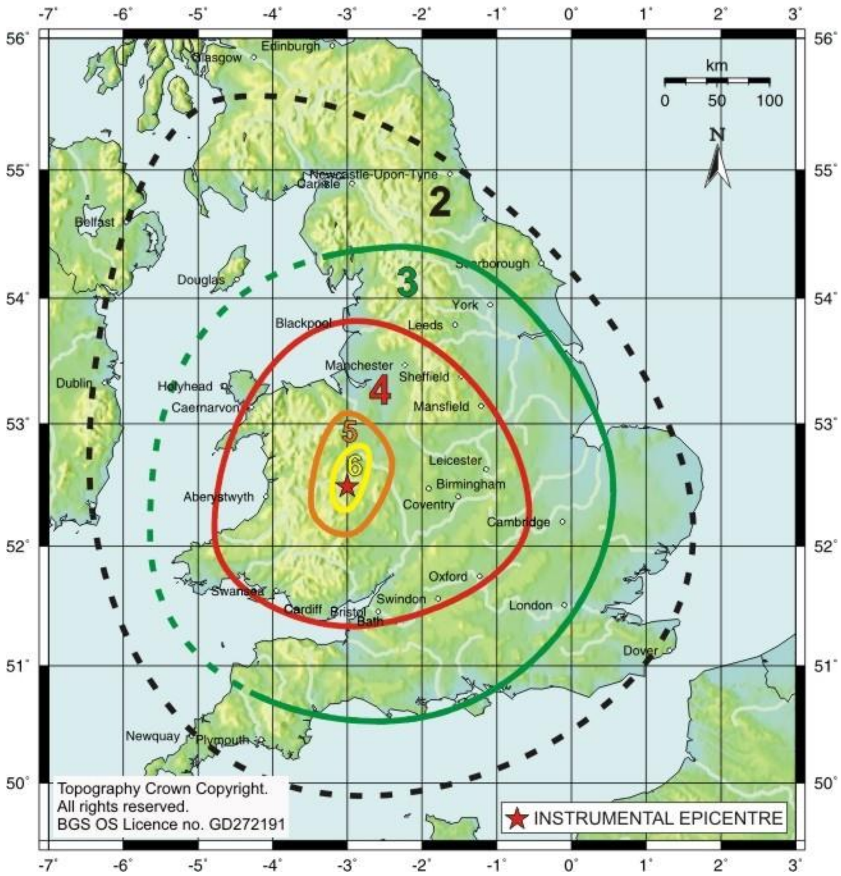
- Bishop's Castle, 1990, M_L 5.1, depth 14km (photographs taken by A Coburn, CAR, Section 3.2.1)
- Melton Mowbray, 2001, M_L 4.1, depth 11km (BGS & press reports & photos, Section 3.2.2)
- Dudley, 2002, M_L 4.7, depth 14km (BGS & press reports & photos, Section 3.2.3)
- Folkestone, 2007, M_L 4.2, depth 5.3km (survey of a sample of Victorian houses carried out on the day of the earthquake by M Free, Arup et al, section 3.2.4)
- Market Rasen, 2008, M_L 5.2, depth 18.6km (BGS & press reports & photos, Section 3.2.5).

Section 3.2.6 summarises the information gleaned from these earthquakes, along with relevant building populations, to estimate the likelihood of chimney failure among relevant buildings and the proportions of chimney volume falling to the ground in the event of failure. All intensities referred to are based on the EMS scale unless otherwise stated.

3.2.1 Bishop's Castle, Wales - 02/05/90[11]

The earthquake struck at 14km deep and had a magnitude of 5.1M_L at 1.46pm. The highest intensity level was EMS VI and caused minor damage to chimneys in Wales and the North West of England. No injuries or deaths were caused by the tremors.

Figure A2.5 Isoseismals, Bishop's Castle 2 May 1990



Approximately 50 instances of damage needed immediate attention in the Shrewsbury and Wrexham areas. These were mainly cracked and damaged URM chimneys, distributed between intensity V and VI areas[12]. We have assumed in the summary table below that between 20 and 40 of these recorded instances of damage involved chimney failure. Photographs of a number of specific cases were obtained from the photographic record collected by Andrew Coburn of CAR[13].

Chimneys	**No. with significant failure**	**% Fallen**		
EMS		**Low**	**Ave.**	**High**
V-VI	20-40	2%	9%	15%

Figure A2.6 Bishop's Castle 1990, Images of the earthquake damage[3]

3.2.2 Melton Mowbray, UK - 28/10/01[14]

The 4.1 magnitude earthquake struck 11km deep near the town of Long Clawson, 8km North of Melton Mowbray, at 4.25pm. The highest intensity level was EMS V, there were no injuries or deaths reported.

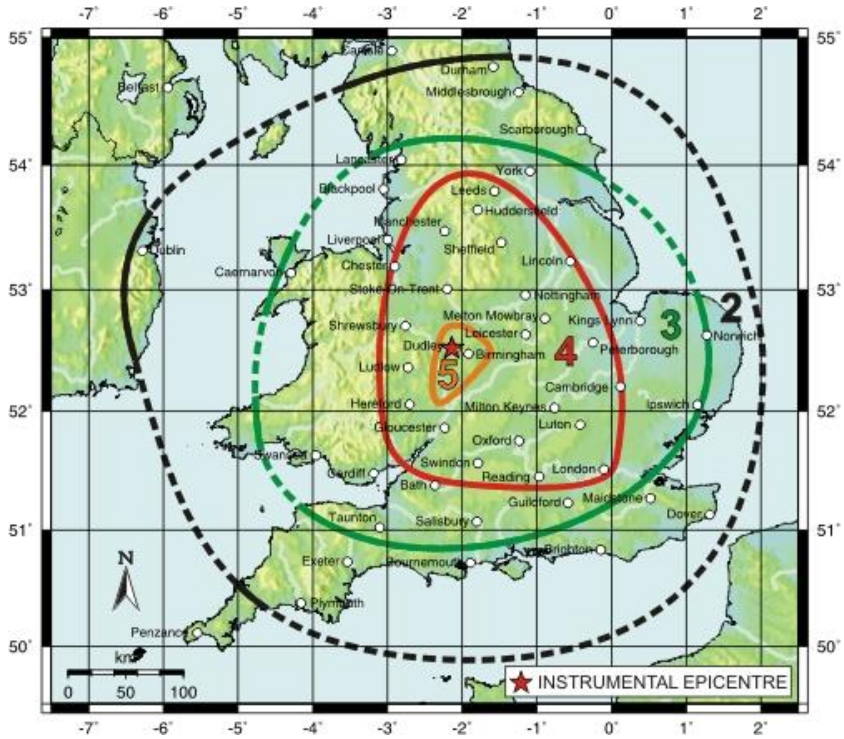
Figure A2.7 Isoseismals, Melton Mowbray, 28 October 2001

Two chimneys were reported to have “collapsed”, one in Melton Mowbray[15] and another in Long Eaton, 30km away (both within the Intensity V contour). The chimney in Long Eaton was on an old row of terrace houses[16]. A case of roof tiles being dislodged was reported from Market Harborough6, while two other buildings, in Coalville and Burbage, were reported as “damaged”. No photographs could be obtained from which to estimate proportions of chimney volumes falling to the ground, but at least one case[15] clearly involved a substantial part of the chimney stack collapsing, rather than just chimney pots and one or two bricks.

3.2.3 Dudley, UK - 22/11/02[17]

At 00.53am, a 4.7M_L earthquake struck the West Midlands. The epicentre was just outside the town of Dudley at a depth of 14km, the highest intensity level reached was EMS V. There were no reported injuries or deaths.

Figure A2.8 Isoseismal Map for Dudley 2002 Earthquake (BGS)



In the West Midlands[18] the moderate level of shaking caused damage to three chimneys, all belonging to older (pre-WW1) houses. There was a total of 1,086,700 households in the West Midlands at the time[19], of which 21.4% were assumed to be pre-WW1[20]. The epicentre was under Brick Kiln Lane, a road with 42 residences, none of these were damaged[21].

In at least one chimney collapse case[18] there was clearly debris scattered on the pavement and road outside the house, indicating that a significant proportion of the chimney had fallen from the roof to the ground.

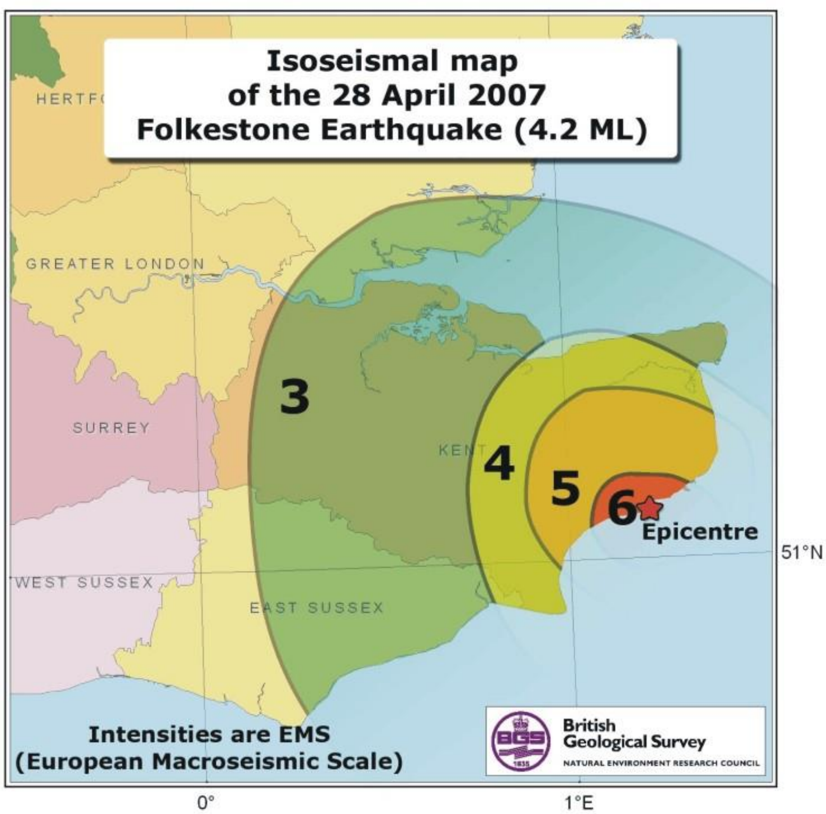
CHIMNEYS	**No. with significant failure**	**% Masonry Volume Fallen to Ground**		
Intensity		**Low**	**Ave.**	**High**
V	3	20%	50%	80%

Figure A2.9 Dudley 2002, Images of the earthquake damage[22]:

3.2.4 Folkestone, Kent, UK - 28/05/07[23]

The 4.2M_L earthquake shook the town of Folkestone, Kent, at 8.18am. The epicentre was 1 km north of the town, and had a relatively shallow depth of 5.3km. There were two minor injuries reported and no deaths. A maximum intensity of VI was determined within a localised area of Folkestone itself.

Figure A2.10 Isoseismal for the Folkestone 2007 Earthquake (reproduced from BGS)



A survey was carried out on the afternoon of the day of the earthquake by staff of Arup and others, who provided copies of their photographs of damage from the surveyed area of 707 houses[24] (see figure A2.11).

12 chimneys were significantly damaged, corresponding to 1.7% of the buildings. The proportion of masonry volume lost from those chimneys ranged from 1% to 20%, with the average volume loss about 9% (see Figure A2.12). In all but one cases, virtually all of the debris detached from the chimney fell to the ground on account of the steep design of the roofs. The one exception was when debris was trapped in a valley between two front roof gables.

Figure A2.11 Survey Area, Folkestone 2007

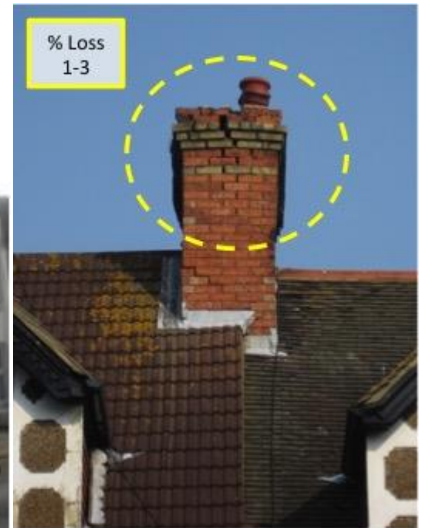
The general style of chimney in the area had several chimney pots per stack. In every chimney damaged at least one chimney pot fell to the ground. All chimneys, apart from one, were located in the middle of the roof; a number of roof tiles were thus damaged by falling chimney debris and added to the debris on the ground. The photographs used to generate the summary table below are provided as Figure A2.12.

The houses in the area were terraced and "predominantly built from the mid Victorian to early Edwardian period. C.1850 – 1910"[25]. Although the houses were over 100 years old, they showed no evidence of structural damage.

CHIMNEYS	**No. with significant failure**	**% Masonry Volume Fallen to Ground**		
Intensity		**Low**	**Ave.**	**High**
VI	12	2%	9%	20%

Figure A2.12 Images of the earthquake damage showing assessment of % volume lost


% Loss
3-10


% Loss
1-3


% Loss
1-3


% Loss
3-10


% Loss
3-10

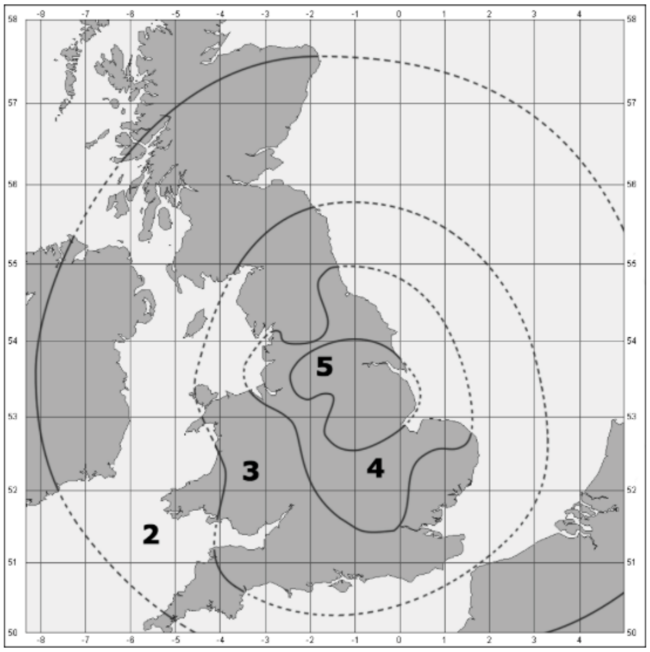

% Loss
3-10


% Loss
3-10


% Loss
10-30

3.2.5 Market Rasen, Lincolnshire, UK - 27/02/08

A 5.2M_L earthquake, the largest recorded in the UK since 1984, struck Lincolnshire at 00.56am. The epicentre was 4 km north of Market Rasen and had a depth of 18.6 km; the highest intensity level determined was EMS V. No deaths were caused; one injury was reported.



The British Geological Survey "received reports of damage to chimneys and masonry over a widespread area" but described the damage as "less serious than that in Folkestone in 2007"[27]. As can be seen from the isoseismal maps, the maximum intensity of shaking from this earthquake was considerably lower than that at Folkestone, but the area over which intensity V shaking was felt was much greater.

We were able to find photographic records of four damaged chimneys: one chimney collapsed in South Yorkshire while three in Gainsborough, near the epicentre, were damaged. All the damaged chimneys were on houses built before WW1. The approximate population of buildings in South Yorkshire and Lincolnshire was 872,400[19], of which 21.4% (English average) were assumed to be pre-WW1[20].

The chimney in South Yorkshire fell through the roof and caused the only reported injury – a broken pelvis sustained by a man as the chimney fell onto his bed in an attic room. The chimney was located in the middle of the roof, in the middle of a row of terraced houses. The chimneys in Gainsborough were only slightly damaged with an average of 5% volume lost[28].

We are confident from the BGS reports that the 4 specific chimneys for which we were able to find photographs represented a small proportion of the total numbers damaged, which could easily have been an order of magnitude higher.

CHIMNEYS	**No. with significant failure**	**% Masonry Volume Fallen to Ground**		
EMS		**Low**	**Ave.**	**High**
V	4-40	2%	21%	40%

Figure A2.13 Images of Market Rasen earthquake damage:
(a) Gainsborough damage[28]

Figure A2.13 (b) Damaged chimney in South Yorkshire and the damage caused by debris inside

3.2.6 Overview of chimney performance in low intensity UK earthquakes

A clear observation from ALL of these earthquakes is that damage was confined to older, pre-World War 1 buildings, and to chimneys (and roof tiles) rather than to any other building elements.

Table A2.1 provides an overview of the estimated numbers of buildings (derived from UK census data for the approximate area covered by the relevant intensity of shaking, based on the BGS isoseismal maps presented above) and of pre-WW1 buildings (based on English Housing Survey data on the national average proportion of buildings built before 1919), along with the resulting estimates of proportions of buildings suffering damage.

Table A2.1 Summary of Proportions of Chimneys Failed, and of % Volumes Fallen

Earthquake	EMS Shaking Intensity	Total buildings (estimated)	Relevant buildings	% Pre-WW1**	No. Pre-WW1 bdgs	No. signif chimney failures	% Pre-WW1 chimneys failed	Ave. % volume fallen
Bishop's Castle	V/VI	141000	Shropshire, Clwyd relevant districts	21.3%	30004	20-40	0.07-0.13%	9%
Melton Mowbray	V	314000	Notts, Leics relevant districts	21.3%	66818	2	0.003%	No data
Dudley	V	1087000	all of W Midlands	21.3%	231308	3	0.001%	50%*
Folkestone	VI	707	Streets surveyed	100.0%	707	12	1.7%	9%
Market Rasen	V	872000	all of S Yorks, Lincs	21.3%	185557	4-20	0.002-0.01%	21%*

** % volume fallen based on small sample of photos found in published media*

*** based on English Housing Survey 2008 averages for all of England*

Folkestone appears to have involved the strongest ground shaking, and, within the highly localized most-affected area, to have sustained considerably the largest proportion of chimneys failing. The proportion of chimneys failing for the earthquakes of maximum intensity V was in the range 0.001 to 0.01% - i.e. very small numbers of isolated examples only. Bishop’s Castle, the only other earthquake estimated to have involved intensity VI shaking, involved a proportion of chimneys damaged intermediate between the most-affected area of Folkestone and the intensity V earthquakes.

We regard the information on proportion of chimney volumes falling to the ground for Folkestone and Bishop’s Castle as being substantially more reliable than those for the other earthquakes, since the others are based only on photographs found in the media, which we consider likely to have been among the most “dramatic” available. It is clear that a large majority of the chimney failures for which we have reliable photographic records involved a modest proportion of the masonry in the chimney stack falling, rather than the whole chimney stack snapping and falling from the roof. In a large majority of such cases the material detached from chimneys on relatively steep roofs and fell to the ground almost in its entirety.

Our conclusions are

1. Damage in intensity V and VI shaking was limited to chimneys and roofs of older (pre-1919) buildings.
2. At intensity V such damage was very rare, occurring in around 0.001 to 0.01% of relevant buildings only.
3. At intensity VI such damage was more significant, occurring in between 1 and 2% of relevant buildings.
4. The primary mechanism of failure of chimneys in these older buildings, at these levels of shaking, was dislodgement of loose bricks, pots and mortar from the chimney stack, rather than collapse of the entire chimney stack.

5. In a large majority of cases the failed material fell onto a steep roof and fell almost in its entirety to the ground.

We consider this performance of URM houses likely to be more typical of that of houses in the Groningen region than, for example, was the performance of houses in the Liège earthquake of 1983, where a combination of exacerbating factors (previous subsidence damage, topographic and soil factors, poor condition housing) were all involved.

4. North American Earthquakes

Out of the many US and Canadian earthquakes to have occurred in recent decades, we selected three for study (before we became aware of the US FEMA reviews of chimney and parapet performance) on the basis of readily available information on damage to non-structural building components in large samples of buildings:

- The Seattle earthquake of 1965, where a substantial survey of chimney damage was carried out as part of macroseismic studies,
- The Nisqually earthquake of 2001, which was an early example of the use of large-scale internet-based reporting of felt earthquake experience by USGS, and where substantial information on the proportions of respondents giving different responses in different communities were published, and
- The Northridge earthquake of 1994, one of the most studied earthquakes in recent decades and of particular interest because older buildings in the area were part-way through being upgraded to comply with a Los Angeles city ordnance prescribing the strengthening to be applied to them.

We have retained our discussion in this Appendix to give a quick idea of some of the sorts of information available on US earthquakes. The FEMA report discussed in Section 3.1 of Appendix 1 provides references to a number of more comprehensive studies.

Our analysis of the Nisqually data and of companion data on the housing stock in selected counties of Washington State is provided in a companion report[29]. We hope to be able to obtain more detailed information on damage to individual buildings for the Northridge earthquake in due course, but for the present have provided (4.3 below) a summary of published information relevant to non-structural component failure.

4.1 Seattle 1965

This strong (MW 6.5), deep (59km) earthquake occurred under Puget Sound at 07:30 am on 29 April 1965. The maximum intensity of MMI VIII was experienced in parts of Seattle; the effects were felt very widely. A total of seven deaths were attributed to the earthquake, four (all elderly women) from heart failure and the other three from falling debris in the industrial area where people were already up and about at work[30].

A study was carried out of relationship between building damage and local geology[31], where the general description of building damage is summarised in the excerpt below:

> **The type of damage caused by the 1965 earthquake was also similar to that resulting from earlier strong earthquakes. Cracking or collapse accompanying the differential subsidence of fill and postglacial sediments was significant locally, but damage attributable to shaking was more widespread. The most severe shattering was sustained by older unreinforced masonry structures and by masonry veneer and chimneys on wood frame buildings. Whereas the majority of damaged buildings were merely cracked, numerous walls, gables, parapets, cornices, and chimneys were broken and partly or wholly thrown down.**

Source: Mullineaux et al[12]

A specific survey of chimney damage was carried out; Figure A2 .14 (reproduced from reference 31) shows the results for the worst affected parts of Western Seattle surveyed (note that the single digits are ONE TENTH of the percentage of chimneys fallen – so a numeral 4 means that 40% of chimneys in that city block had fallen) where the assigned intensity was MMI VIII. No information is available on the make-up of the building stock in these locations; it seems likely (given the strong dependence of failure rates on building age and condition observed in other earthquakes) that the variation in proportions of chimneys failed reflects substantial variations in building age and condition, as well as in local shaking and soil type.

The more general finding of the survey outside this worst-affected area was that at most 1-2% of chimneys collapsed where buildings were located on bedrock, while in otherwise comparable areas on a till-covered ridge above Pleistocene sediments the collapse rate was up to 10%.

Figure A2.14 Seattle 1965 Chimney Survey (from Mullineaux et al[30])

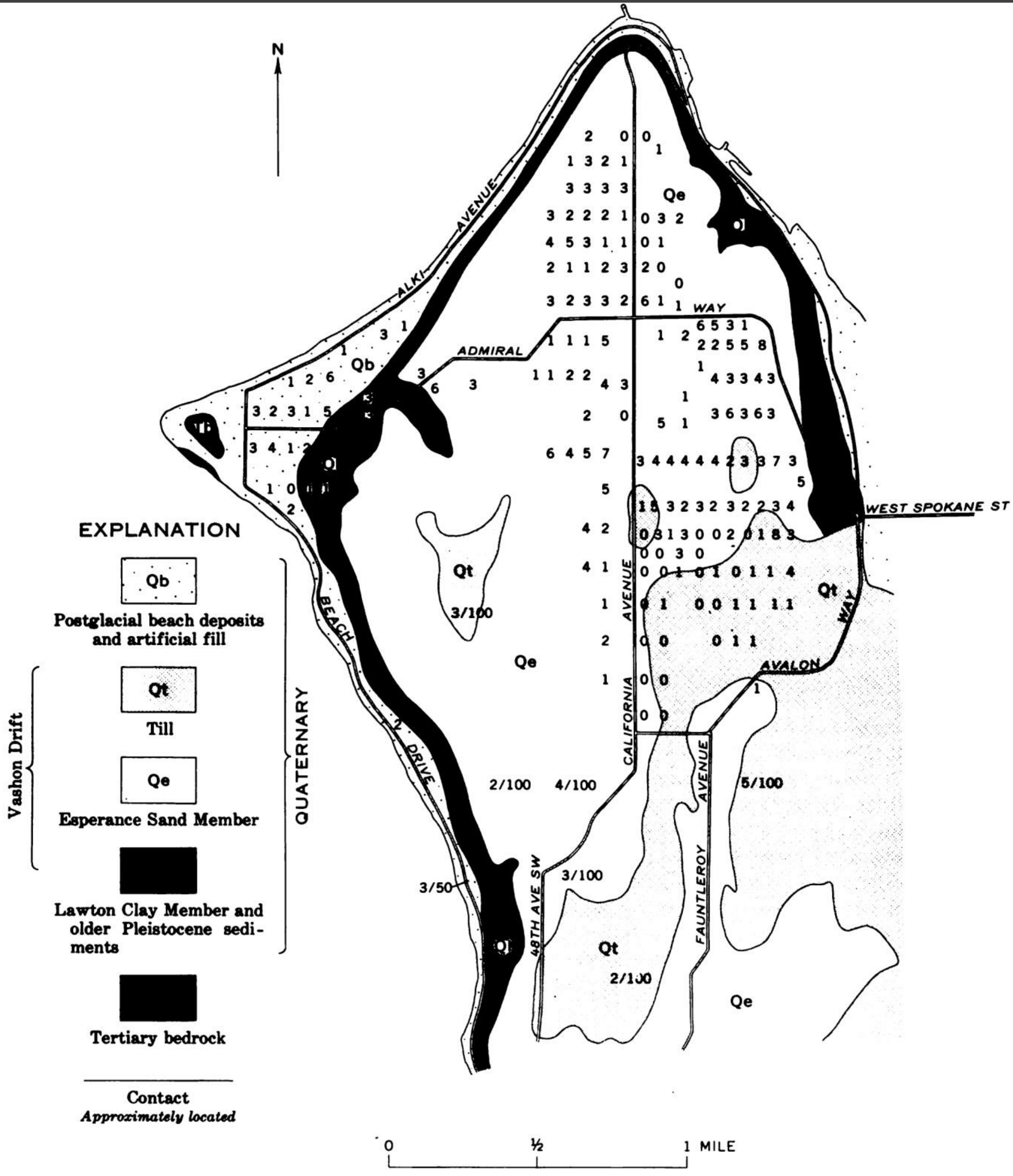


Figure 3.—Distribution of chief geologic units and fallen chimneys in part of West Seattle. The approximate percentage of fallen or partly fallen chimneys in counted city blocks is shown by plotted whole numbers that are 1/10 of the actual percentage. Fractions represent the proportion of similarly damaged chimneys in larger areas where less than 10 percent fell. Geology modified from Waldron and others (1962).

As was observed for several of the other earthquakes analysed, damage to "well built" buildings was generally described as "slight", with damage being concentrated among poorly built or badly designed buildings[11].

4.2 Nisqually 2001

This 6.8 M_L earthquake occurred deep (52km) under Puget Sound at 10:54 am on 28 February 2001. It was very widely felt and was the subject of a substantial USGS study comparing the traditional USGS approach to evaluation of intensity (based on responses to postal questionnaires) with the new Community Internet-based approach[32]. A large sample of responses to "Did You Feel It" (DYFI) reports was published in terms of percentages of respondents reporting (among other things) major damage to old and modern chimneys (note that what constitutes "old" and "modern" is not defined in the USGS DYFI questionnaire) and whether bricks or blocks had fallen from masonry walls. A significant step in moving from the traditional to the community internet-based assessment of intensity was that it removed a direct link between building damage and assessed intensity; under the community internet-based approach intensities could be and are assigned based on other reports of felt shaking, objects shaken from shelves etc and are less directly driven by building damage reports.

These DYFI responses were aggregated according to the intensity of shaking associated with each community; the analysis is presented in our companion paper[29]. This enabled us immediately to discern a major difference in response rates for "old" and "modern" chimneys damaged, but in the absence of knowledge of the building stock the significance of this was difficult to assess. As described in the paper, we were able to obtain substantial building stock information on two of the counties exposed to the highest intensity shaking, and used this information to "normalise" the DYFI in relation to numbers of masonry buildings (and numbers estimated to have masonry chimneys).

While it is difficult to draw direct quantitative conclusions on failure rates given the major assumptions that had to be made about the building stock, it was clear that

1. Modern chimneys had at least a factor of 10 lower reported failure rate than older ones
2. There was a strong correlation between chimney damage, bricks/blocks detached from walls and shaking intensity, and
3. Tens of % of walls and older chimneys sustained damage (involving bricks/blocks detached from walls, or "major damage to older chimney") at intensity VII-VIII shaking, while several % or more sustained such damage at intensities V-VI.

USGS DYFI reports represent a very large and potentially valuable resource from which to combine massive scale reporting of effects by the public with the more detailed and local surveys of damage carried out by experts post-earthquake, particularly if ways can be found to bring together DYFI reports with relevant building stock information.

4.3 Northridge 1994

NOTE – this earthquake was very extensively studied and we understand that a substantial dataset with information on damage to individual buildings may still be available. If available this may warrant substantial reanalysis with a particular focus on performance of non-structural building elements. This report section is currently based on reviews of damage that are in the public domain.

The ML 6.8 earthquake took place at 04:31 am on 17 January 1994, causing massive damage to buildings and infrastructure. Direct measurements of ground motion were available from a network of monitoring stations in the Los Angeles (LA) area, with PGA >1g at the epicentre, and with shaking at 0.3g and above extending around 100km outward.

An EEFIT mission was carried out for 7 days from 27 January 1994; their report[33] provides a good overview of the earthquake and its effects. Damage clustering in the San Fernando valley and LA, at some distance from the epicentre, was attributed to significant soil effects on local ground motions. URM buildings were particularly affected, but many timber framed and concrete buildings also suffered severe damage.

The death toll of 57 was later revised upwards to 70[34], comprising

- 22 killed through structural damage to buildings:
  - 16 in the partial collapse of a 3-storey apartment building,
  - 4 in the collapse of 3 separate timber-framed family houses,
  - 1 in a mobile home collapse, and
  - 1 policeman who rode his motorcycle off the end of a collapsed freeway overpass
- 7 killed through non-structural damage:
  - 1 death from heart failure after being struck on the head by a falling microwave oven
  - 2 buried under a large weight of objects falling from shelves in their homes
  - 3 deaths when respirators lost electrical power and stopped running, and
  - 1 person electrocuted when trying to remove power lines from his car
- 43 deaths from other causes:
  - 30 from heart attacks attributed to the earthquake
  - 5 from falls
  - 3 from road traffic accidents with causes attributed to the earthquake
  - 2 from exposure
  - 1 from fire, and
  - 1 suicide.

Of particular interest in the context of building strengthening for the Groningen region, the Los Angeles building code introduced in 1981 the “Division 88” requirements for strengthening existing buildings against seismic loads. These included, for example, the requirement for URM diaphragms to be tied into walls, and for walls not complying with specified height/thickness requirements to be braced. At the time of the earthquake, of the 8,247 URM buildings present in the city of LA in 1981[35],

- Over 6000 had been brought into full compliance with Division 88
- Just over 1600 had been demolished, and
- Several 100’s remained non-compliant, mostly in Southern LA where shaking was lower and relatively little damage occurred.

Much of the older URM building stock in the San Fernando valley had been “culled” in earlier earthquakes, so that the URM exposure to high shaking was largely that in LA, and had largely been strengthened in compliance with Division 88.

The overall effect of the Division 88 strengthening was very positive. A collation of data on building performance using an overall "% damage" rating is shown in Table A2.2; the same information is collated by intensity band and presented graphically in Figure A2.15. The data are sourced from a special edition of Earthquake Spectra which provided detailed articles on both URM[36] and reinforced masonry[37].

Table A2.2 URM Building Damage by LA City District

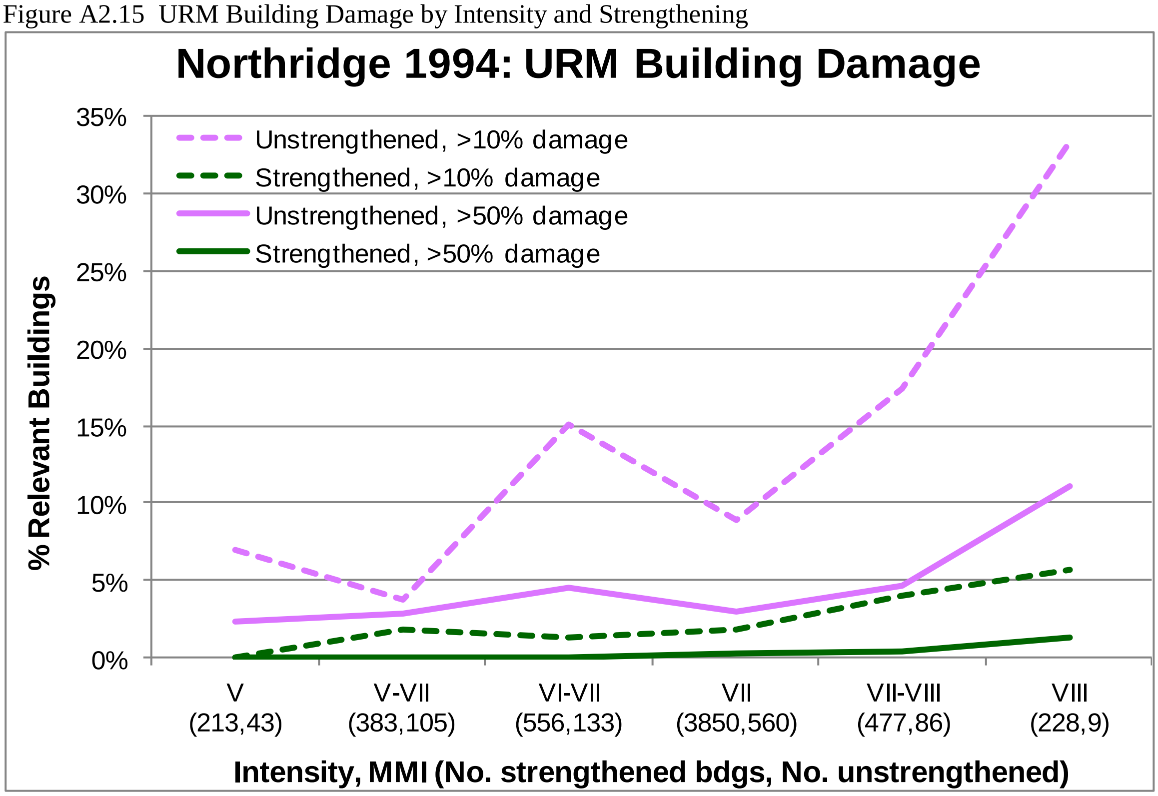
				URM Status				Unstrengthened			Strengthened		
Council District	Location (approx.)	MMI	Total URM Buildings	Prior Demolition	Exempt	Divison 88 Strengthened	Non-Division 88 Unstrengthened	< 10% Damage	< 50% Damage	> 50% Damage	< 10% Damage	< 50% Damage	> 50% Damage
1	[25,-15]	VII	906	151	15	654	86	10	5	2	94	9	0
2	[20,5]	VII	31	3	1	23	4	0	0	0	2	0	0
3	[-5,0]	VIII	54	7	1	45	1	0	0	0	8	7	2
4	[20,-10]	VII	644	81	7	490	66	15	9	2	73	8	2
5	[10,-10]	VII-IX	220	20	9	183	8	1	2	1	7	3	1
6	[10,-25]	VI-VII	265	34	12	178	41	2	2	1	9	1	0
7	[10,10]	VII-VIII	23	5	0	11	7	5	0	1	1	2	2
8	[20,-25]	V-VII	613	105	20	383	105	4	1	3	22	7	0
9	[25,-20]	VII	3013	735	41	1935	302	23	11	6	74	27	1
10	[15,-20]	VII-VIII	607	51	11	466	79	12	11	3	80	15	0
11	[5,-10]	VII	125	18	0	94	13	1	4	2	13	3	2
12	[0,10]	VIII-IX	3	1	0	2	0	0	0	0	0	1	0
13	[25,-10]	VII	858	101	14	654	89	17	7	5	90	9	8
14	[30,-15]	VI-VII	560	78	12	378	92	15	12	5	18	6	0
15	[25,-45]	V	320	60	4	213	43	5	2	1	0	0	0
			8242	1450	147	5709	936	110	66	32	491	128	18

Figure 7

URM Data for City of Los Angeles Arranged by City Council District and MMI

(Earthquake Spectra, January 1996 Supplement C to Volume 11)

Figure A2.15 URM Building Damage by Intensity and Strengthening



Notwithstanding the beneficial effects of strengthening, in particular in terms of preventing structural collapse, there were very numerous examples of detached parapets and wall sections, both in the cities further out from LA where shaking was lower but retrofitting less advanced, and in the LA area among strengthened buildings. These non-structural failures were considered to have represented a very severe life safety hazard, but because the earthquake took place at 04:30 am there was no-one present outside buildings to be harmed. Bruneau[35] wrote:

> *"To this day, the severe seismic hazard created by falling non-structural components, such as masonry veneers and cladding in general, has not received the attention it deserves from the structural engineering community, even though these can be as life-threatening as structural failures."*

Examples of damage to walls, showing how "strengthening" using stays and tie-bars with plates or anchors failed to be effective, are provided in Figure A2.16 (parapets), A2.17 (URM walls) and A2.18 (delamination from URM and reinforced masonry walls). All photos are reproduced from the EEFIT report[33].

Figure A2.16 Damage to Strengthened Parapets

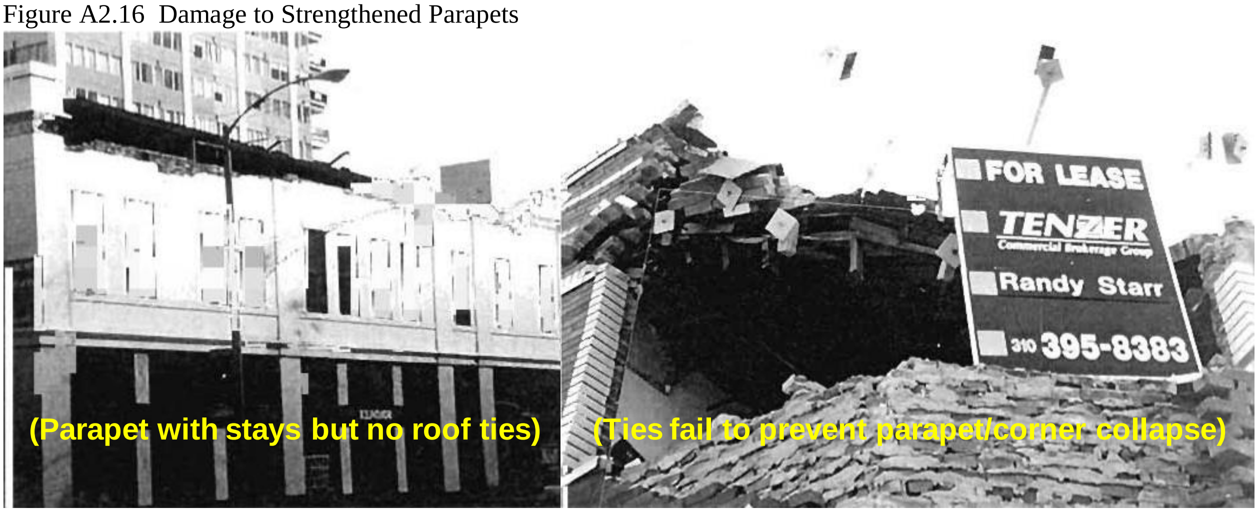


Figure A2.17 Damage to URM Walls (roof ties only – no ties at 1st floor)

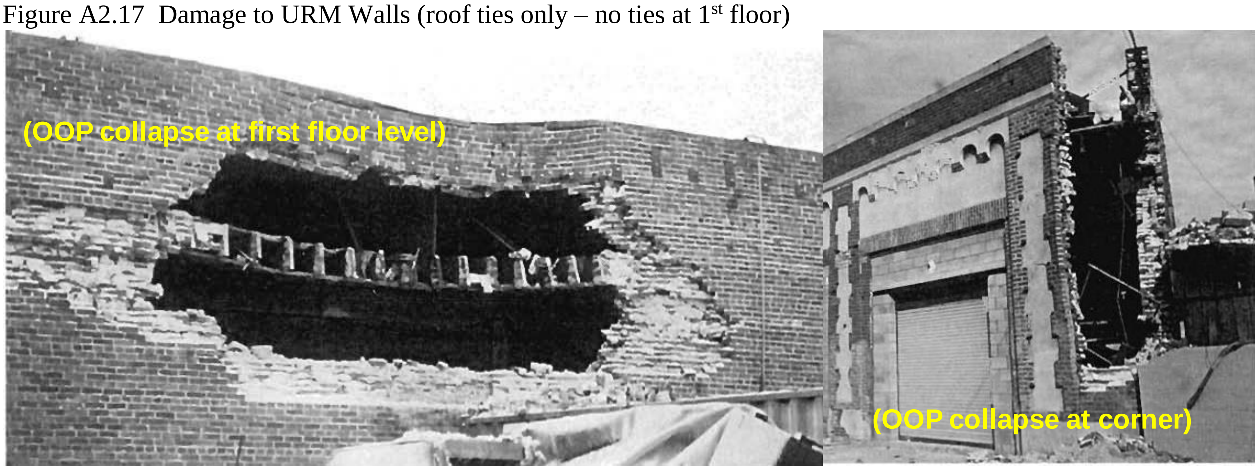


Figure A2.18 Delamination from URM and Reinforced Masonry Walls

We do not (currently) have data from which to carry out quantitative analysis of proportions of buildings suffering given failures, but from the sources reviewed in this analysis conclude that

1. Strengthening of buildings had a strong positive effect, reducing damage to URM buildings generally to lower levels than were observed in previous major California earthquakes.
2. URM buildings did, though, sustain very considerable non-structural damage to parapets, gables, veneers and plane walls generally – both in areas of lower shaking where buildings were mostly unstrengthened, and in areas of higher shaking where buildings had been strengthened – creating severe debris falling hazards outside buildings.
3. There is much to be learnt from the Northridge experience about ways in which strengthening measures can prove ineffective.

5. Earthquakes in Australia and New Zealand

We consider here

a) Two much-studied earthquakes in Australia (Newcastle NSW in 1989 and Kalgoorlie, WA in 2010)
b) Three of our own studies on the Christchurch, Canterbury earthquake swarm of 2010/11, and
c) Other New Zealand earthquake information including a special study on parapet performance in the Gisborne earthquake of 2007.

The Australian earthquakes are of particular interest because they both involved exposure to shaking of substantial URM building stock designed and built without any thought for seismic hazard (though in neither case were direct measurements of ground motion available).

The Christchurch earthquakes are of very great interest because the city had in place a substantial network of seismic monitoring stations, and is the only earthquake for which we have been able to assembled reasonably extensive records of ground motion on the one hand, and specific building damage on the other. The Gisborne earthquake in 2007 led to a detailed survey of the performance of parapets. Other New Zealand experience, collated from various GNS Science reports is also summarised.

5.1 Newcastle 1989

This ML 5.6 earthquake occurred at 10:27 am on 28 December 1989, with strong shaking in the Newcastle Central Business District (CBD) lasting 3-4 seconds. The intensity was originally reported as maximum MMI VII but this was later revised to MMI VIII. Extensive building surveys were carried out by the City Council and others; a database of individual buildings and damage appears to have been assembled by the City Council but we have not to date been able to locate it. This summary is based on

- A brief overview paper by Geosciences Australia[38]
- The Institution of Engineers, Australia earthquake study[39]
- The EEFIT mission report[40]
- A University of Adelaide review of URM building performance[41], and
- A retrospective published by the New Zealand Society for Earthquake Engineering[42].

The city had a large stock of URM buildings, many built before 1920; no thought had ever been given to the possibility of earthquakes when any of the buildings in the city were designed and built. The damage to URM buildings in particular was extensive, with "many examples of partial or total collapse, particularly of gable ends, parapets, facades and chimneys"[40]. Of particular interest in the context of the Groningen region there was a large stock of cavity walled URM buildings, which suffered numerous out of plane failures of outer brick leaves which were inadequately tied to the inner, structural leaves (Newcastle is by the sea and many ties were found to have corroded).

Timber and reinforced concrete buildings generally performed well, with two or three very notable exceptions (all concrete buildings) including the Newcastle Working Mens' Club where 9 people were killed when the building collapsed. Three other people were killed by falling debris (shop awnings, collapsed by the fall of parapet and facade debris from above them). Schools were extensively damaged but were empty during the holiday period.

The nearest seismic monitoring station was over 100km away, so there are no direct measurements of shaking. Subsequent estimates of shaking based on the known parameters of the earthquake and ground motion prediction equations estimated shaking in the CBD up to about 0.2g[40] or between 0.2 and 0.3g[42].

Among the housing stock, much of the older suburbs (pre-1920) were built of cavity brick where damage was extensive. More modern masonry houses fared better, but with some examples of poor design and construction leading to failures. Commercial URM buildings suffered particular damage among newer as well as older buildings, particularly to tall parapets and gable ends.

Examples of damage are illustrated in Figures A2.19 to A2.21 for a solid wall and gable (Fig A2.19), a cavity wall and facade (Fig A2.20) and parapets (Fig A2.21). All photos are reproduced from the EEFIT report (photos taken over a week after the earthquake, so debris on the floor has largely been cleared up).

Figure A2.19 Gable and Solid Wall Damage

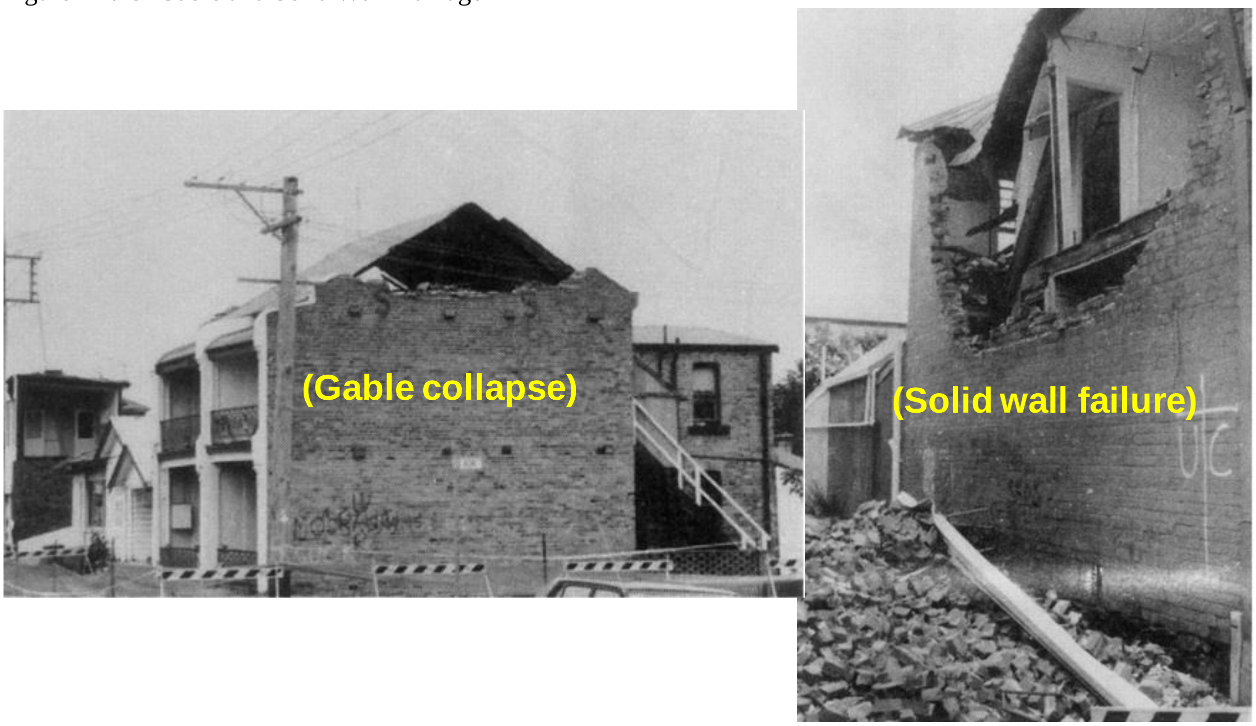


Figure A2.20 Cavity Wall and Facade Damage

Figure A2.21 Parapet Damage example on a Modern URM Building

The Institution of Engineers, Australia report published maps produced by the City Council allocating individual buildings a letter code for construction type, a letter code for usage type, and a number corresponding to the damage estimated on the MMI scale. It would be possible but difficult to analyse the distribution of damage states from their maps, but considerable uncertainty would remain as to what specific damage to non-structural elements was associated with a given MMI rating.

The EEFIT mission carried out detailed photographic surveys of 625 buildings in the worst-affected parts of the city, which were subsequently analysed by CAR. Each building was allocated a damage state based on the MSK scale, where for URM

- D1 (slight damage) = hairline cracking
- D2 (moderate damage) = cracks 5-20mm
- D3 (heavy damage) = cracks > 20mm or wall material dislodged
- D4 (partial collapse) = complete collapse of individual wall or roof support
- D5 (collapse).

The results in terms of proportions of buildings of different construction, age and height are summarised in Figure A2.22, 23 and 24 respectively (all reproduced from the EEFIT report).

Figure A2.22: Damage vs Construction Type

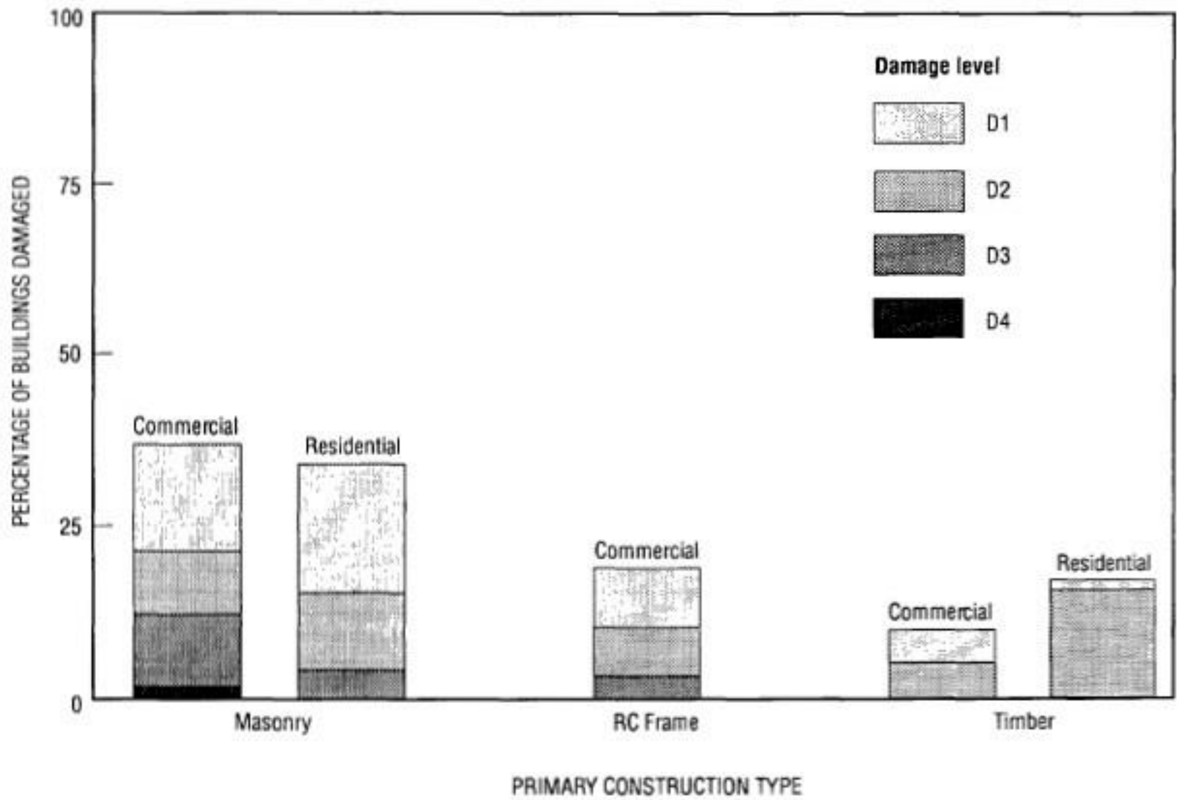


Figure A2.23: Damage vs Age

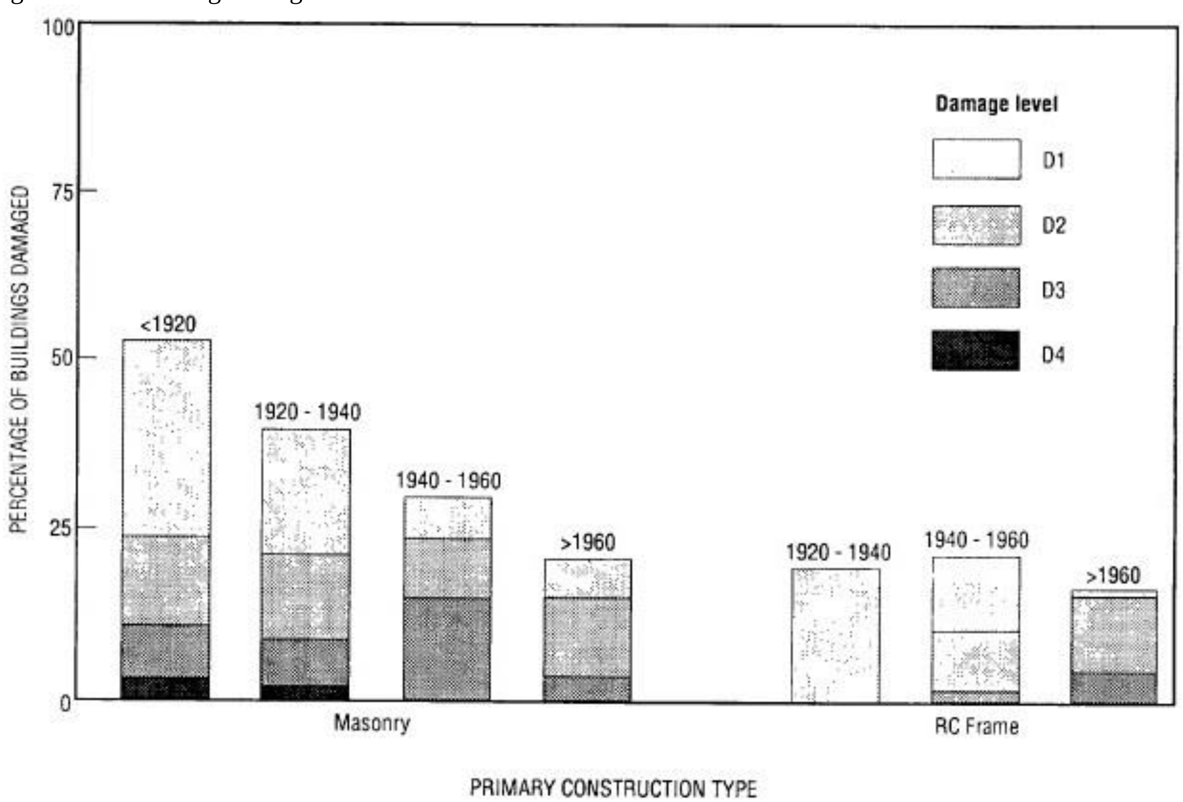
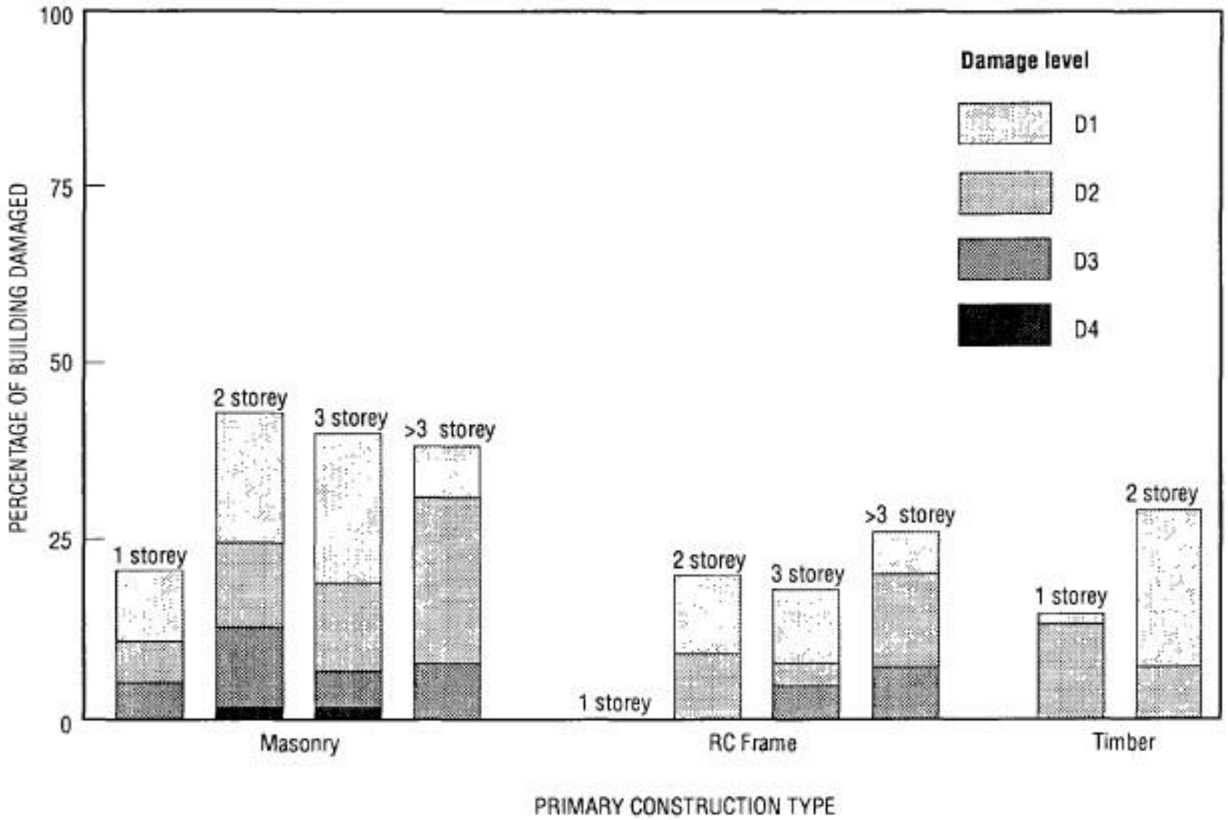


Figure A2.24: Damage vs Building Height



Of particular interest for this study is damage to levels D3 and above, where masonry is detached from buildings. Such damage affected about 12% of commercial and 5% of residential URM buildings, plus a few percent of reinforced concrete commercial buildings (damage to parapets and infill walls). Age was a major factor, with newer (post 1960) buildings suffering about one third the incidence of D3+ damage of older buildings. Single storey buildings suffered about half the incidence of D3+ damage as taller buildings, but the EEFIT authors point out that height and age are not independent, and concluded that age was a more important influencing factor than height. The EEFIT data was not analysed in terms of cavity vs solid walled brick buildings, but noted, as did all of the other sources referenced above, that failure of cavity wall outer leaves was particularly prevalent.

Our simple conclusion from the Newcastle earthquake is that URM buildings designed without regard to earthquakes can fail in a manner leading to substantial quantities of debris falling outside them in somewhere between a few per cent of cases (for modern, more robust buildings – but where ornamental masonry features such as parapets and facades may still be vulnerable) up to in excess of 10% of cases (for older buildings and non-structural walls or leaves of walls).

Finally, we were able to obtain a large sample of photographs from the CAR archive of about half of the buildings surveyed by the EEFIT team. We re-analysed these[43] to identify the numbers and proportions of parapets and gables in particular that were damaged to different damage states as defined in the main report. The quantitative results are included in Appendix 3.

5.2 Kalgoorlie 2010

This was a moderate magnitude earthquake (ML 5.0) which occurred at shallow depth (1.7 km), leading to shaking in Kalgoorlie of intensity MMI V and in the adjoining community of Boulder of MMI VI. No measured values of ground acceleration were available in the vicinity of the event. A particularly thorough and detailed survey of URM building stock covering the two communities was carried out by Geosciences Australia in conjunction with the Universities of Melbourne and Adelaide[44]. This included details not only of each chimney and parapet that failed, but also of the % of its volume that toppled. Wall damage was described in less detail (but there was also less of it at these relatively modest levels of shaking).

We are extremely grateful to Geosciences Australia for making the survey dataset available to us. The survey, and our re-analysis of its results, is described in our companion paper[45]. Our conclusions, in terms of proportions of URM building elements that failed and typical percentages of volume falling to the ground, are presented in Table A2.3. No damage was observed to chimneys or parapets on buildings built later than 1920 (almost all of which were built from the 1950's onwards).

Table A2.3: Summary of Failure Probabilities and Volumes Falling

Building element & failure mode	**MMI 5**		**MMI 6**	
	Proportion failed	**Average % volume fallen**	**Proportion failed**	**Average % volume fallen**
Chimneys toppled, pre-1920	~1%	~5%	~16%	~12.5%
Parapets toppled, pre-1920	~0.5%	~5%	~20%	~50%
Walls damaged to Level 7 or more*, pre-1920	~1%	~50%*	~5% (1-2 brick, solid) ~15% (3+ brick, solid) ~50% (cavity)	~50%*
Walls damaged to Level 7 or more*, post-1920	~1%	~50%*	~1%	~50%*

** Note this is the percentage of wall area DAMAGED, not the % fallen to the ground. Our assumption after discussion with the survey authors is that perhaps 30-70% of these cases would* *involve masonry falling, with the % volume falling being significantly lower than the average % of wall area damaged.*

5.3 Christchurch 2010-11

Alone among all the earthquakes for which data was available for this study, Christchurch had in place a network of seismic monitoring stations before the first and largest earthquake occurred, centred on Darfield in Canterbury, on 4 September 2010. This M_W 7.1 earthquake caused ground shaking throughout most of the Christchurch area with horizontal PGA in the range 0.16 to 0.4g, leading to extensive building damage and falling debris from URM buildings in the city, but no deaths (the event took place at 04:09 in the morning when the streets were deserted).

The most destructive earthquake, at 12:51pm on 22 February 2011 was a lower intensity (M_L 6.3) aftershock which, being shallower and much closer to Christchurch, led to much larger ground motions (up to 1g horizontal and 2.2g vertical) in the city. Building damage was again extensive, and 185 people were killed, of whom 133 died in two large reinforced concrete buildings which collapsed, 1 in another concrete building, 41 from falling masonry debris (37 of them outside, 4 inside the buildings from which the debris fell), and 10 from other causes not related to building failure. Subsequent earthquakes in June and December 2011 caused considerable further damage but no further deaths.

As this was the only earthquake for which we were able to find both substantial, detailed damage reports AND local strong ground motion measurements, we have been to particular lengths to obtain and analyse relevant data, and have carried out studies (papers in preparation, intended for publication) covering

a. a re-analysis of the database on URM building performance in Christchurch carried out by the Universities of Auckland and Adelaide following the 22/2/2011 earthquake in particular[46]

b. analysis of a Geoscience Australia photographic dataset on Christchurch URM buildings, collected after the first (Darfield) earthquake of 4/9/2010[47] and

c. analysis of chimney performance in the immediate vicinity of strong ground motion stations based on Street View, aerial photography and Earthquake Commission claims data following the 4/9/10 and 22/2/11 earthquakes[48].

The conclusions of these studies are described in turn. An important observation from both (a) and (c) was that there was a clear, apparent correlation between damage to non-structural building elements and PGA.

5.3.1 The universities' URM damage data

Our first major quantitative information source for this study was the damage database of 627 URM buildings throughout Christchurch collated by the Universities of Auckland and Adelaide[49]. This provides information on the buildings sustaining damage levels 1-5 in each of the four earthquakes, and more detailed information on the performance of parapets, gables and walls in the February 2011 earthquake, as well as information on the strengthening measures in place (or otherwise) for individual buildings. We are extremely grateful to the universities for making this dataset available to us. Our re-analysis of the data focusing on non-structural elements' performance is in preparation for publication[46].

The database provides the results of detailed building damage studies carried out after the 22 February 2011 earthquake, along with summaries of damage recorded in other sources after the 4/9/10 Darfield earthquake and the two other large quakes in Christchurch in the earthquake swarm (13 June and 23 December 2011). The information available on the 22/2/11 event is much the most detailed, though its interpretation is complicated by the confounding effect of damage incurred during the previous (4/9/10) event.

Figure A2.25 provides an overview of the extent of damage at different shaking levels across the four major earthquakes. Figures A2.26 to A2.28 provide an overview of some of our analyses of the buildings data, for parapet collapse, out of plane wall damage and gable collapse respectively.

Notes on Figures A2.25 to A2.28:

1. The ground motion associated with each building was that measured at the nearest strong motion station; these can be a considerable distance (100's of metres or even a few km in some cases) away from the building in question.
2. The percentage collapsed is the percentage of BUILDINGS with parapets recorded as having an damage state of collapse or partial collapse, rather than a percentage of PARAPETS.
3. The interesting out of plane damage in Figure A2.27 is unfortunately not further broken down in terms of the nature and extent of the out of plane damage involved. Photographs of the Christchurch central business district show building after building with the front walls having virtually completely fallen away leaving the insides near-intact and on open view.

Our conclusions from this analysis are as follows:

1. For a given level of shaking the earthquakes show different levels of damage to these building elements, with February 2011 > Sept 2010 & June 2011 > Dec 2011.
2. A plausible hypothesis to explain this order is that
    a. Damage was greater in the February 2011 event because of the pre-existing damage from the Sept 2010 event and the exceptionally high vertical as well as horizontal ground accelerations associated with the February earthquake.
    b. Damage was lower in the December 2011 event because most of the buildings susceptible to damage had already been seriously damaged,
    c. Damage in the June 2011 event was mixed – at low shaking greater than that experienced in September 2010 while at higher shaking somewhat less. This suggests competing effects in operation – high levels of pre-existing damage tending to increase damage, with a reduced residual stock of buildings susceptible to damage tending to reduce it.
3. The extent of building damage, in terms of both the proportion of buildings damaged and the severity of damage, increased consistently with horizontal ground shaking measured in PGA terms for each earthquake and for each type of damage metric available.
4. With the aid of a number of plausible (but by no means proven) hypotheses, conclusions have been drawn from the observed building performance data as to the values for different levels of ground shaking from <0.1g up to 0.9-1g of
    a. the probability of parapets and plane wall sections suffering significant damage (Table A2.4), and

b. the proportion of the volume of parapets and plane wall sections that might fall to the ground in the event of significant damage occurring (Table A2.5).

Figure A2.25 Christchurch URM Damage, Major 2010/11 Earthquakes

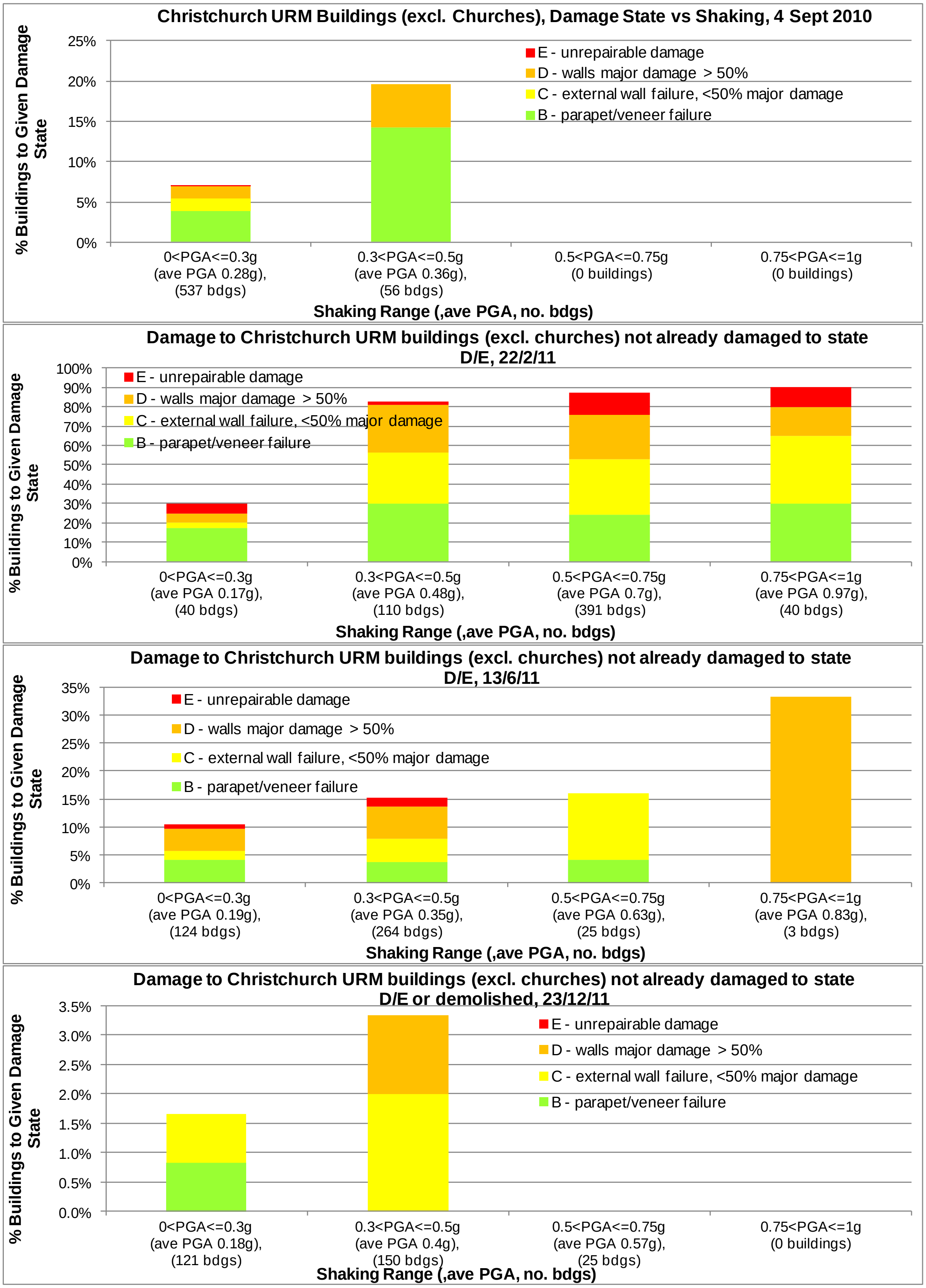


Figure A2.26 Christchurch URM Parapet Collapse, 22/2/11

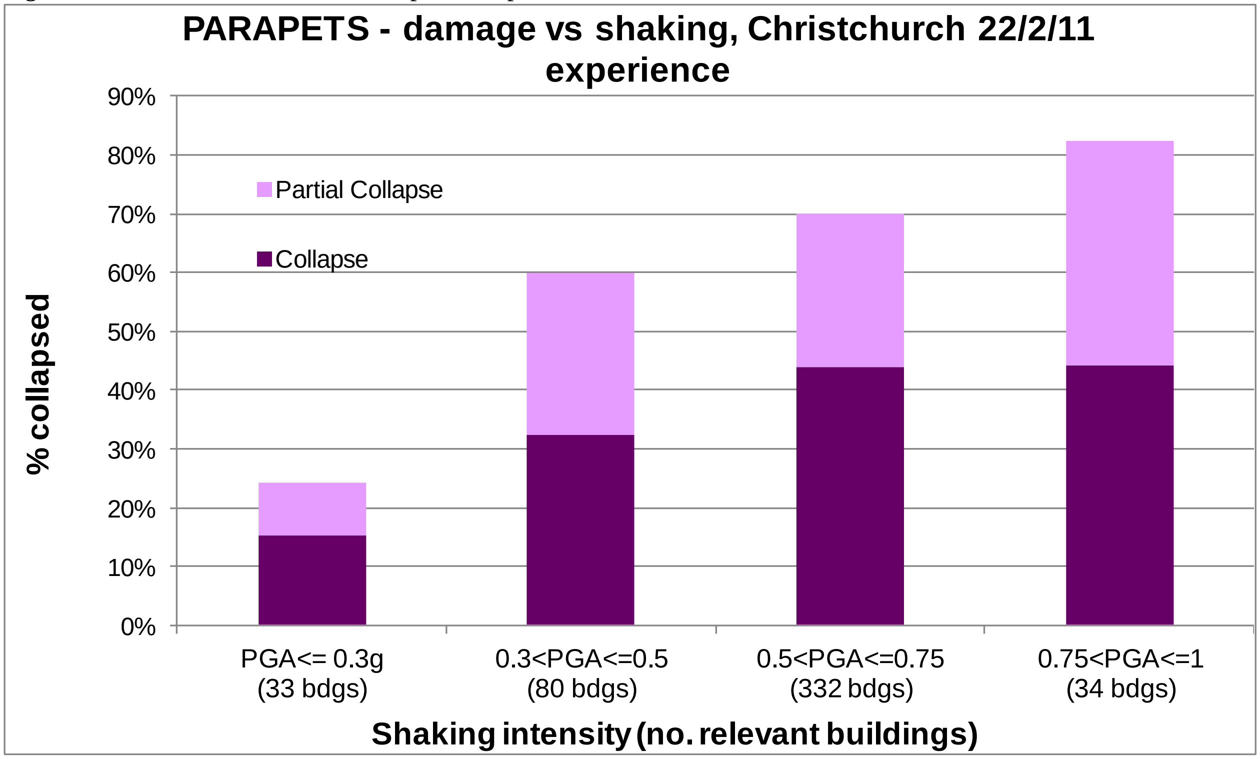


Figure A2.27 Christchurch URM Out of Plane Wall Damage, 22/2/11

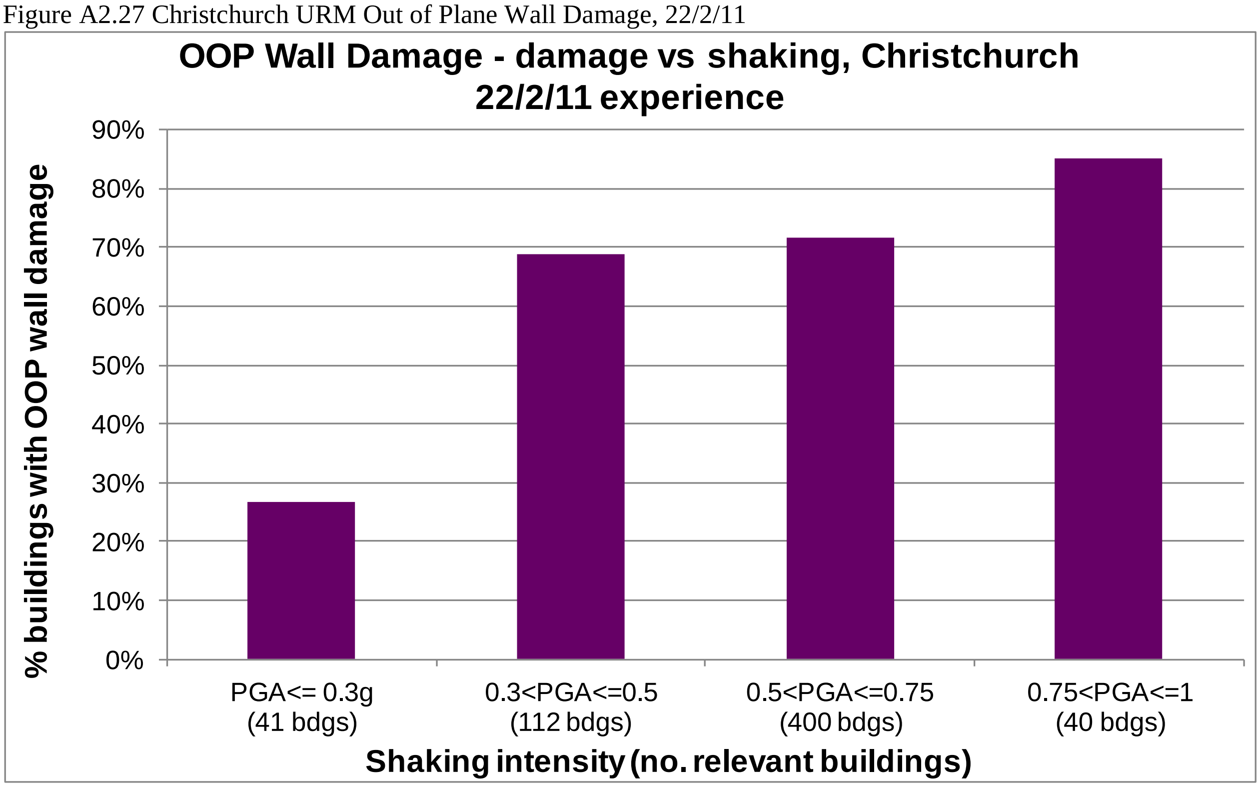


Figure A2.28 Christchurch URM Gable Collapse, 22/2/11

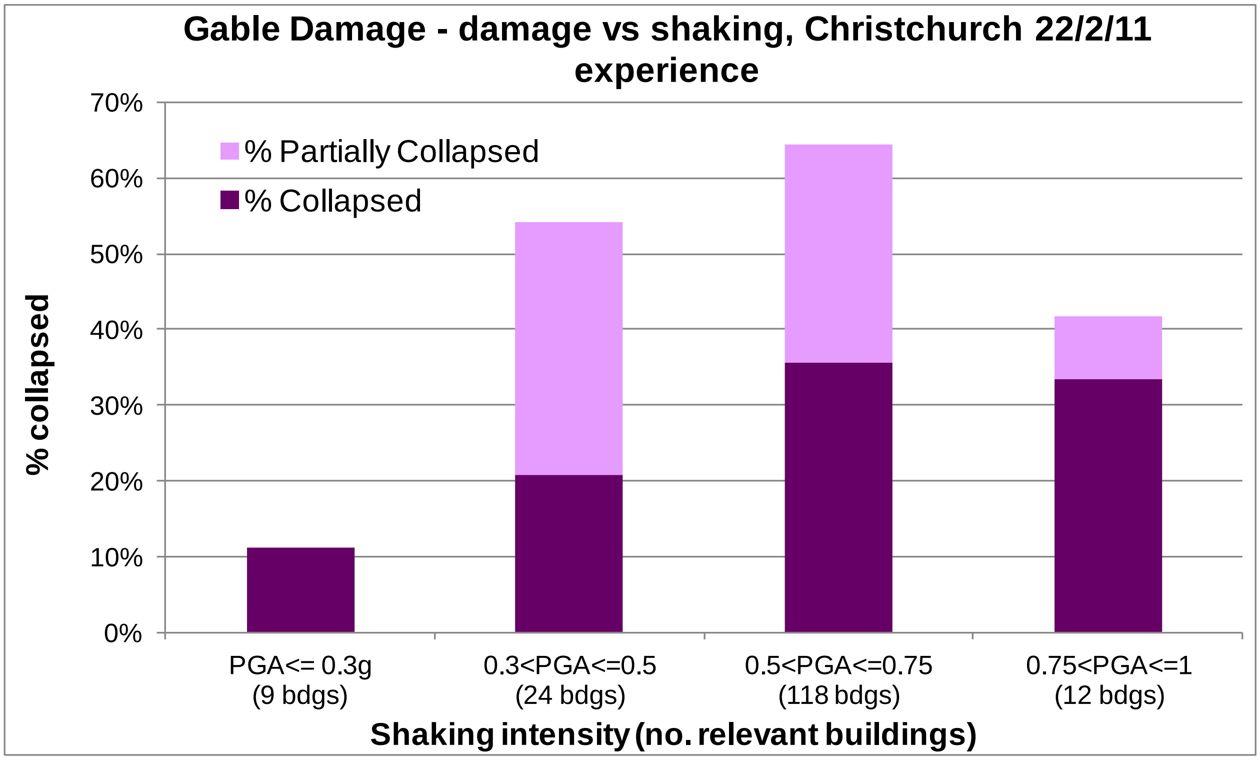


Table A2.4: Christchurch Conclusions: Probabilities of Significant Damage

PGA Band	**Lower**	**Higher**	**Notes**
0<PGA<=0.1	1.0%	2.0%	Estimated as 4-5x less than for pre-damaged buildings (as in Feb, June events)
0.1<PGA<=0.2	2.0%	5.0%	Based largely on observed damage levels in Sept 2010 earthquake
0.2<PGA<=0.3	5.0%	10.0%	
0.3<PGA<=0.4	10.0%	20.0%	
0.4<PGA<=0.5	15.0%	30.0%	
0.5<PGA<=0.6	25.0%	45.0%	Interpolation between Sept 2010 and Feb 2011 observations, on the assumption that probability of damage to undamaged buildings (with "normal" vertical shaking) will progressively become nearer to that for pre-damaged buildings (with "abnormally high" vertical shaking) as shaking increases.
0.6<PGA<=0.7	35.0%	55.0%	
0.7<PGA<=0.8	45.0%	65.0%	
0.8<PGA<=0.9	50.0%	75.0%	
0.9<PGA<=1	55.0%	80.0%	

Table A2.5: Christchurch Conclusions: Proportions Falling to the Ground

PGA Band	**Wall Sections**		**Parapets**	
	Lower	**Higher**	**Lower**	**Higher**
0<PGA<=0.1g	5%	10%	5%	10%
0.1<PGA<=0.2g	10%	20%	10%	20%
PGA>0.2g	40%	60%	60%	80%

5. These probabilities of failure apply to the Christchurch URM building stock, which is entirely pre-1930, and to earthquake shaking of duration 10's of seconds. They may be reduced by factors of 2 or more for parapets or gables subject to well-devised seismic restraints. They do not show significant variation with building location, height or typology except at the lowest level of shaking, for which factors of about two reduction apply to detached relative to row buildings and to single storey relative to multiple storey buildings.

In applying the Christchurch data when forming our judgment as to the failure probabilities to be expected in the Groningen region we have taken particular note of the failure probabilities observed as a function of PGA in the 22/2/11 earthquake, which is that for which this dataset had considerably the most detailed information on building damage. We have assumed that failure probabilities for a given PGA in Groningen region would be considerably lower than those observed in this earthquake, because of a) the much shorter anticipated shaking duration, and b) the prior damage sustained in the Darfield earthquake of 4/9/10.

The Darfield earthquake, though still of large magnitude and long duration in comparison with any earthquakes that can be imagined for Groningen, is considered to provide a more valuable starting point for our purposes, as the damage there was not confounded by substantial prior shaking as was the case on 22/2/11 and subsequently.

5.3.2 Darfield earthquake – analysis of Geoscience Australia dataset

GNS Science brought to our attention the existence of a large photographic dataset of buildings in Christchurch compiled by Geoscience Australia in the days following the Darfield earthquake of 4/9/2010 and, with the permission of Geoscience Australia, provided us with a copy.

The photographs were taken and matched to buildings in a GIS system using the Geoscience Australia specially equipped car that had previously been used in the Kalgoorlie earthquake (see above). Using the Universities database of URM buildings, we "drove around" the city (following the map in ArcGIS), examining photographs, matching them to URM buildings and then surveying the damage in terms of the damage states defined for this study to visible walls and parapets (1-3% fallen, 3-10%, 10-30%, 30-70% and >70% of the object volume fallen to the ground as debris. In a number of cases the percentage fallen could not be established (for example where walls were covered in tarpaulins, or where there had obviously already been work done to demolish damaged walls), but in most cases this provide straightforward, though time-consuming.

In this way we were able to survey 594 masonry buildings, of which 561 also appeared in the Universities' URM dataset (the other 33 are a mixture of occasional URM buildings missed by the Universities survey and possibly some which are reinforced masonry). This enabled us to observe the damage state of 618 visible facades, of which 494 had parapets present.

The results in terms of proportions of walls and parapets damaged to different extents (in terms of the % of volume that had fallen as debris) are shown in Figures A2.29 and A2.30 respectively.

Figure A2.29 Wall Damage in the Darfield Earthquake, 4/9/2010

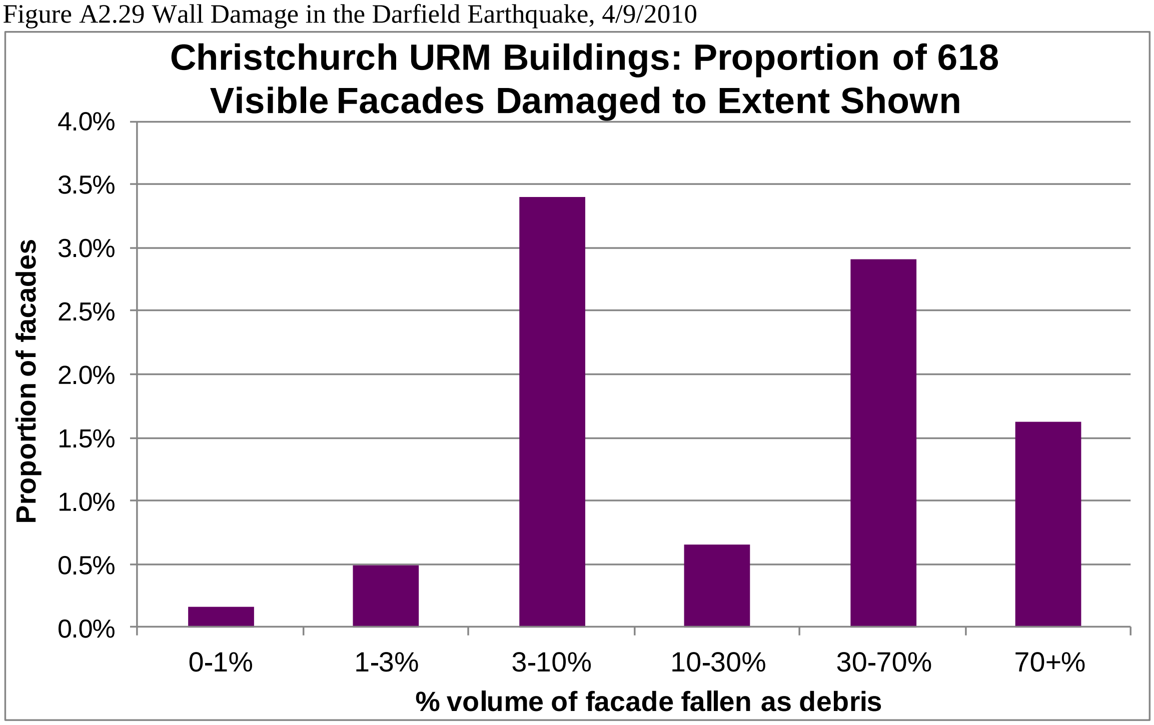
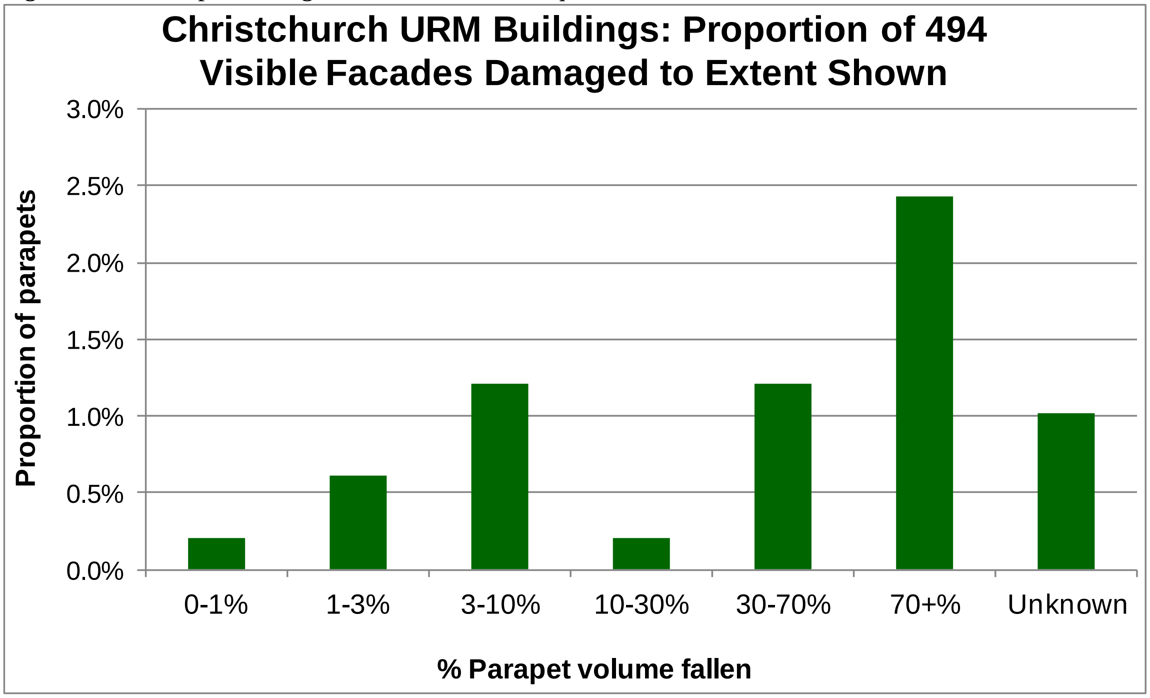


Figure A2.30 Parapet Damage in the Darfield Earthquake, 4/9/2010



We concluded that it was relatively straightforward to use the damage state definitions adopted in this study and to match photographs of damaged buildings to damage states. About 9% of walls and 7% of parapets had failed in the context used in this study (with debris falling to the ground as a result). For both parapets and gables, the damage states were concentrated in the middle and upper end of the range, with relatively few cases of minor damage.

We note that this is a rather unusual study of earthquake damage, in that the Geoscience Australia vehicle was unable to enter some parts of the central business district where damage was greatest. It thus missed a number of the worst damaged buildings (most damage studies tend to make sure they focus on the most damaged buildings first, and tend to be less complete for buildings with little r no damage; this study has done the converse). Wherever possible we attempted to “fill in” the areas missing from the GA photographs by searching for publicly available photographs on-line, but we were left with 75 of the buildings identified as URM in the Universities’ dataset that we were unable to survey in this study.

The statistics derived from this study are used in Appendix 3 to help inform our judgment as to appropriate probabilities of failure and distributions of damage states for the Groningen region. The GA dataset has not previously been the basis of analysis and publication; a study combining analysis of the GA photoset and other published photographs of damage to URM buildings in the Darfield earthquake is in progress and a paper is in preparation[47].

5.3.3 Canterbury earthquake swarm – analysis of chimney performance

The URM datasets discussed above did not include information on chimneys; the volumes of debris produced by them were, in comparison with the much larger volumes of walls and parapets falling, a relatively minor matter (for the 22/2/11 earthquake in addition a large proportion of chimneys in the CBD area had already failed on 4/9/2010).

Much useful information on chimney performance was provided in the book “All Fall Down” devoted to the loss of Christchurch chimneys in the earthquakes[29]. Figure A2.31(all photos reproduced from the book with the author’s permission) illustrates well the different failure mechanisms that applied to newer/better condition and to older/poorer condition chimneys.

Figure A2.31: Failure Mechanisms for Chimneys

By January 2011, more than 30,000 of the 175,000 claims for domestic damage lodged with New Zealand’s universal insurance provider the Earthquake Commission (EQC) were for chimney or fireplace damage. There were 161,000 households in Greater Christchurch recorded in the NZ 2006 census, which suggests that roughly 20% of all Christchurch homes sustained chimney damage in the September 2010 earthquake.

We carried out a detailed study[48] of damage to chimneys in the immediate vicinity of Canterbury strong motion measurement stations, combining information obtained from examination of Street View photographs before and after the earthquake swarm, examination of detailed aerial photographs of the Christchurch region taken on 24/2/2011, and claims data provided by the New Zealand Earthquake Commission.

This provided us with a database of about 1,350 chimneys within 300m of strong motion measurement stations prior to the 2010/11 earthquake swarm. It was straightforward determining which had been damaged in one or other earthquake by comparing before and after photographs. The two main difficulties were

a. Determining which earthquake had caused the damage to which chimney, and

b. Determining whether and to what extent chimneys had failed (in the context of this study – i.e. with some portion falling to the ground).

Neither could be established with precision in all cases. What we were able to assemble was a set of chimneys damaged where we could be highly confident that damage was associated with a particular earthquake (typically for some of the more distant locations from Christchurch such as Timaru and Ashburton, where the only significant shaking to occur happened in the Darfield earthquake of 4/9/2010).

Figure A2.32 shows the proportion of chimneys damaged for different shaking bands, based on the set of chimneys for which we could associate damage confidently with a single earthquake. Figure A2. 33provides a more “blunt” picture of the proportion of chimneys damaged as a function of the maximum PGA experienced in any of the 2010/11 earthquakes. The lilac bars on the figures show the 10-90% confidence intervals based on the sample size shown along the X axis in each figure.

As regards the proportion of damaged chimneys that failed (in terms of debris falling to the ground) and the mix of damage states, the information we could obtain with confidence was limited to a relative handful of chimneys where we could observe debris on roofs and the ground below in aerial photographs taken on 24/2/2011. Overall, we believe that a high proportion of the damaged chimneys did “fail” in our sense, because

a. a very high percentage of claims for chimneys recorded by the Earthquake Commission described the chimney damage state as “collapsed”, and

b. numerous reports from local people described getting up on 5 September 2010 and wondering why the streetscape looked odd, only to realise that it was because the chimneys had disappeared.

Figure A2.32 Chimneys Damaged vs PGA – Single Earthquake

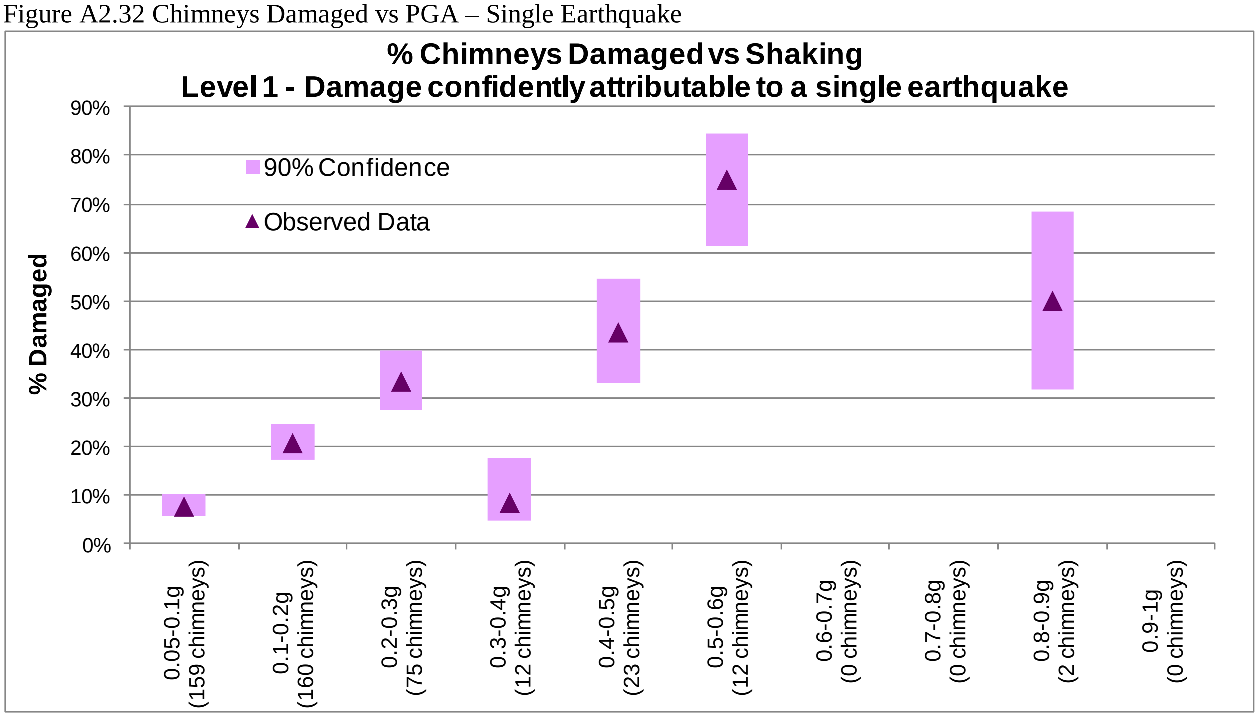
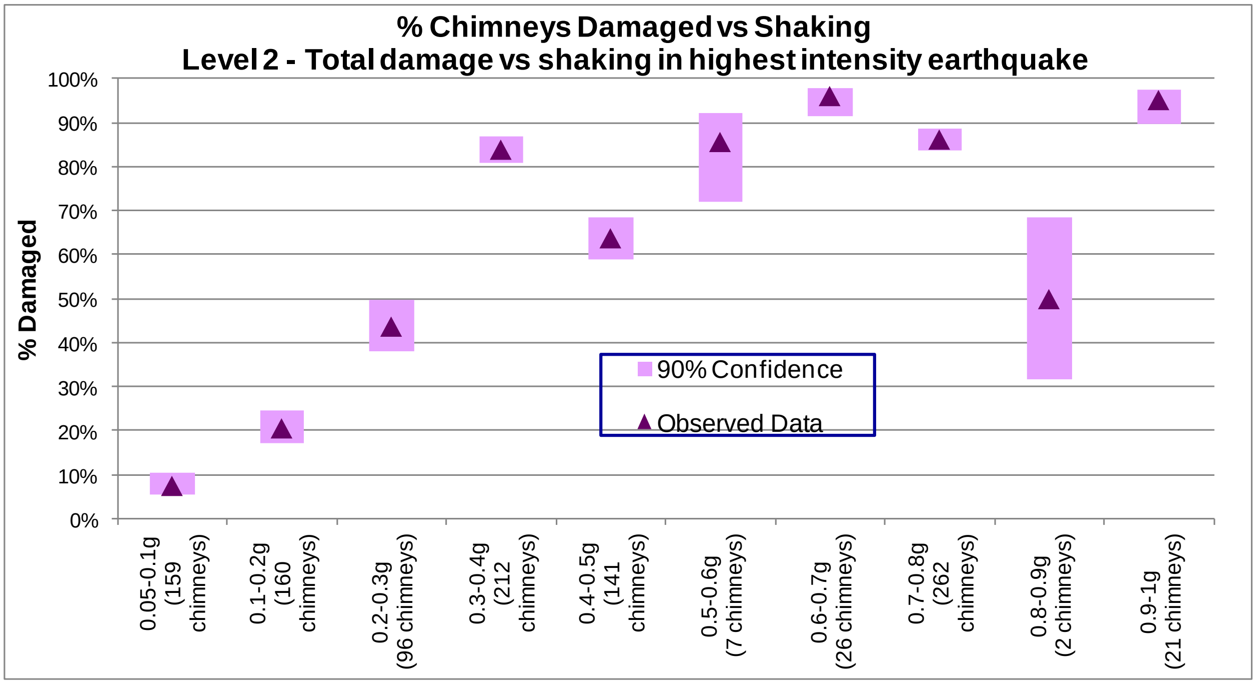


Figure A2.33 Chimneys Damaged vs Maximum PGA Experienced at Site



The data shown in Figure A2.32 is used in Appendix 3 to help inform our judgment as to the appropriate failure probabilities to be applied in the Groningen region. A key feature of both figures is that they appear to demonstrate, as did the Universities' URM dataset, a good correlation between PGA and proportions of objects damaged.

5.4 Gisborne 2007

The 6.6 MW earthquake that struck Gisborne at 20:35 on 20 December 2007 caused measured ground acceleration of 0.28g in the city centre – the third earthquake causing ground accelerations in excess of 0.25g in the area since 1966. Interpretation of damage generally from the earthquake is complicated by the mix of strengthening measures already in place on buildings, and by the large proportion of vulnerable buildings already "culled" in the previous earthquakes.

Of particular interest for this study, a detailed survey of parapet performance was carried out by Opus Consulting on behalf of the EQC[51]. The author and EQC kindly made the report available to us, and our re-analysis of its contents is described in a companion paper[52]. 22 of the 360 parapets in Gisborne had collapsed or partially collapsed in the earthquake; the survey examined 19 of the 22 collapsed parapets and 89 of the other 338.

Our conclusions based on the survey results are as follows.

1. Overall about 6% of the parapets in Gisborne collapsed or partially collapsed in the earthquake.
2. It is difficult to tell whether this overstates or understates the proportion of collapses to be anticipated from buildings typical of those in Gisborne. On the one hand many buildings had been strengthened and parapets “culled” following previous earthquake (which would tend to reduce the proportion failing in this event) while on the other there could have been substantial pre-existing damage in Gisborne parapets prior to this earthquake as a result of previous substantial quakes.
3. About one third of the parapets that failed toppled inward onto/through roofs rather than outward into the street. From photographs available of the earthquake and its aftermath this may be because a substantial proportion of the Gisborne parapets were plain and un-ornamented (parapets with substantial corbels or other decorative features on the outside would normally be expected to topple outwards).
4. Significant effects were anticipated of building height (i.e. height of parapet base above the ground) and of parapet slenderness (height to thickness ratio). Modest effects were observed, but were not substantial – they would have disappeared if a single failure case were reclassified.
5. The greatest observable effect on failure performance was of parapet restraint. Either short separation between parapet ends (less than 15m) or the presence of sturdy ribs (thickness > 300mm) appeared to reduce proportions of parapets failing by about a factor of 2.

5.5 Other New Zealand earthquakes

Much information on performance of non-structural building elements has been collected in other New Zealand earthquakes. Our information on these derives largely from the published reports of GNS Science. Dowrick[53] provided a retrospective review of the Hawke’s Bay earthquake of 1931 which caused massive damage to URM buildings and caused 261 deaths. He noted

> *“the damage to brick buildings varied from total destruction to virtually undamaged. Even in the zone of strongest shaking (Hastings/Napier), some brick buildings were essentially undamaged. Features of brick buildings .. considered to have caused much of the damage were:*
>
> i) *Permitting adjacent buildings of different heights to abut one another.*
> ii) *Insufficient area of footings, where the subsoil was silt.*
> iii) *Absence of ties across foundations [in silty ground?].*
> iv) *Interior timber partitions inadequately fixed to the exterior brick walls.*
> v) *Poor mortar and inefficient band-course reinforcement.*
> vi) *Support of heavy roofs on piers or walls too thin to withstand the racking effects produced.*
> vii) *Heavy brick shop fronts inadequately connected to the rest of the building.*

In relation to item (v) above, the good performance of some brick buildings was attributed not only to the use of strong mortar but also to the use of wire-mesh strips used on average at every 9th or 10th brick course."

Dowrick and Rhoades[54] reviewed the casualties that occurred in this and other NZ earthquakes and attributed a large majority of deaths to falling masonry debris, as shown in Table A2.6.

table A2.6: Deaths in the Hawkes Bay Earthquake, 1931 (from Dowrick & Rhoades[54])

Cause of death	Number of deaths
Falling URM buildings or parts thereof[(1)]	236-252
Collapse of weak-storey r.c. building[(2)]	8
Falling domestic brick chimneys	~6
Scalded by boiling beer	1
Falling domestic water tank[(3)]	1
Collapsing excavation[(4)]	1
Total	253-269

Notes: [(1)] Some people trapped by rubble were killed by fire;
[(2)] Napier Nurses Home;
[(3)] Wairoa;
[(4)] Near Mohaka.

Detailed information on building damage for the Hawke's Bay earthquake is not available though it is clear that chimneys, parapets, gables and other walls all suffered major damage.

References – Appendix 2

1. T. Camelbeeck et al, "The impact of the earthquake activity in Western Europe from the historical and architectural heritage records", in ***Intraplate Earthquakes***, ed. Pradeep Talwani, Cambridge University Press 2014.

2. See for example Die Welt, "Laufend neue Schadensmeldungen nach Erdbeben", 19 May 2014. *http://www.welt.de/regionales/frankfurt/article128199249/Laufend-neue-Schadensmeldungen-nach-Erdbeben.html*

3. See for example GDNW, "Erdbeben bei Alsdorf am 22. Juli 2002", Geologischer Dienst Nordrhein-Westfalen, 2002. *http://www.stadtklangnetz.de/assets/hilfen/08_ANLAGE_Alsdorf.pdf*

4. D. Jongmans & M. Campillo, "The 1983 Liege Earthquake: Damage Distribution and Site Effects," *Earthquake Spectra*, Vol. 6, No. 4, (1990)

5. D. Garcia Moreno & T. Camelbeeck, "Comparison of ground motions estimated from prediction equations and from observed damage during the M = 4.6 1983 Liège earthquake (Belgium)", Nat. Hazards Earth Syst. Sci., 13, pp 1983–1997, 2013.

6. T. Taig & F. Pickup, "Performance of Non-Structural Building Elements in Earthquakes: The Liège Earthquake, 1983", TTAC Ltd paper produced for Arup & NAM, 2015.

7. J.W. Pappin, A.R. Coburn, C.R. Pratt, "Observations of damage ratios to buildings in the epicentral region of the 1992 Roermond earthquake, the Netherlands," *Geologie en Mijnbouw* No. 73 (1994)

8. T. Taig, "Performance of Non-Structural Building Elements in Earthquakes: The Roermond Earthquake, 1992", TTAC Ltd paper produced for Arup & NAM, 2015.

9. P. Murphy Cordella, "Quick Field Report, Lorca Earthquake 11 May 2011", Broadway Malyan, Madrid, 2011.

10. L. Cabañas Rodríguez et al "Informe del Sismo de Lorca del 11 de Mayo de 2011", Instituto Geografico Nacional, Universidad Complutense de Madrid, Unversidad Politecnica de Madrid, Institute Geologico y Minero de España, Asociacion Española de Ingenieria Sismica, July 2011.

11. BGS, "Bishop's Castle, Shrops," British Geological Survey, accessed 17 November 2014, *http://earthquakes.bgs.ac.uk/earthquakes/UKsignificant/19900402134437.html#page=maps*

12. R. Kunar & J. Donald, "Earthquake Report," EERI Newsletter vol. 24 No. 7 (July, 1990), 6.

13. Private communication from R Spence, CAR (Photographs taken by Andrew Coburn, CAR)

14. BGS, "Melton Mowbray, Leics," British Geological Survey, accessed 30 October 2014, *http://earthquakes.bgs.ac.uk/earthquakes/UKsignificant/20011028162524.html#page=maps*

15. BBC News, *http://news.bbc.co.uk/1/hi/england/1625090.stm*, accessed 23 Feb 2015

16. Keyworth District Local History Society, "The Day We Trembled…," accessed 30 October 2014, *http://www.keyworth-history.org.uk/about/newsletter/melton-earthquake.htm*

17. BGS, "Dudley, W Midlands," British Geological Survey, accessed October 28, 2014, *http://earthquakes.bgs.ac.uk/earthquakes/UKsignificant/20020922235325.html#page=maps*

18. BBC News, "In Pictures: UK Earthquake", accessed October 29, 2014, *http://news.bbc.co.uk/1/hi/uk/2276188.stm* .

19. 2011 Census: Population and household estimates for England and Wales

20. Average % of English houses built pre-1919, English Housing Survey 2008, Annex Table 1.3, *https://www.gov.uk/government/statistics/english-housing-survey-2008-housing-stock-report*

21. The Telegraph, "The Day Dudley Rocked," accessed October 29, 2014, *http://www.telegraph.co.uk/news/uknews/3301405/The-day-Dudley-rocked.html*.

22. BBC News, "In Pictures: UK Earthquake." 2002 *http://news.bbc.co.uk/1/hi/uk/2276188.stm*

23. BGS, "Folkestone Earthquake," British Geological Survey, accessed October 28, 2014, *http://www.earthquakes.bgs.ac.uk/education/reports/folkestone/folkestone_28_april_2007.htm*.

24. Personal communication, Matthew Free, Arup, October 2014.

25. Personal communication, Nick Hubbard, Shepway District Council, 27/10/14
26. R. Musson, "The macroseismic survey of the 27 February 2008 Market Rasen earthquake," British Geological Survey Internal Report OR/08/029, 4
27. BGS, "Market Rasen Earthquake 27 February 2008, 00:56 UTC 5.2 ML," British Geological Survey, accessed 21 November 2014, *http://web.archive.org/web/20080406143541/http://www.earthquakes.bgs.ac.uk/earthquakes/reports/market_rasen_27022008/market_rasen_27022008_damage.htm*
28. The Daily Mail, "How residents at the centre of the quake woke up ... and then went back to sleep", accessed 7 November 2014, *http://www.dailymail.co.uk/news/article-521510/How-residents-centre-quake-woke---went-sleep.html*
29. T. Taig, "Performance of Non-Structural Building Elements in Earthquakes: The Nisqually Earthquake, 2001", TTAC Ltd paper produced for Arup & NAM, 2015.
30. "Some Pictures and Notes/Quotes from Coverage of the 1965 Puget Sound Earthquake," nisquallyquake.wordpress.com, accessed 31 October 2014, *https://nisquallyquake.wordpress.com/2014/07/01/some-pictures-and-notesquotes-from-coverage-of-the-1965-puget-sound-earthquake/*
31. D. R. Mullineaux et al, "Relation of Building Damage to Geology in Seattle, Washington, during the 1965 Earthquake", Geological Survey Research, USGS Professional Paper 575-D, 183-191, 1967
32. J. Dewey et al, "Intensity Distribution and Isoseismal Maps for the Nisqually, Washington, Earthquake of 28 February 2001", USGS Open-File Report 02-346, 2002.
33. A. Blakeborough et al, "The Northridge, California Earthquake of 17 January 1994", EEFIT, Institution of Structural Engineers, London, England 1994.
34. M. Durkin, "Casualty Patterns in the 1994 Northridge, California Earthquake", 11th World Conference on Earthquake Engineering (Paper no. 979) , 1996.
35. R. Hess, "The ShakeOut Scenario, Supplemental Study: Unreinforced Masonry (URM) Buildings", Report for USGS and California Geological Survey, U.S. Geological Survey Open File Report 2008-1150, 2007.
36. P. Somers et al, "Unreinforced Masonry Buildings", Earthquake Spectra: January 1996, Vol. 12, No. S1, pp. 195-217.
37. R. Klingner et al, "Reinforced Masonry Buildings", Earthquake Spectra: January 1996, Vol. 12, No. S1, pp. 177-193.
38. Geoscience Australia, "Newcastle Earthquake", updated June 2004.
39. R. Melchers (ed), "Newcastle Earthquake Study", Institution of Engineers, Australia, 1990.
40. J. Pappin et al, "The 1989 Newcastle Australian Earthquake: A Field Report by EEFIT", Institution of Structural Engineers, London, 1991.
41. M. Griffith, "Performance of Unreinforced Masonry Buildings during the Newcastle Earthquake", University of Adelaide Research Report no. R86, July 1991.

42. J. Rynn et al, “The 1989 Newcastle, Australia, Earthquake: The Facts and the Misconceptions”, Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 21, No. 2, June 1992.

43. F. Pickup & T. Taig, “Re-analysis of EEFIT Photographic Data from the 1989 Newcastle Earthquake”, TTAC Ltd paper produced for Arup & NAM, 2015.

44. M. Edwards et al, “The Kalgoorlie Earthquake of the 20th April 2010 :Preliminary Damage Survey Outcomes”, Australian Earthquake Engineering Society 2010 Conference, Perth, Western Australia.

45. T. Taig, “Performance of Non-Structural Building Elements in Earthquakes: The Kalgoorlie Earthquake, 2010”, TTAC Ltd paper produced for Arup & NAM, 2015.

46. T. Taig & F. Pickup, “Performance of Non-Structural Building Elements in Earthquakes: Re-analysis of the Universities of Auckland and Adelaide data on URM Performance in the 2010-11 Canterbury Earthquake Swarm”, TTAC Ltd report for Arup & NAM, 2015

47. T. Taig & F. Pickup, “Performance of Non-Structural Building Elements in the Darfield Earthquake – Re-analysis from Photographic Data”, TTAC Ltd report in preparation for Arup & NAM, 2015.

48. T. Taig & F. Pickup, “Performance of Non-Structural Building Elements in Earthquakes: Performance of Chimneys in the Canterbury NZ Earthquake Swarm of 2010/11”, TTAC Ltd report for Arup & NAM, 2015

49. L. Moon et al, “The Demise of the URM Building Stock in Christchurch duing the 2010-2011 Canterbury Earthquake Sequence”, Earthquake Spectra, Volume 30, No 1, pp 2530276, February 2014.

50. G Rice, “All Fall Down – Christchurch’s Lost Chimneys”, Canterbury University Press, 2011.

51. E. Blaikie, “Predicted & Actual Performance of Masonry Parapets in the 2007 Gisborne Earthquake”, Report prepared for the New Zealand Earthquake Commission, Wellington, 2009.

52. T. Taig, “Performance of Non-Structural Building Elements in Earthquakes: Parapet Performance in the 2007 Gisborne Earthquake”, TTAC Ltd paper produced for Arup & NAM, 2015.

53. D. Dowrick, “Damage and Intensities in the Magnitude 7.8 1931 Hawkes Bay, New Zealand, Earthquake”, Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 31 No. 3, September 1998.

54. D. Dowrick & D. Rhoades, “Risk of casualties in New Zealand earthquakes”, Bulletin of the New Zealand Society for Earthquake Engineering, 38(2) 53-72, 2005.

[end of Appendix 2]

Appendix 3: Fragility Assumptions for V1 Model

1. Introduction

The fragility assumptions used in the risk model are based on judgment, informed by (but not in any sense directly determined by) the performance of chimneys, parapets and gables discussed in Appendix 1. The assumptions are broadly consistent with observations from other earthquakes, but are not, and should not be viewed as though they were, scientifically objective and verified directly against empirical evidence.

This appendix works through each of these three object types in turn, presenting the assumptions used in the V1 model and explaining their basis. In each case the values of the parameters P1 and P2 (as defined in Equation [2] in Section 3.7 of the report) are presented in that order.

The lower and higher probabilities of failure in individual earthquakes studied are expressed as 10-90% statistical confidence intervals wherever numerical data is available on numbers of objects present and numbers failing.

The probabilities proposed for use in the model are also expressed as ranges for each PGA band, but these ranges do not have any particular statistical significance. They are not 10-90% confidence limits, nor absolute maxima and minima. Rather, we regard them as representing a range of plausible possible values for each shaking band, in that an argument could be made and supported with reference to observations in other earthquakes for any value within the range. There is no basis in our view for judgments that any part of the range is more or less likely than any other; the best way to understand the contribution of these assumptions to uncertainty in risk outcomes is to model risk using values from either end of the range.

2. Chimneys

2.1 Chimneys – Probability of Failure vs PGA

The empirical data we have assembled on failure performance of chimneys is collected in Table A3.1 and displayed alongside the values of failure probability we have adopted for V1 of the risk model in Figure A3.1 for PGA bands up to 0.5-0.6g.

The full V1 risk model assumptions are shown in Table A3.2 and Figure A3.2.

Table A3.1 Overview of Empirical Chimney Performance Data Sources

Source Description	**Numbers of objects and failures (involving some part of the object collapsing/falling) by PGA band**											
	0.05-0.1g		0.1-0.2g		0.2-0.3g		0.3-0.4g		0.4-0.5g		0.5-0.6g	
	N chimneys	N failures	N chimneys	N failures	N chimneys	N failures	N chimneys	N failures	N chimneys	N failures	N chimneys	N failures
FEMA US synthesis												
Dowrick NZ synthesis												
Roermond: Pre-1920 buildings	725	22	581	22	251	38						
Roermond - 1920-1960 buildings	485	3	429	3	416	12						
Roermond - post-1960 buildings	361	0	373	1	311	0						
Liège - St Nicholas					9829	2904						
Liège - Flémalle					5773	465						
Liège - Suburbs/villages	20981	1227	21833	2056	4946	1217						
UK EMS 5/6	2.4E+06	29-80	707	12								
Kalgoorlie: Pre-1920	81	1	38	6								
Kalgoorlie: Post-1920	13	0										
Canterbury 2010/11	159	12	160	33	96	42	212	178	141	90	7	6
Percentage Failures (10-90% Confidence)												
FEMA US synthesis	0.0%	0.5%	0.5%	7%	7%	20%	20%	36%	36%	50%	50%	62%
Dowrick NZ synthesis			0%	3%	2%	20%	12%	100%				
Roermond: Pre-1920 buildings	0.3%	1.5%	0.4%	1.9%	1.3%	6.6%						
Roermond - 1920-1960 buildings	0.1%	0.3%	0.1%	0.7%	0.2%	1.1%						
Roermond - post-1960 buildings	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%						
Liège - St Nicholas					11.0%	44.0%						
Liège - Flémalle					1.3%	13.0%						
Liège - Suburbs/villages	0.0%	20.0%	0.0%	20.0%								
UK EMS 5/6	0.01%	0.03%	1.2%	2.3%								
Kalgoorlie	0.1%	3.0%	10%	23%								
Canterbury 2010/11	6%	10%	19%	35%	27%	46%	34%	56%	19%	32%	61%	85%
Unweighted Averages	**0.7%**	**4.5%**	**3.4%**	**10.3%**	**6.2%**	**18.8%**	**22%**	**64%**	**28%**	**41%**	**56%**	**73%**
Range - Min low to max high	**0%**	**20%**	**0%**	**35%**	**0%**	**46%**	**12%**	**100%**	**19%**	**50%**	**50%**	**85%**

Figure A3.1 Overview of Empirical Data and V1 Chimney Failure Probability Assumptions

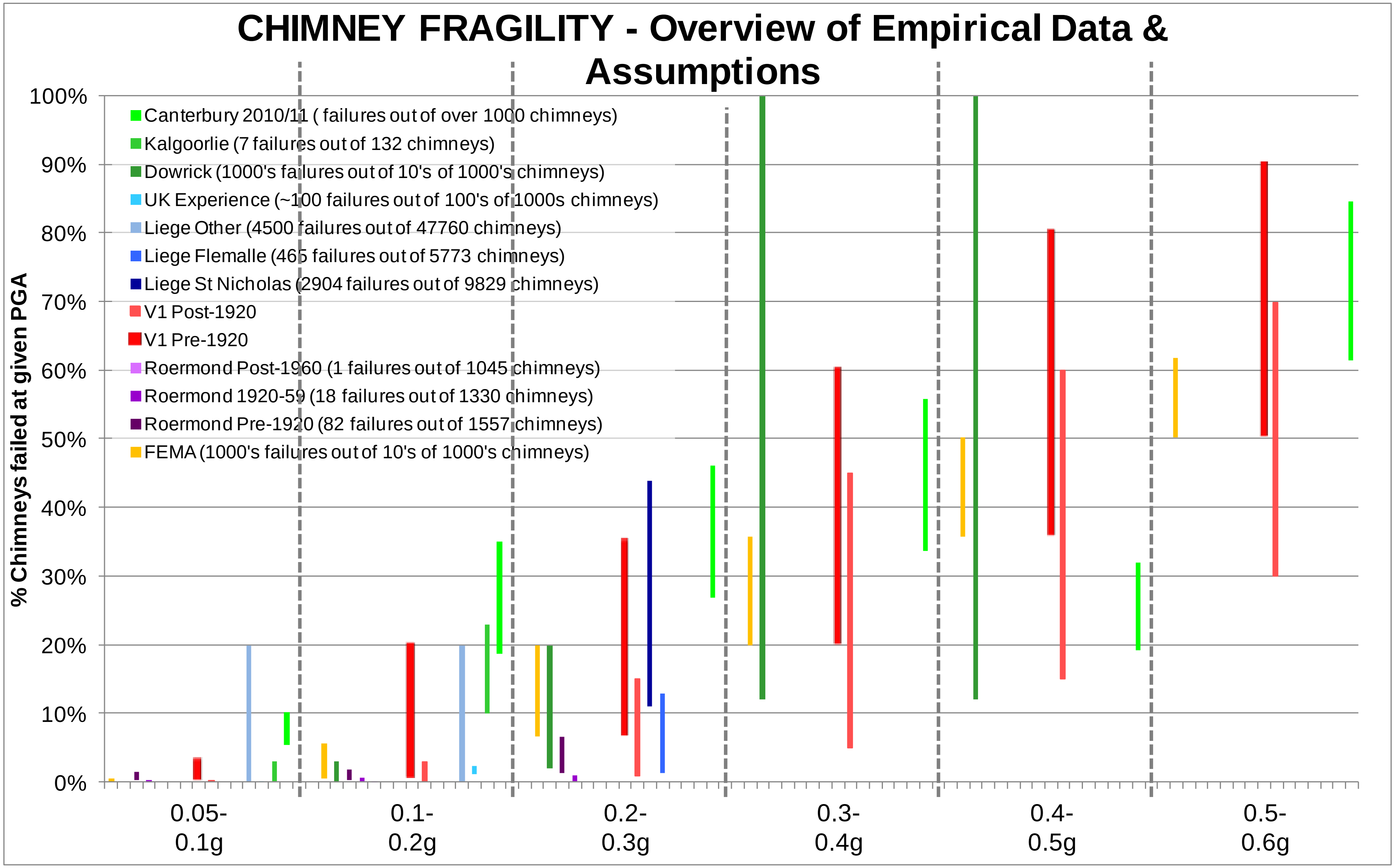
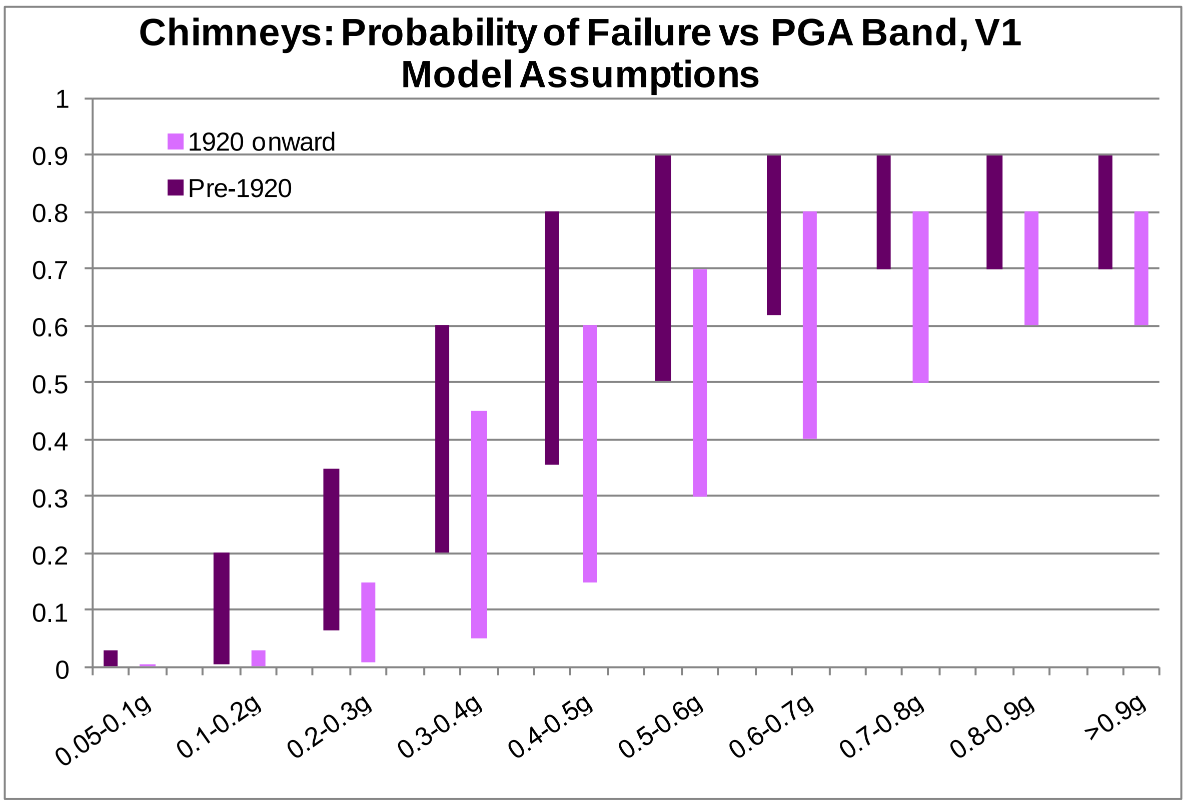


Table A3.2 Chimneys – V1 Assumed Probabilities of Failure for Each PGA Band

PGA band	Pre-1920		1920 onward	
	lower	higher	lower	higher
0.05-0.1g	0.001	0.03	0.0001	0.003
0.1-0.2g	0.005	0.2	0.001	0.03
0.2-0.3g	0.066	0.35	0.01	0.15
0.3-0.4g	0.2	0.6	0.05	0.45
0.4-0.5g	0.357	0.8	0.15	0.6
0.5-0.6g	0.502	0.9	0.3	0.7
0.6-0.7g	0.619	0.9	0.4	0.8
0.7-0.8g	0.7	0.9	0.5	0.8
0.8-0.9g	0.7	0.9	0.6	0.8
>0.9g	0.7	0.9	0.6	0.8

Figure A3.2 Chimneys – V1 Assumed Probabilities of Failure for Each PGA Band



Notes on the basis for the values in Table A3.2 and Figure A3.2:

1. At the lower end of the shaking range, there is large uncertainty as to the failure probabilities to be anticipated in the Groningen region. On the one hand, the evidence from local earthquakes at Huizinge and Roswinkel, and from UK earthquakes of EMS

intensity 5 and 6, suggests that even for pre-1920 chimneys failure in the bottom PGA band would be limited to isolated cases among tens of thousands of chimneys (i.e. to of order 10^{-4} or 0.01%).

2. On the other hand, experience in the (very short duration) earthquakes at Liège and Kalgoorlie (Appendix 1) suggests that up to several percent of older chimneys (if in poor condition and subjected to shaking enhanced by soft soils and/or local topography) might fail even in the lowest PGA band, and that this might extend up to 20% or more for the second PGA band (which approximately corresponds to EMS 6 shaking).

3. None of the European earthquakes discussed in Appendix 1 provide any evidence for modern (post-1920) chimneys failing under shaking in the lower two risk bands (roughly EMS 5 and 6). On the other hand the study of Canterbury chimneys suggests that even at the lowest shaking levels there is no particular distinction between chimneys of different ages for longer duration tectonic earthquakes.

4. Higher values for probabilities of chimney failure are judged to lie somewhere between

    a) the FEMA values for the higher ends of our PGA bands (which are for mixed age chimneys and are considered too low in light of the large proportion of older, relatively more fragile chimneys in the region), and

    b) the Canterbury proportions failing, which are considered too high for the Groningen region as they are associated with long duration shaking and are not consistent with the evidence from the UK, Liege and Roermond for lower shaking levels.

5. Liege is geographically the closest of the earthquake site with substantial data on chimney failure, but the worst case there (St Nicholas) is too high for general comparison with Groningen region given the extensive previous damage and subsidence present.

6. Kalgoorlie, Liege & Canterbury all suggest the possibility of substantial single %-ages failing in our lowest (0.05-0.1g) PGA band, while the UK, Roermond & FEMA data all suggest that failure probabilities in that band could be significantly smaller. A wide range of values has thus been adopted, from 0.1% to 3%, for this lowest shaking band.

7. For our second PGA band (0.1-0.2g) the data from Kalgoorlie, Liege & Canterbury all suggest 20-30%+ failure rates may be plausible. We consider the upper end of this range to be implausibly high for application in the Groningen region and have adopted 20% as an upper plausible failure probability for this PGA band.

8. For our second and subsequent PGA bands we consider that the FEMA values for mixed age chimneys based on the lower end of each PGA band provide a reasonable lower estimate of failure probability for older Groningen chimneys. We adopt these as our lower estimates for such chimneys for PGA up to the PGA where the probability of failure reaches 70%, which we consider a reasonable upper "plateau" level (see point 7 below).

9. For our third (0.2-0.3g) PGA band, we consider it feasible as a higher estimate for the Groningen region that as many as a few 10's of % of chimneys might fail, but regard the Liege St Nicholas and Canterbury proportions failing as too high for general application

in the region. We have adopted 35% as a compromise higher feasible estimate for older chimneys in the Groningen region.

10. There remains a small percentage of chimneys which survive even the strongest shaking (as observed in New Zealand and other earthquakes, Appendix 1). This percentage is greater for newer than for older chimneys. For the highest PGA bands in the V1 model, our higher estimates of chimney failure probability are assumed to rise from 60% for our 0.3-0.4g PGA band, rising to 90% for PGA above 0.5g and "plateauing" thereafter.

11. For newer (post-1920) buildings we anticipate at least an order of magnitude lower failure rates for our lowest shaking band (0.05-0.1g) based on the absence of any post-1920 chimneys from the failures observed in North European earthquakes in the UK, Belgium, the Netherlands and Germany. We have assumed a failure probability 10x less than that for older chimneys.

12. For such newer chimneys we assume that, as PGA rises, failure probabilities converge towards, but do not reach, those for older buildings/chimneys (more modern mortar is much better bonded, and since about 1920 chimneys have virtually universally been lined with steel or other liners which prevent bricks and mortar being corroded by smoke – a major factor identified in the Liege earthquake).

13. The Roswinkel earthquake, where over 100 chimneys survived measured PGA of about 0.3g (in fact most of the chimneys were nearer to the epicentre than the location of strong motion measurement), has been treated as an outlier in all of the above. It does suggest, thought, the possibility that even the lower ends of the ranges adopted in the V1 model might be conservative (tend to overstate risk) at shaking up to 0.3g.

2.2 Chimneys – Damage State Distribution vs PGA

The limited direct evidence we have been able to glean from photographs of damaged chimneys is summarised in Table A3.3.

Table A3.3 Raw Data on Chimney Damage States

Event	**Shaking Bands**	**1-3%**	**3-10%**	**10-30%**	**30-70%**	**70+%**	TOTAL
Folkestone	0.1-0.2g	2	7	4	1	0	14
Bishop's Castle	0.1-0.2g	0	2	2	0	0	4
Kalgoorlie V	0.05-0.1g	0	1	0	0	0	1
Kalgoorlie VI	0.1-0.2g	0	3	3	0	0	6
Other UK V	0.05-0.1g	1	4	0	0	0	5
Liege	0.2-0.3g	2	1	4	3	3	13
Darfield 2010	~0.3g	0	1	3	4	13	21

Folkestone and Kalgoorlie, in Table A3.3, are the only earthquakes for which we know precisely the size of the sample of buildings surveyed and can be confident the sample is complete and representative. The others are likely to overstate the proportion of chimneys damaged to higher states, as the sample photos available had been chosen to illustrate instances of damage rather than as part of a random sample.

The Darfield 2010 data in particular was obtained from media sample photographs and is not considered at all a reliable guide. On the other hand eyewitness reports of "noticing the streetscape had changed and realising it was because the chimneys had gone" and the classification of a large majority of chimney damage claims by the NZ Earthquake Commission as "Collapsed" does suggest that the percentage of chimneys failing towards the higher damage states was large in the Darfield earthquake of 2010.

It is clear from reports of the other earthquakes discussed in Appendix 1 that despite the paucity of "hard" photographic data there are significant qualitative and quantitative differences between the performance of older and newer chimneys, and between the damage state mix at lower and higher levels of shaking. For older chimneys at lower levels of shaking, the primary failure mechanism is dislodgement of loose bricks, chimney pots and other components. For newer chimneys the primary failure mechanism appears to be snapping around or above the roof line. (See main report). For both older and newer chimneys there is a strong increase of the proportion of the chimney dislodged and falling as shaking increases.

Table A3.4 shows our quantitative interpretation of these qualitative factors in terms of the the lower and higher range assumptions adopted in the V1 model for the proportion of chimney failures resulting in different damage states (proportions of the chimney volume falling to the ground). Table A3.4(a) is for pre-1920 and Table A3.4(b) for chimneys from 1920 onward.

Table A3.4(a) Pre-1920 Chimneys – Object Volume Falling for Each PGA Band

PGA band	LOWER % element falling, given failure (P2)					HIGHER % element falling, given failure (P2)				
	DS 1-3%	DS 3-10%	DS 10-30%	DS 30-70%	DS>70%	DS 1-3%	DS 3-10%	DS 10-30%	DS 30-70%	DS>70%
0.05-0.1g	80%	20%	0%	0%	0%	20%	60%	20%	0%	0%
0.1-0.2g	40%	40%	20%	0%	0%	10%	40%	20%	20%	10%
0.2-0.3g	20%	20%	20%	20%	20%	5%	5%	30%	30%	30%
0.3-0.4g	10%	10%	20%	30%	30%	0%	0%	30%	40%	30%
0.4-0.5g	10%	10%	20%	30%	30%	0%	0%	0%	50%	50%
0.5-0.6g	10%	10%	20%	30%	30%	0%	0%	0%	50%	50%
0.6-0.7g	10%	10%	20%	30%	30%	0%	0%	0%	50%	50%
0.7-0.8g	10%	10%	20%	30%	30%	0%	0%	0%	50%	50%
0.8-0.9g	10%	10%	20%	30%	30%	0%	0%	0%	50%	50%
>0.9g	10%	10%	20%	30%	30%	0%	0%	0%	50%	50%

Table A3.4(b) 1920 Onward Chimneys – Object Volume Falling for Each PGA Band

PGA band	LOWER % element falling, given failure					HIGHER % element falling, given failure				
	DS 1-3%	DS 3-10%	DS 10-30%	DS 30-70%	DS>70%	DS 1-3%	DS 3-10%	DS 10-30%	DS 30-70%	DS>70%
0.05-0.1g	40%	30%	30%	0%	0%	10%	30%	20%	20%	20%
0.1-0.2g	20%	30%	30%	10%	10%	0%	10%	10%	40%	40%
0.2-0.3g	10%	10%	20%	30%	30%	0%	0%	0%	50%	50%
0.3-0.4g	5%	5%	10%	40%	40%	0%	0%	0%	50%	50%
0.4-0.5g	5%	5%	10%	40%	40%	0%	0%	0%	50%	50%
0.5-0.6g	5%	5%	10%	40%	40%	0%	0%	0%	50%	50%
0.6-0.7g	5%	5%	10%	40%	40%	0%	0%	0%	50%	50%
0.7-0.8g	5%	5%	10%	40%	40%	0%	0%	0%	50%	50%
0.8-0.9g	5%	5%	10%	40%	40%	0%	0%	0%	50%	50%
>0.9g	5%	5%	10%	40%	40%	0%	0%	0%	50%	50%

Notes on the basis for the values in Table A3.4:

1. In the lower scenario we start at the lowest levels of shaking with a large majority of failures assumed to be to the first (1-3%) damage state. The shift to higher damage states suggested by the data we have is quite rapid as shaking increases. We have assumed for the lower scenario that by the time shaking exceeds 0.3g the mix of damage states has shifted to being dominated by the highest 2 states, but with a modest percentage still involving lower damage states at even the highest levels of shaking.

2. In the higher scenario we start at the lowest levels of shaking with a more aggressive mix of the lower damage states, and assume that this shifts rapidly until beyond 0.3g the mix is simply 50:50 between the highest two damage states.

Table A3.5 provides the remaining parameter assumptions which complete the basis for risk assessment of chimneys in the V1 model.

Table A3.5 Other Chimney Parameters vs Damage State

	DS 1-3%	DS 3-10%	DS 10-30%	DS 30-70%	DS>70%
α, proportion of volume falling	2.0%	6.5%	20.0%	50.0%	85.0%
P (death if in path, thru roof, 'normal' chimney)	0	0.1	0.5	0.7	1
P (any 'normal' chimney falls through the roof of the building on which it sits)					0.03
P (death if in path, thru roof, 'elevated risk of fall from height onto roof' chimney)					1

The first parameter, α, is the assumed proportion of the object volume that falls to the ground for each damage state (simply the arithmetic average of the % at either end of the range defining the damage state).

The second and third parameters characterise the performance of “normal” chimneys in terms of falling through the roof on which they sit. “Normal” means that the chimney would fall no more than 2m onto the roof below it. The Falling Hazards Survey identifies chimneys and other objects that could fall more than 2m onto a roof below as “elevated risk of falling through a roof”. Such chimneys are assumed to have a probability of 1 (applies to all damage states) of falling through the roof and through any intervening floors until they reach ground level, with a probability of 1 of killing anyone whose head is in their path as they fall.

This is a good assumption for large heavy objects falling onto timber framed roofs (as revealed, for example, by the impacts of boulders onto houses in the Port Hills area of Christchurch in the 22/2/11 earthquake), but clearly becomes more pessimistic for lower damage states. Given the primary purpose of this risk assessment (to prioritise buildings for inspection) and the importance of such situations for risk (see risk assessment results in the companion reports), we have chosen in this particular area to err on the side of caution – there are relatively few situations where chimneys or other objects (generally gables) could fall from height onto roofs and the proportion of such situations involving significant risk, though low, is much higher than that for objects situated above doorways or public space.

All "normal" chimneys are assumed to have a small (currently 3%) chance of falling through the roof on which they sit, based on observations from around 100 chimneys for which we had video and photographic evidence available for Liege and the UK. Two chimneys out of a sample of just over 50 on an aerial video from Liege had clearly fallen straight through the roof beneath (one elderly lady was killed in her bed by such a chimney falling through the roof though we do not know if it was one of the chimneys in the video clip we have available). One chimney in Yorkshire partially collapsed and fell through a roof during the Market Rasen earthquake in England, crushing the pelvis of a person in bed in the attic room beneath; had it struck their head instead they would almost certainly have been killed.

The probability of 3% of penetrating the roof is assumed for all chimney damage states; it clearly is less pessimistic for higher and more pessimistic for lower damage states, but the Market Rasen chimney was only DS2 (around 10% of the volume of chimney material), so there is clearly potential for even modest portions of chimneys to fall through weaker roofs.

We consider it too pessimistic, though, to assume (as for objects elevated at height above roofs) that any part of a chimney toppling onto its own roof would fall directly through all intervening floors/ceilings to the ground below, killing anyone whose head was in its path as it fell through the roof. The second row of Table A3.4 provides the assumptions we have made as to the probability of death of a person whose head is in the path of a part of a "normal" chimney as it penetrates the roof of the building on which it sits. For the highest damage state, we assume (as for "elevated above roofs" objects) that anyone situated beneath the chimney debris has a 100% chance of being killed by it. This then tapers down to 10% for DS2 and zero for DS1, for which we consider the combination of protection from the building structure and small object size would make fatality unlikely.

3. Parapets

3.1 Parapets – Probability of Failure vs PGA

The empirical data we have assembled on failure performance of parapets is collected in Table A3.6 and displayed alongside the values of failure probability we have adopted for V1 of the risk model in Figure A3.3 for PGA bands up to 0.5-0.6g.

The full V1 risk model assumptions are shown in Table A3.7 and Figure A3.4.

Table A3.6 Overview of Empirical Parapet Performance Data Sources

Source Description	Numbers of objects and failures (involving some part of the object collapsing/falling) by PGA band											
	0.05-0.1g		0.1-0.2g		0.2-0.3g		0.3-0.4g		0.4-0.5g		0.5-0.6g	
	N parapets	N failures	N parapets	N failures	N parapets	N failures	N parapets	N failures	N parapets	N failures	N parapets	N failures
FEMA US synthesis	Review of data on 566 parapets surveyed in Loma Prieta & Northridge earthquakes, PLUS review of analytical studies											
Kalgoorlie Pre-1920	162	1	98	18								
Gisborne					101	19						
Newcastle							156	18				
Darfield Sep 2010					106	18	380	17				
Christchurch Feb 2011	18	1			15	7			80	48		
Liege 1983	No specific parapet damage studies; estimate of 5-10% parapets toppled in worst affected parts of city centre											
Lorca 2010	No specific parapet damage studies; clear from photos that several 10's % at least of parapets collapsed in streets inundated with rubble (9 deaths)											
Percentage Failures (10-90% Confidence)												
FEMA US synthesis	0.0%	1.4%	1.4%	13%	13%	29%	29%	50%	50%	66%	66%	75%
Kalgoorlie Pre-1920	0.3%	1.4%	14%	23%								
Gisborne					14%	23%						
Newcastle							9%	15%				
Darfield Sep 2010					5.6%	8.4%	5.6%	8.4%				
Christchurch Feb 2011	3%	12%			34%	60%			53%	66%		
Liège estimate			5%	10%								
Lorca estimate							20%	50%				

Figure A3.3 Overview of Empirical Failure Data & V1 Parapet Failure Probability Assumptions

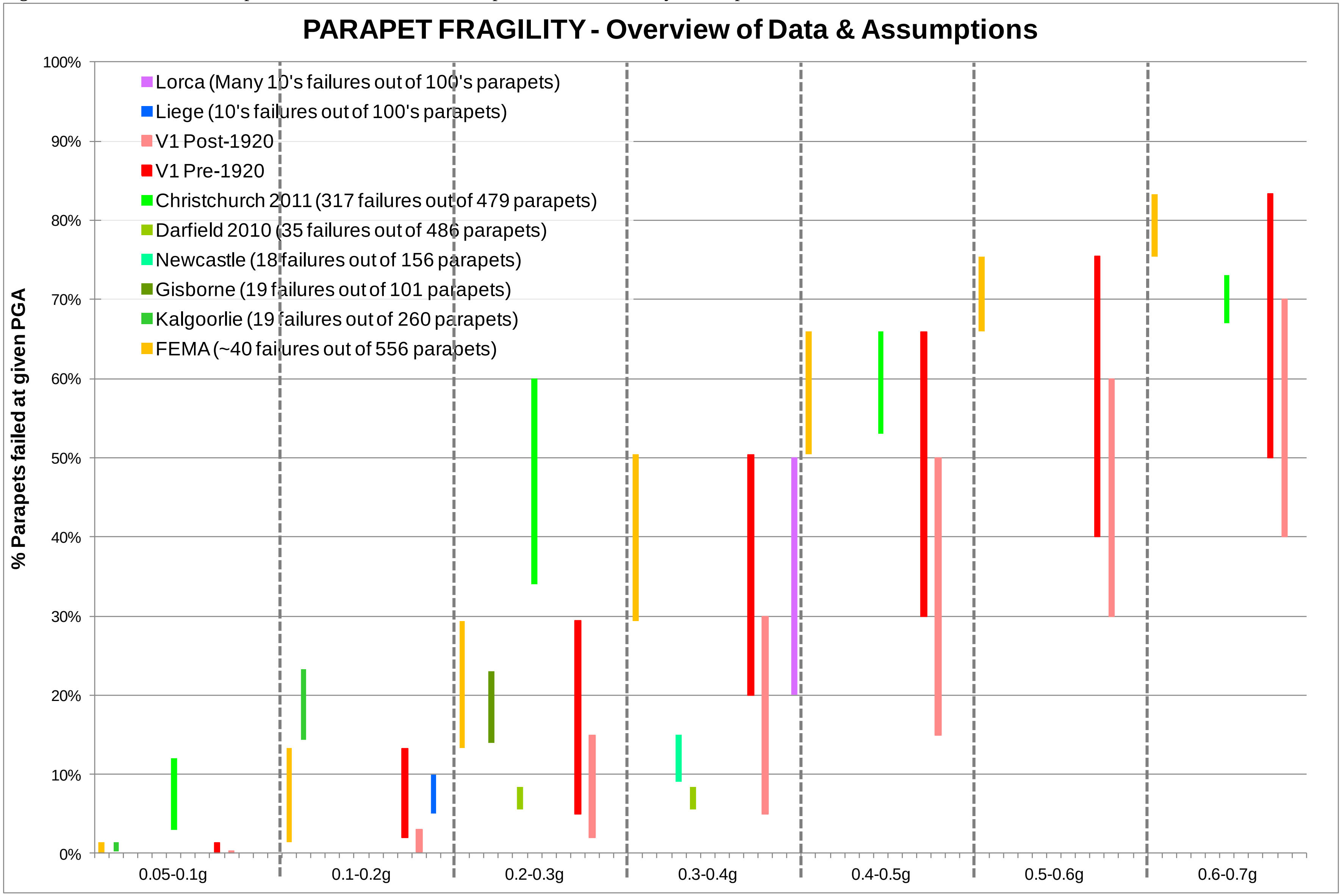
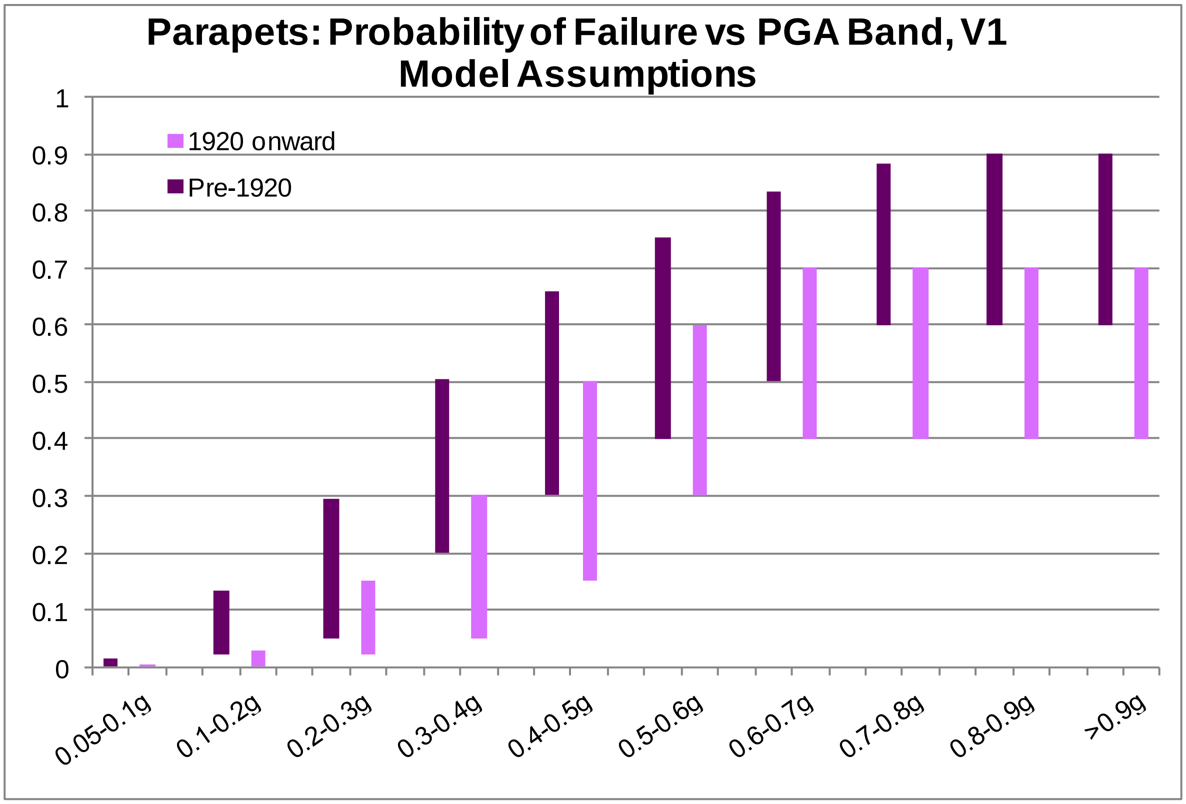


Table A3.7 Parapets – V1 Assumed Probabilities of Failure for Each PGA Band

PGA band	Pre-1920		1920 onward	
	lower	higher	lower	higher
0.05-0.1g	0.001	0.014	0.0001	0.0030
0.1-0.2g	0.02	0.133	0.0020	0.0300
0.2-0.3g	0.05	0.294	0.0200	0.1500
0.3-0.4g	0.2	0.504	0.0500	0.3000
0.4-0.5g	0.3	0.659	0.1500	0.5000
0.5-0.6g	0.4	0.754	0.3000	0.6000
0.6-0.7g	0.5	0.833	0.4000	0.7000
0.7-0.8g	0.6	0.884	0.4000	0.7000
0.8-0.9g	0.6	0.9	0.4000	0.7000
>0.9g	0.6	0.9	0.4000	0.7000

Figure A3.4 : Parapets – V1 Assumed Probabilities of Failure for Each PGA Band



Notes on Table A3.7 and Figure A3.4:

1. Empirical data is very limited behind the US FEMA estimates; Lorca, Kalgoorlie & Gisborne appear broadly consistent with FEMA's proposed fragilities, while Newcastle and Darfield appear somewhat lower (though given the unavailability of local strong ground motion measurements for any of these except Darfield, such comparisons are difficult).

2. Darfield provides what we regard as our most reliable source of comparative information on chimney and parapet performance; parapets performed considerably better (over half of chimneys but only about 6% of parapets failed).

3. Given the high fragility of many Dutch parapets (e.g. those on many older Dutch gables) we regard the FEMA values for the upper end of our PGA bands as providing a plausible higher estimate for use for older (pre-1920) parapets in the Groningen region, truncated at 90% failure.

4. Based on European experience a lower failure rate for older parapets of 0.1% is considered appropriate for the lowest PGA band. A lower rate of 5% is considered reasonable for the 0.2-0.3g PGA band.

5. Lower failure probabilities are then filled in to provide a smooth progression between 0.1% (lowest PGA band), 5% (0.2-03g) and 60% failure (assumed asymptote above 0.7g PGA).

6. Very limited data is available for newer parapets. Lorca suggests several 10's % failures for mixed age parapets including quite a lot of more modern brick parapets on concrete buildings, but is considered too high to be representative for the Groningen region as it was a relatively long duration and extremely shallow tectonic earthquake.

7. For Groningen, we consider 50% failure a reasonable upper estimate for 0.4-0.5g (one PGA band higher than that experienced at Lorca)

8. The higher asymptote for newer parapets, as for chimneys, is considered to be somewhat lower than that for older parapets given the generally more robust construction (older Dutch parapets often have minimal restraint/ ribs/ side support whereas newer parapets designed to wind specifications tend to have more of all the above, as well as better bonded mortar).

9. For the lowest PGA band, failure probabilities an order of magnitude lower than for older parapets are considered appropriate. Failure probabilities are then assumed to rise so as smoothly to erode the differential between older and newer parapets (but, as for chimneys, never quite to reach the failure probabilities for older parapets).

3.2 Parapets – Distribution of Damage States vs PGA

Table A3.8 collects the limited data we have been able to gather on the mix of parapet damage states that resulted from the earthquakes shown. In interpreting the Christchurch 2011 data the damage states used by the Universities of Auckland and Adelaide have been mapped onto our damage state definitions as follows

Universities' Damage State	**Interpreted here as**
Partial collapse	50% DS1 (1-3%), 50% DS2 (3-10%)
Collapse	50% DS3 (10-30%), 50% DS4 (30-70%)
Full Collapse	100% DS5 (>70%)

Table A3.8 : Raw Parapet Damage State Empirical Data

Earthquake	**PGA Band (approx)**	**N parapets**	**N failures**	**1-3%**	**3-10%**	**10-30%**	**30-70%**	**70+%**
Kalgoorlie	0.05-0.1	162	1		100%			
Kalgoorlie	0.1-0.2	98	18		13%	50%	25%	13%
Darfield	0.2-0.3	486	38	5%	26%	11%	37%	21%
Christchurch (Auckland University Data)	0.05-0.1	18	1	50%	50%	0%	0%	0%
	0.2-0.3	15	7	14%	14%	36%	36%	0%
	0.4-0.5	80	48	23%	23%	25%	25%	4%
	0.6-0.7	*303*	*212*	*19%*	*19%*	*13%*	*13%*	*37%*
	0.7-0.8	*32*	*23*	*15%*	*15%*	*26%*	*26%*	*17%*
	>0.9	*31*	*26*	*23%*	*23%*	*17%*	*17%*	*19%*
	All >0,6	366	366	17%	17%	14%	14%	38%

Our observations on the variation of the damage state mix with building age and PGA are virtually identical to those made above on chimneys. With the limited available data we have chosen to adopt the same values for P2 (the probability of a given damage state arising from failure at a given PGA) for parapets that we have used for chimneys.

4. Gables

The number of earthquakes from which we have direct quantitative data is limited, and we have no convenient FEMA or other review to provide us with the combined fruits of empirical and analytical studies. In this area our Falling Hazards work potentially overlaps with the NAM Hazard and Risk modelling efforts which tackles wall failure issues with far greater sophistication than we wish to attempt here.

Table A3.9 provides a summary of the empirical data and our observations on it from those earthquakes which provided information about gable failure. We have combined in a single table information on number/probability of failure, and distribution of damage states.

Significant numbers of partial gable failures occurred in the Roermond earthquake, limited typically to the fall of a few bricks to a few tens of bricks from the apex of gables in older (pre-1920) buildings. Substantially more gable and wall failures occurred in the Liege earthquake, but as at Roermond were around an order of magnitude less frequent than chimney failures. While a small proportion involved very serious wall damage (described in macroseismic studies as “DS5” in a few cases and DS4 or 5 in over 100, though all the newspaper accounts of the time feature the same two houses which have had a wall fail outwards out of plane, leaving the space inside intact), a large majority, as was the case at Roermond, involved small failures at the gable apex.

Our re-analysis of photographic datasets from the Newcastle and Darfield earthquakes, and our re-analysis of the Christchurch 22/2/11 damage dataset developed by the Universities of Auckland and Adelaide, showed a similar picture of gable fragility (probabilities of failure) being significant lower than chimney fragility, but with the gap narrowing as shaking increases.

The data on damage state distribution showed qualitative similarities with that on chimneys and parapets. The major distinction was between the low intensity earthquakes at Roermond and Liege, and the higher magnitude, higher intensity earthquakes in the Antipodes. The former involved very largely DS1 and DS2 (1-3% and 3-10% of volume falling), while the latter involved a mix across all five damage states. Newcastle was something of an “outlier” with a particularly high proportion of DS5 (>70% of volume falling), but this may be an artefact of the area selected by the EEFIT team to survey and then to archive as being the most interesting in terms of building damage.

Our translation of the above relativities into quantitative estimates for use in the V1 falling hazard risk model are shown in Table A3.10 and Figure A3.5. Figure 3.5 is provided in both linear and logarithmic form to enable both ends of the PGA range to be clearly seen.

Table A3.9 : Overview of Gable Failure and Damage State Empirical Data

Earthquake	Intensity/PGA	Wall type	N failures	N total	P(fail)	Failures in given band of debris generated: 0-1%	1-3%	3-10%	10-30%	30-70%	70+%	Notes
Newcastle	VIII	Cavity Gables	9	27	0.333	0	0	0	1	1	7	Based on TTAC Ltd reanalysis of EEFIT photos
	(0-3-0.4g+)	Solid Gables	1	6	0.167	0					1	(supplied from CAR archives)
		Unknown	2	14	0.143	0	2					
		ALL GABLES	12	47	0.255	0	2	0	1	1	8	
		Failures, % by band				0%	17%	0%	8%	8%	67%	
		Smoothed % by band			**0.255**	**7.0%**	**7.0%**	**7.0%**	**7.0%**	**7.0%**	**65.0%**	Tapered down to allow for "surveyed the worst bit" effect
	Newcastle conclusion: Averaged over all building ages (v difficult to tell mix of ages - certainly included some older as well as more modern buildings; cavity walls largely more modern) estimate of order 25% gables fail at shaking in 0.3-0.4g band. Failures heavily weighted towards larger % of gable falling.											
Darfield 4/9/10	ALL	**Gable**	**25**	**188**	**0.133**	**0**	**3**	**15**	**0**	**4**	**3**	Analysed by cavity v solid & made no discernible difference
	(largely 0.2-0.3g)	Not gable	32	425	0.075	1	0	6	4	14	7	Basis of "gable" allocation to be discussed with FEP
	(ave PGA 0.29g)	Unknkown	0	5	0.000	0	0	0	0	0	0	
		TOTAL	57	618	0.092	1	3	21	4	18	10	
		All Walls, Failures, % by band				1.8%	5.3%	36.8%	7.0%	31.6%	17.5%	
		Gable Walls, Failures, % by band				0.0%	12.0%	60.0%	0.0%	16.0%	12.0%	
		GABLES - SMOOTHED					**10.0%**	**50.0%**	**15.0%**	**15.0%**	**10.0%**	
	0.2<=PGA<0.3g	All Walls	22	144	0.153							
	0.3<=PGA<0.4g	All Walls	33	461	0.072							
	Darfied conclusion: Virtually all these buildings are pre-1920 or "unknown" date (but no NZ URM after 1931 so pretty safe assuming they are all in the 'older' category). Conclusion for this category: about 10-15% gable failures at just below 0.3g (long duration shaking), with "failure" heavily dominated by modest proportion of gables fallen. [Note - OOP wall failures about half this prevalence]											
Christchurch 22/2/11	ALL	**Gable**	95	163	0.583		**14%**	**14%**	**23%**	**29%**	**20%**	
	(ave PGA 0.64g)											
	0.2-0.5g	Gable	14	27	0.519		17%	17%	29%	24%	13%	No significant difference - take whole set as representative of
	>0.6g	Gable	81	130	0.623		13%	13%	22%	30%	21%	the 0.6-0.7g shaking band for TT analysis
	Christchurch conclusion: High % of gables failed under prolonged, heavy shaking. Wide mix of extents of gable failure with slight dominance of high % falling (>10%) as opposed to low % falling to ground. Difficult interpreting these quantitative observations given extensive pre-existing damage after Darfield event, but given the high levels of shaking it is not unexpected that a majority of fragile building components would fail.											
Roermond	VI-ish	Gable	8	???			4	2	1	1		Re-analysis of EEFIT photos provided by A Coburn & J Pappin
	Treat as approx 0.1-0.3g band		4						2	1	1	Analysis of publicly available archive photos
			8.8	~10,000	~0.001		4.0	2.0	1.4	1.2	0.2	Combined, public weighted 0.2x as presumed weighted to higher DS
		Gable			**0.003**		**45%**	**23%**	**16%**	**14%**	**2%**	Probably somewhere in 0.2 to 0.5% for pre-1920 buildings
	Roermond Conclusion: Cases of gable failure were about an order of magnitude less prevalent than those of chimney failure. Where gable failure did occur it most commonly involved a modest % of the chimney volume falling to the floor as debris.											
Liege	VII	St Nich DS4+	109	9829	0.011							DS4 only recorded for St Nicholas
	(0.2-0.3g band)	St Nic DS2-3	2904	9829	0.295							Chimneys, but will also include a proportion of gables
		EEFIT Report phot	8				4	2	1		1	Given likelihood of recording the more spectacular, clearly suggests a
							50%	25%	13%	0%	13%	substantial proportion of gable failures involved small debris volumes fallinc
		Estimated overall gable failure proportion			0.050							St Nicholas worst case
		(worse for older; better for newer buildings)			0.005							Elsewhere (shaking slightly lower, buildings better)
	Liege conclusion: As for Roermond, cases of gable failure were about an order of magnitude less common than those of chimney failure, with around 5-20% of the oldest and worst buildings in St Nicholas exhibiting gable failure to some extent. Most failures involved modest volumes of debris falling but a few involved more. It would be VERY useful to be able to access the detailed building damage information held in the Fond de Calamité in Belgium to find out more about the DS4 cases, which are thought (from examination of the photo archives in the Royal Observatory of Belgium) largely to involve cases of out of plane gable and wall failure. There were certainly one or two cases of roofs collapsing as walls moved out of plane but none known of a whole building collapsing with significant loss of volume in the internal space.											

Table A3.10 : Gables – V1 Assumed Probabilities of Failure for Each PGA Band

PGA band	Pre-1920		1920 onward	
	lower	higher	lower	higher
0.05-0.1g	0.0001	0.001	0.00001	0.0001
0.1-0.2g	0.0005	0.005	0.0001	0.001
0.2-0.3g	0.002	0.1	0.001	0.03
0.3-0.4g	0.05	0.3	0.01	0.1
0.4-0.5g	0.1	0.5	0.05	0.3
0.5-0.6g	0.2	0.65	0.1	0.4
0.6-0.7g	0.3	0.8	0.2	0.5
0.7-0.8g	0.4	0.8	0.3	0.6
0.8-0.9g	0.4	0.8	0.3	0.7
>0.9g	0.4	0.8	0.3	0.7

Figure A3.5 : Gables – V1 Assumed Probabilities of Failure for Each PGA Band (linear version)

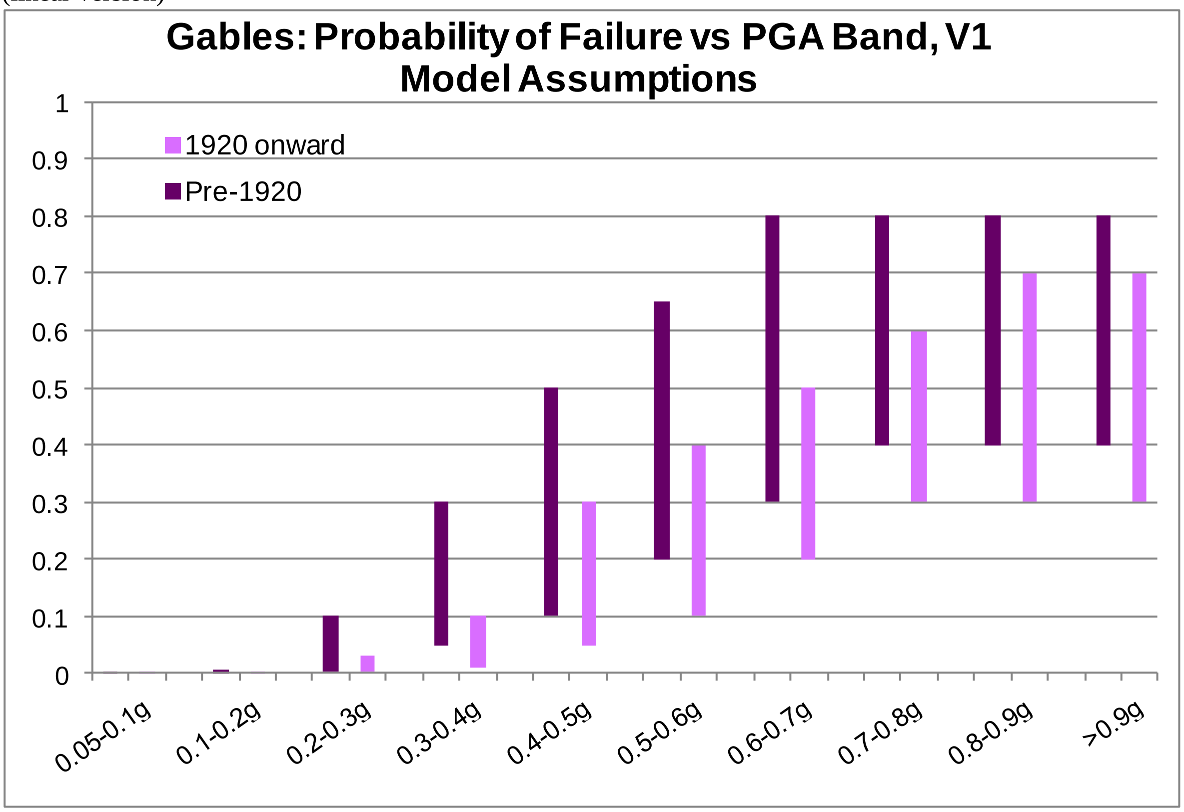
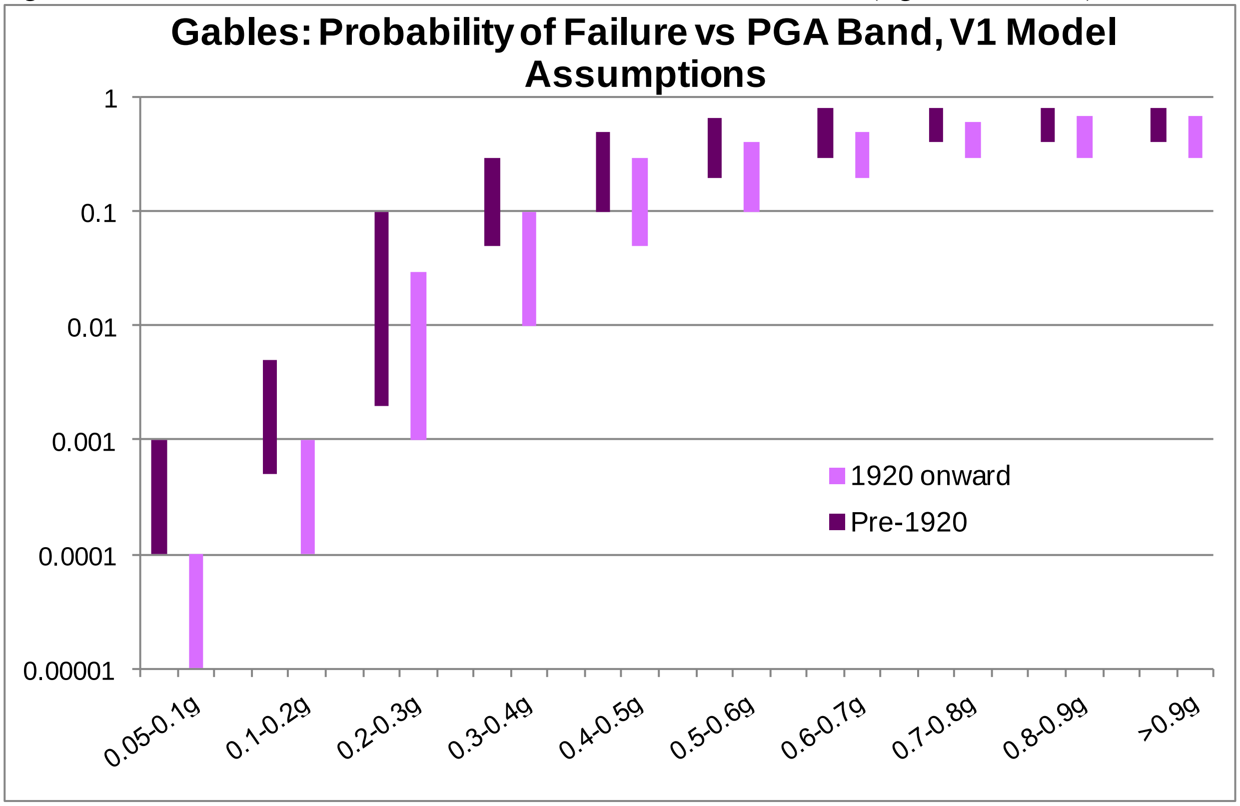


Figure A3.5 : Gables – V1 Assumed Probabilities of Failure for Each PGA Band (logarithmic version)



Notes on Table A3.10 and Figure A3.5:

1. Gable failure is exceptionally rare for older buildings in lowest shaking band (unknown in UK, but small non-zero have been assumed in light of the possibility of minor gable failure revealed at modest shaking in Roermond & Liege).

2. There is very limited data for the 0.1-0.2g band even for older buildings. Kalgoorlie "failures" (Table A3.9) did not involve bricks falling so are not counted as true failures (involving material falling to the ground) in the context of this report. Roermond suggests that a significant fraction of 1% of gables may fail in this band, involving very small (few bricks) quantities of debris falling. 0.5% has been taken as a reasonable upper estimate for use in the Groningen region

3. The large proportion of older gables that failed in Christchurch 22/2/11 earthquake is considered of low relevance; shaking was long duration, tectonic, and buildings were previously damaged by the 4/9/10 Darfield earthquake.

4. The Darfield earthquake is considered a potentially more useful source of data as buildings had not previously been damaged by shaking, but was again a long duration tectonic earthquake of much higher magnitude than is possible in the Groningen region so almost certainly overstates probability of damage for Groningen.

5. Newcastle, though tectonic and longer duration, had a mix of older & newer brick houses of both solid and cavity wall construction which is of considerable interest in the Groningen context. It is considered plausible that proportions of gables damaged in older Groningen buildings might be a substantial proportion of the average for masonry

buildings at Newcastle for similar PGA - but they could also be very much lower. 30% has been adopted as the higher estimate for Groningen region for the 0.3-0.4g PGA band

6. Above 0.4g, gable damage in older buildings is assumed to increase rapidly with PGA until reaching a plateau of 80% above 0.6g.
7. For newer buildings, Newcastle suggests a significant possibility of damage to gable & unloaded walls, and has been assumed to imply up to 10% probability of failure for Groningen region (shorter duration shaking) around the 0.3-0.4g PGA band.
8. Arup LS-DYNA simulation also suggests the possibility of significant gable damage in some post-1950 houses from shaking in the range 0.3 to 0.5g.
9. The probability of failure for newer gables is assumed to rise rapidly above 0.4g, approaching a plateau of between 30% (lower value) and 70% (higher value) at high PGA.
10. In the absence of data, the probability of failure of newer gables has been assumed to be an order of magnitude below the (already very low) probability for older ones for the lowest shaking band (0.05-0.1g).

Finally, Table A3.11 provides a summary of the smoothed empirical data from the earthquakes in Table A3.9, the assumptions on the probability of different damage states that have been adopted for the V1 risk model, and notes on how the judgments were formed in light of the empirical data.

Table A3.11 : Gable Damage State Distribution – Smoothed Empirical Data and V1 Model Assumptions

Smoothed Empirical Data		**Failures in given band of debris generated**					
		1-3%	**3-10%**	**10-30%**	**30-70%**	**70+%**	**NOTES**
Darfield, smoothed data	0.2-0.3g	0.10	0.50	0.15	0.15	0.10	
Newcastle, smoothed data	*0.3-0.4g*	*0.14*	*0.07*	*0.07*	*0.07*	*0.65*	Deeply suspect - photos available are of worst damaged area only
Christchurch 22/2/11	0.4-0.5g	0.17	0.17	0.29	0.24	0.13	
Christchurch 22/2/11	0.6-0.7g	0.13	0.13	0.22	0.30	0.21	
Liège/Roermond judgment	0.2-0.3g	0.60	0.30	0.05	0.03	0.02	
V1 - OLDER (pre-1920 Gables:	**The above earthquakes all involve older buildings so are more relevant than for newer buildings**						
LOWER values - Groningen	0.05-0.1g	0.9	0.1	0	0	0	Lower % fallen interpretation of N Europe experience
Pre-1920	0.1-0.2g	0.8	0.2	0	0	0	Interpolated between 0.05-0.1g and 0.2-0.3g
	0.2-0.3g	0.65	0.30	0.03	0.02	0	Basis - as estimated for Liège & Roermond
	0.3-0.4g	0.5	0.2	0.15	0.1	0.05	Interpolated between 0.2-0.3g and 04-0.5g
	0.4-0.5g	0.25	0.25	0.2	0.2	0.1	As Chch but modest shift to lower bands recognising shorter duration shaking
	0.5-0.6g	0.2	0.2	0.2	0.2	0.2	Extrapolation to higher PGA assumes significant % still at low DS
HIGHER values - Groningen	0.05-0.1g	0.7	0.3	0	0	0	Higher % fallen interpretation of N European experience
Pre-1920	0.1-0.2g	0.6	0.2	0.15	0.05	0	Interpolated between 0.05-0.1g and 0.2-0.3g
	0.2-0.3g	0.40	0.30	0.15	0.10	0.05	Higher interpretation of Liège/Roermond observations; lower than Darfield
	0.3-0.4g	0.3	0.2	0.2	0.2	0.1	Interpolated between 0.2-0.3g and 04-0.5g
	0.4-0.5g	0.1	0.1	0.2	0.3	0.3	Higher interpretation of Chch data
	0.5-0.6g	0.05	0.05	0.1	0.4	0.4	Higher interpretation of Chch data
V1 - NEWER (1920+) Gables:	**As for parapets & chimneys, general shift relative to older gables from "shaking loose bricks" to "snapping"**						
LOWER values - Groningen	0.05-0.1g	0.8	0.2	0	0	0	Still assumed non-credible to fail >10% of masonry
Post-1920	0.1-0.2g	0.6	0.3	0.1	0	0	
	0.2-0.3g	0.40	0.30	0.20	0.05	0.05	Interpolated between "mostly low DS" at low PGA and "mostly all fail" at higher
	0.3-0.4g	0.2	0.3	0.2	0.2	0.1	
	0.4-0.5g	0.1	0.2	0.35	0.2	0.15	
	0.5-0.6g	0.1	0.2	0.2	0.25	0.25	Assumed similar "Mostly fall but few still failed via loose bricks" plateau as for older gables
HIGHER values - Groningen	0.05-0.1g	0.5	0.3	0.2	0	0	Now assumed credible to have chance of >10% failure IF failure occurs
Post-1920	0.1-0.2g	0.3	0.3	0.2	0.1	0.1	Ramps up at earlier PGA than for the lower values
	0.2-0.3g	0.1	0.1	0.2	0.3	0.2	
	0.3-0.4g	0	0.1	0.1	0.5	0.3	Transition to 'plateau' mix assumed to occur at lower PGA
	0.4-0.5g	0	0.1	0.1	0.4	0.4	
	0.5-0.6g	0	0.1	0.1	0.4	0.4	

[End of Appendix 3]

Appendix 4: Occupancy Assumptions for OIA Calculation

1. Introduction

Commission Meijdam has proposed that an occupancy-weighted individual risk metric (objectgebonden individueel aardbevingsrisico, or OIA – referred to in the main report of this study as object-related individual risk or OIR) should be used both for prioritisation and for deciding whether or not buildings require upgrade in relation to non-structural falling hazards from buildings in the Groningen region. OIA is defined as the product of Local Personal Risk and the percentage of time spent by the individual of interest in the at-risk location.

This note discusses some of the issues associated with defining the individual of interest and their time at risk, and in combining OIA via different exposure pathways, for application to the risk from falling hazard objects. It covers

- Falling hazard exposure pathways and who is at risk
- Defining “individuals of interest” for those exposure pathways, and
- Proposed occupancy factors for those individuals of interest.

2. Exposure Pathways and Who is at Risk

Three exposure pathways are considered in the current falling hazards risk model:

a. Building occupants running out of doorways into falling debris
b. Building occupants struck by objects falling through roofs, and
c. People outside buildings struck by objects falling outside.

For (a) and (b) the people at risk are the occupants/users of the building. We can therefore safely assume that

% time at risk = ***% time spent inside the building***

x ***probability at risk if inside building when earthquake occurs***

For (c) the people at risk can include some or all of:

i. People walking past in the street outside
ii. Building users or others entering/leaving the building or otherwise spending time around the building facades where objects might fall (including e.g. children in a school playground, smokers having a cigarette outside doorways, people gardening or cleaning windows), and
iii. Other people approaching the building facade for other reasons, typically carrying out some function on behalf of the building users (e.g. postmen, window cleaners).

In terms of individual risk, any one building will only ever contribute a very small amount via (i) or (iii). For example:

- Someone who walks 10x per day past a 10m long building facade at a normal walking speed of about 1m/s will spend just 100 seconds per day, or about 0.1% of their time, outside the building facade. A dedicated shopper might spend many minutes outside a shop window, but would do so considerably less frequently.
- People who frequently come to the outside of buildings (e.g. to deliver mail) tend to spend only a very short time outside the building facade. People who spend longer per visit (e.g. to clean windows) tend to do so less frequently. A postman who spent 1 minute per day in front of a building facade or a window cleaner who spends 30 minutes once per month would each spend less than 0.1% of their time outside the building facade.

Given these very small occupancy levels I propose that we treat the building user as the representative “worst case” individual for the purposes of calculating OIA for people outside buildings, and adopt a reasonably conservative (high) estimate of the proportion of time building users spend outside close to each building facade. The level of OIA for other individuals will be considerably less than that so calculated for the building user.

The proportion of time spent outside building facades for a representative building user could include, for example

- Time at risk while entering or leaving the building
- Time spent on building or garden maintenance close to building facades, and
- Leisure time spent sitting outside, smoking or playing close to building facades.

In this way we get over the problem, for any individual risk metric, of different people being at risk from different parts of the risk source. There may in exceptional cases be people who are not building users but spend significant amounts of time outside individual buildings (places where people tend to congregate or individuals tend to spend time for whatever reason), which I suggest should be dealt with locally on a case by case basis.

3. Proportion of Time at Risk

My suggestion for proportions of time we should assume in calculating OIA for falling hazards are as follows:

1. For churches and other occasionally occupied gathering places: assume 5% occupancy (corresponding to just over 1 hour daily). This would cover, for example, someone attending a (rather long) daily service, or a minister spending just over 8 hours per week in the building.

2. For space outside buildings, assume 1% occupancy. This would cover, for example (see Table 1 below):
   a. 30 seconds per entry and exit to a building, 10x per day
   b. Smoking several cigarettes per day outside a doorway
   c. Children spending 20 minutes of playtime by the same facade every schoolday
   d. Someone spending an hour every week on house or garden maintenance tasks outside one facade (e.g. cleaning windows, cutting grass, weeding...), or
   e. Someone spending 2 hours per day sitting on a patio on each of 40 fine days per year.

Table 1: Activities that Fit Within 1% Time Outside a Building Facade

Activity	Typical				TOTAL	
	Duration (minutes)	Times	per Time Unit	Time Units/yr	Hrs/yr	% time
Entering/leaving the building	0.5	20	Day	365	60.8	0.7%
Smoking a cigarette in doorway	5	5	Workday	210	87.5	1.0%
Schoolyard play by building wall	10	2	Schoolday	200	66.7	0.8%
Home/garden work by building wall	60	1	Week	52	52.0	0.6%
Leisure outside building wall	120	40	Year	1	80	0.9%

3. For “Notverblijfsobjecten” such as sheds and garages, assume 0% occupancy (on a similar basis to that assumed in leaving out CC0 buildings from specific seismic design requirements in Eurocode and other international seismic standards).

4. For hospitals and care homes with resident, immobile populations assume 100% occupancy. In practice in the current buildings database it is not easily possible to distinguish these from other healthcare facilities so I propose assuming 100% occupancy for ALL buildings with primary use “Healthcare”.

5. For residential buildings (including hotels and other buildings with primary use “Accommodation”), assume 70% occupancy (rounded from the 69.2% assumed in the current NAM buildings/exposure database, based on 43.6 hours per week spent inside the home on average during daytime and 72.7 hours during night-time derived from the Netherlands Time Use Survey).

6. For workplaces in general (offices, industrial sites, shops, sport/leisure facilities, schools) assume 20% occupancy (very close to 8 hours per day x 210 days per year).

IMPORTANT NOTE – these suggestions are proposed as a basis for defining typical individuals and their time spent in different locations. Commissie Meijdam advised that for the purpose of comparing risk from an object with individual risk norms, it would be appropriate to assume 100% occupancy of all regularly occupied buildings such as homes, shops, schools and workplaces. The risk assessment in the main body of this study is primarily intended to help estimate numbers of objects that might be non-compliant with risk norms, so for this purpose replaces the proposals numbered 4, 5 and 6 above with the assumption of 100% occupancy in calculating OIA/OIR.

4. Differences between OIA and CR

The current risk metric used as the primary output of the Falling Hazards risk model is Community Risk (CR), which is defined as

CR = LPR x (time-averaged number of people at risk), whereas

OIA = LPR x (% of time at risk for a given individual).

The time-averaged number of occupants is generally greater than one, whereas the % of time at risk for an individual is always one or less. Thus OIA will generally be lower than CR.

Like any other individual risk metric, OIA does not distinguish between situations where many people are at risk as opposed to those where a single person is at risk. Thus for example a busy street is not distinguished from a quiet one, or an object falling through the roof of a school where 50 pupils are present on average is not distinguished from one falling through the roof of a similar building with a single occupant.

Individual risk metrics are clearly preferred in the Netherlands as the basis for deciding whether somewhere is safe enough not to require action to reduce risk. Once a set of buildings or objects requiring action has been established, a simple aggregate risk measure such as Community Risk has the advantage for prioritisation that it takes into account the number of people at risk as well as the individual risk level.

Tony Taig

TTAC Ltd

13 January 2016

[end of Appendix 4]

Client: Nederlandse Aardolie Maatschappij

Arup Project Title: Groningen Earthquakes Structural Upgrading

Risk Assessment of Falling Hazards in Earthquakes in the Groningen region: Appendices 5-6

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Job number 229746
External Ref

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PO Box 57145
1040 BA
Amsterdam
The Netherlands

ARUP

Contents

Appendix 5: Populations at Risk Outside Buildings from Falling Hazards in Earthquakes

1. Introduction

Debris falling from masonry chimneys, parapets, gables and other walls can create a significant hazard for people outside buildings in earthquakes. 37 people were killed by such debris as they walked or drove past buildings, ran outside, or were struck by debris falling through the roof of next-door buildings in the earthquake in Christchurch on 22 February 2011. Many others would probably have died in a similar way had the earthquakes in Liège (1983), Roermond (1992), Northridge (1994) and Newcastle (Australia, 1989) not occurred at times when the streets involved were virtually empty.

This appendix addresses the risk outside buildings from falling debris that might be generated in earthquakes in the Groningen region, for three particular purposes

a. To help delineate the area outside buildings within which people are at risk from falling debris (section 2)

b. To explain the basis on which exposed populations outside buildings were estimated for the NAM V2.0 exposure database (sections 3 & 4.1), and

c. To explain the current approach used in the Falling Hazards risk model to defining populations at risk from falling debris not only outside buildings, but also inside buildings due to objects falling through the roof (section 4.2).

Comparisons between the different risk exposure pathways described in Sections 3 and 4 are discussed in Section 5 of the appendix, before drawing conclusions in Section 6.

Reference is made throughout to the Falling Hazards Survey (‘the Survey’) of buildings in the Groningen region carried out by TTAC Ltd during summer 2015, and to the way in which parameters discussed in this appendix are treated in or interpreted from that Survey.

2. Delineation of Area at Risk in front of Building Facades

Debris falling from buildings represents a hazard only relatively close to the building itself. The primary hazard of concern is of people being hit by debris as it falls through the air. A secondary potential hazard is that of people being hit by debris after it hits the ground and scatters. Clearly both hazards will fall off rapidly to zero as the distance from the building increases, while for some buildings it is possible that overhanging eaves or other structures may provide a “shelter zone” immediately next to the building wall.

We have carried out two studies to explore the variation in risk from these hazards with distance from the building wall:

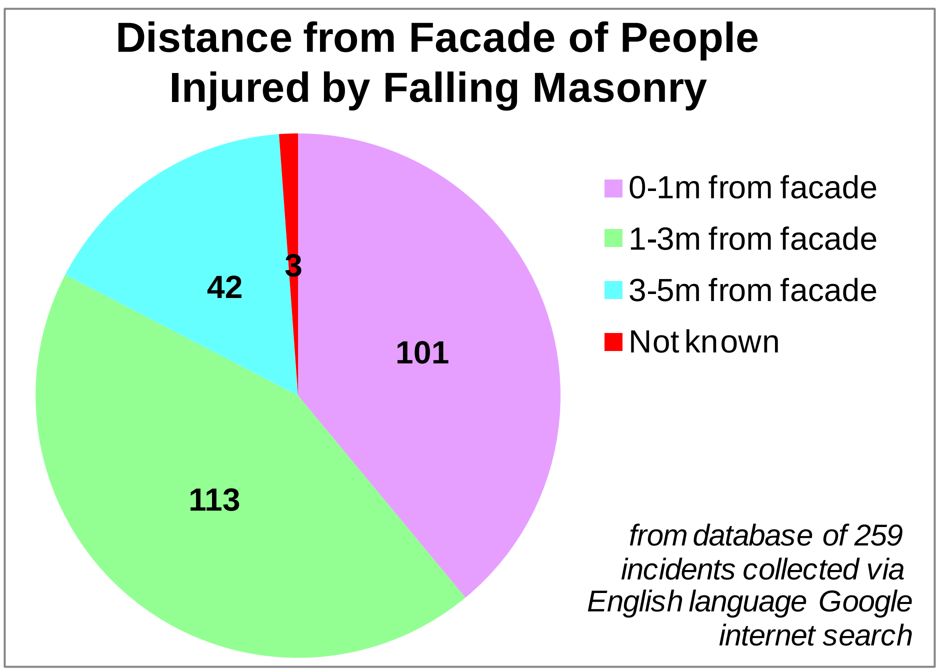
a. A review of experience of a substantial number of incidents involving people being injured by masonry falling into public places[1], and
b. Theoretical calculations of the ranges of travel of objects sliding off or toppling from roofs.

2.1 Review of Incident Experience

The first study involved 259 cases of people being injured, 95 of them fatally, in incidents where masonry or concrete debris fell into public places. The incidents were identified by English language searches using Google. The important conclusions of this study are:

1. All of the injuries occurred via the primary hazard (debris hitting people as it fell through the air), not via the secondary hazard (debris scattered after hitting the ground).
2. The injuries were heavily concentrated in the first 3 metres from building walls. We found no injuries that had occurred more than 5 metres from building walls, even for debris falling from very tall buildings (see Figure A5.1).

Figure A5.1: Injuries vs Distance from Facade

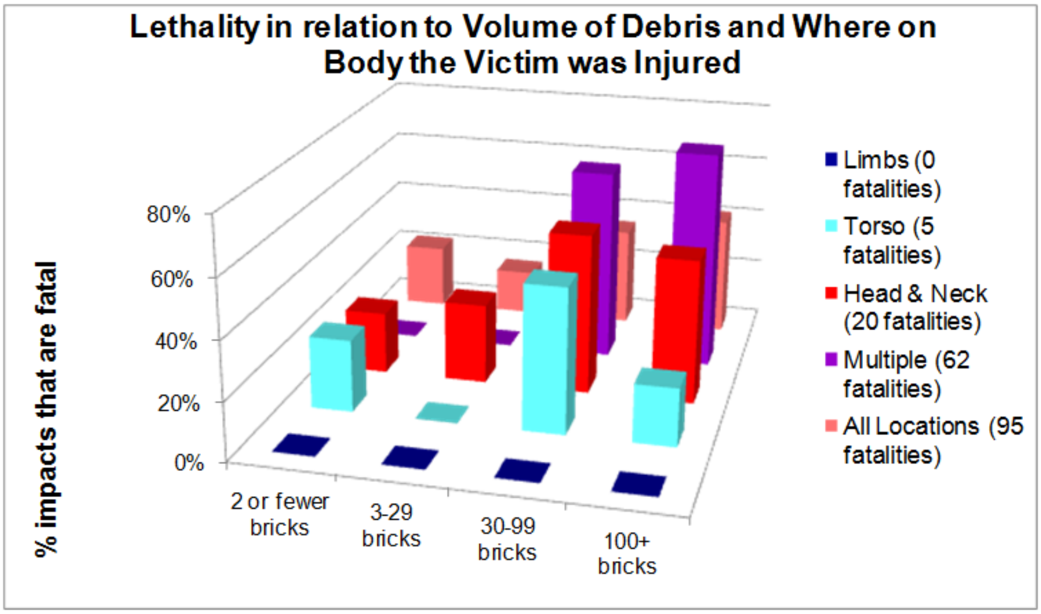


3. Fatal injuries generally involve either a) impact of heavy debris on the head, or b) inundation by debris with impact or crush damage to multiple parts of the body (see Figure A5.2).

[1] Reported more fully in Appendix 6.

4. To a good approximation[2], the probability of death can be estimated as 1 if the head is impacted, and zero otherwise (incidents where the head is impacted with a glancing blow and people survive are offset by others where the head is not impacted but death occurs).

Figure A5.2: Lethality, Part of Body Impacted and Size of Impacting Object



2.2 Theoretical Calculations

Theoretical calculations were carried out of the distance to which objects could fall if they slid down roofs and fell from them, or toppled from the edge of buildings, as described below. The hazard range could in theory extend to the maximum dimension of the object plus 2-3 metres for buildings up to 2 storeys high, and a little further for taller buildings. In practice, the evidence of our survey of experience suggests that masonry objects tend to break up in the course of failing, sliding down, toppling or otherwise falling from roofs, making the hazard range smaller in practice than the theoretical maximum. The calculational approaches are summarised below for objects sliding and toppling from roofs respectively.

2.2.1 Objects sliding from roofs

Calculation of the travel distance outward from a building facade of an object sliding down a sloped roof was carried out as explained in the spreadsheet excerpt (Table A5.1) below.

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[2] This approximation works well for larger objects (from 2-3 bricks in scale upward) but errs on the side of pessimism for smaller objects. It works particularly well in combination with specific assumptions as to the orientation of falling objects (see below, Section 5.2)

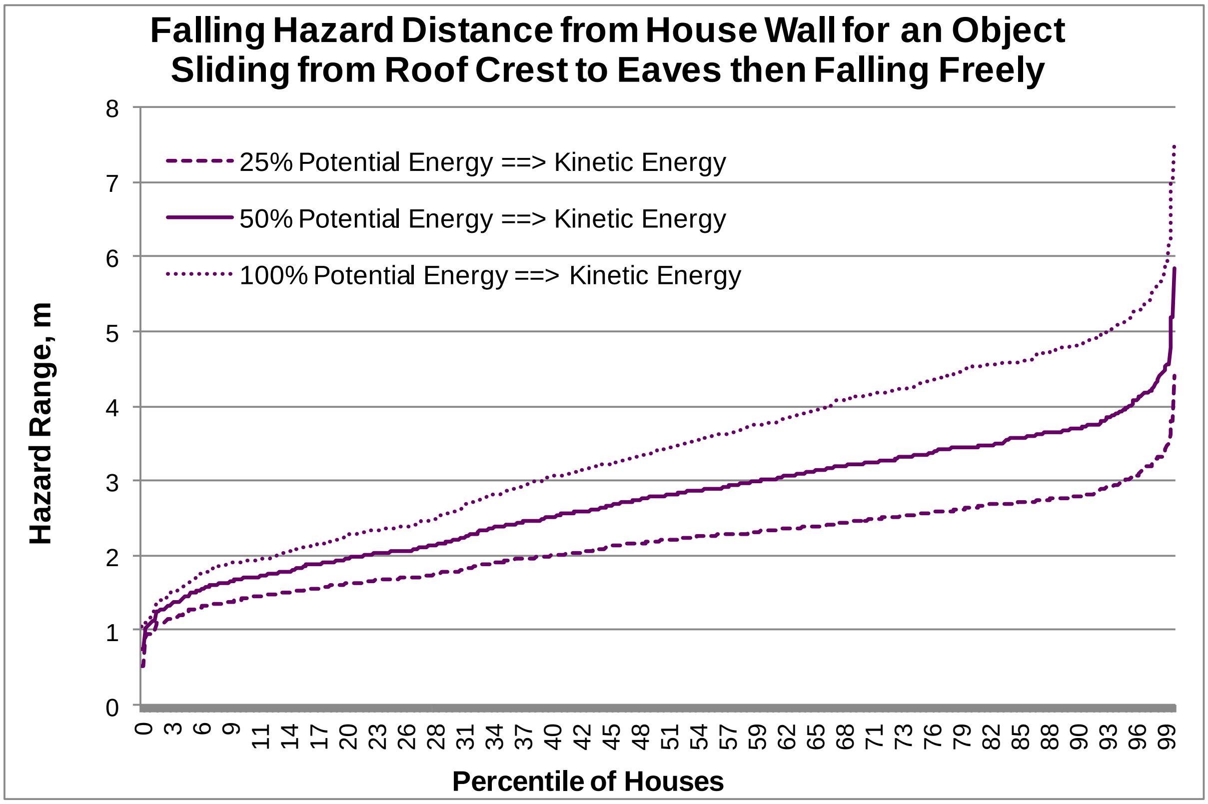
Table A5.1: Calculation of Distance Travelled by Object Sliding down Roof

Suppose	h	metres	is the height of the roof crest above the eaves
and	A	degrees	is the angle of the roof to the horizontal
	m	kg	is the mass of an object at the roof crest that fails and slides down and off the roof
	E	dimensionless	is the proportion of the object's initial potential energy translated into kinetic energy
			at the moment it leaves the roof
	H	metres	is the height of the eaves above the ground through which the object then falls
	U	m/sec	is the speed of the object on leaving the roof
	V	m/sec	is the speed of the object when it hits the ground
	t	seconds	is the fall time
	g	m/sec2	is the acceleration due to gravity
	R	metres	is the distance travelled out from the building by the object when it hits the ground
Then	$0.5mU^2 = E.mgh$		
	U =	SQRT (2gh/E)	
The vertical component of U (U sinA) is then used with H to calculate the final velocity V and drop time t			
	$V_{vert}^2 = (UsinA)^2 + 2gH$		
So	$t = (V_{vert} - UsinA) / g$		
The horizontal component of U (U cosA) is now used to calculate the distance travelled away from the wall:			
	R = UcosA . T		

Figure A5.3 shows the hazard ranges calculated for roof crest objects (generally likely to be chimneys) sliding down approximately 5,000 roofs of buildings in the Loppersum municipality, based on the data on roof heights and slopes collected in Rapid Visual Surveys up to November 2014. Ranges are shown for different assumptions as to the proportion of potential energy of the object converted into kinetic energy as it leaves the roof, of which the 25 and 50% curves are considered more realistic for typical conditions than the 100% curve.

Our conclusion from Figure A5.3 is that the observations of our study of injury impacts of falling masonry (that the hazard is confined to within 5m of building facades) appears consistent with these simple calculation of hazard ranges for objects sliding from roofs.

Figure A5.3 Hazard Ranges – Sliding Down Roof



2.2.2 Object toppling from a roof edge

In a similar way, a simple calculation was made of the distance travelled outward from a building facade by an object at the top of that facade toppling outwards. The calculation is as shown in the spreadsheet excerpt (Table A5.2) below.

Figure A5.4 shows hazard ranges for different heights of object toppling from the edge of a roof 5m (approx 2 storeys) high, assuming that the toppling object retains its integrity and falls at an orientation so as to maximise its outward travel from the building facade. For fall heights corresponding to a 1 or 2 storey building the hazard range is limited to the height of the object itself. For taller buildings it appears plausible for the hazard range to extend an additional 1-2 metres.

Most falling hazards (parapets, dormers, sections of wall weakened out of plane) are likely to have “object heights” of 1-2m or less. Some others (balconies, canopies) are more likely to fall vertically than to topple; they lack a mechanism by which to acquire horizontal momentum away from the building. All such objects are thus unlikely to lead to parts of the object impacting on the ground more than 2-3 metres from the building wall, even for tall buildings. The likeliest exception to this general rule is chimneys; a tall chimney situated on a tall building edge directly above a street could conceivably pose a hazard 5-10m out from the building wall IF the chimney were to topple intact as a single large object.

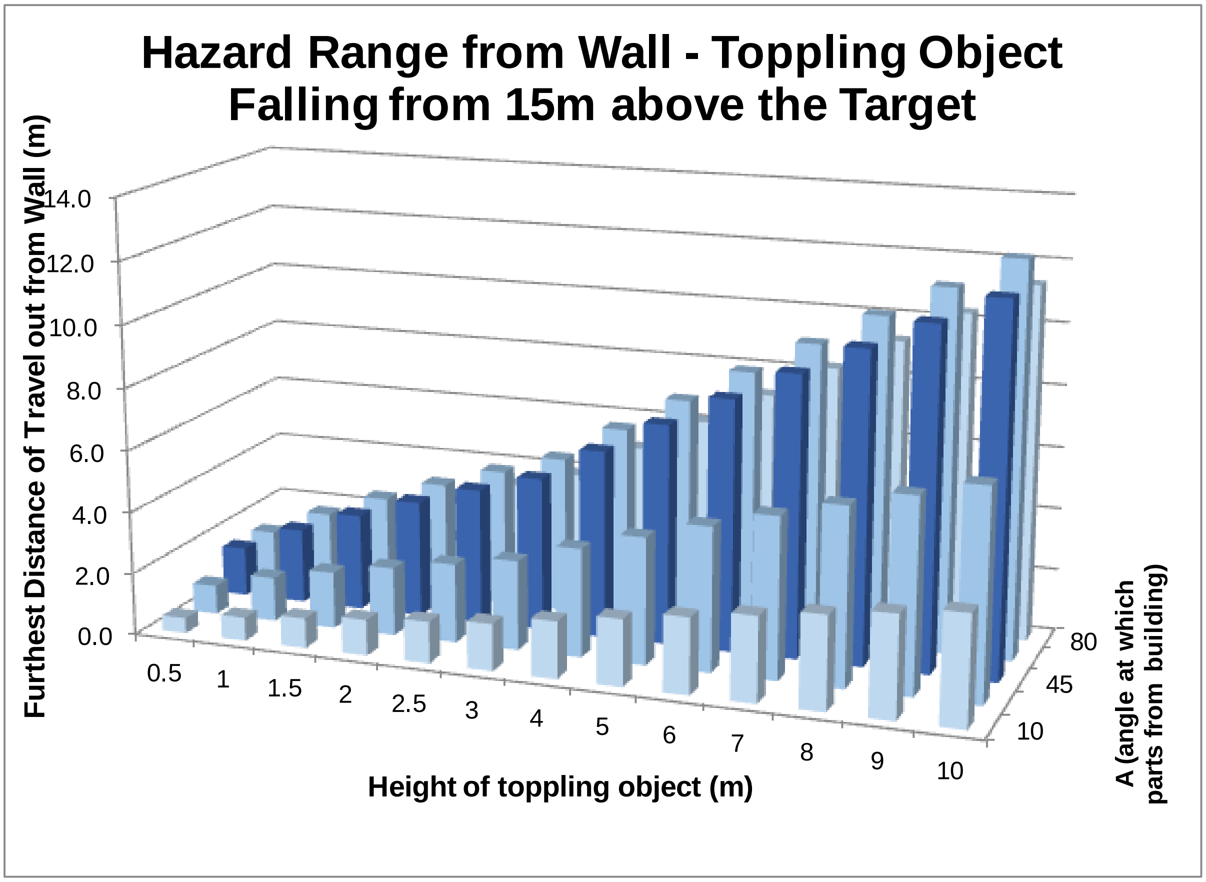
Table A5.2: Calculation of Range of Toppled Object Outward from Building Facade

Consider a chimney, parapet or other falling hazard as a rod of length (height) h								
Suppose it rotates about the base, reaching an angular velocity W having rotated through angle A,								
at which point it leaves the roof and falls freely.								
Moment of Inertia =		$m.h^2 / 3$						
Potential energy lost having rotated through angle A =					m.g.(0.5h).(1 - cosA)			
So rotational kinetic energy (= $0.5\ I\ W^2$) at point of leaving = Potential energy lost, and								
	$(1/2)\ ,\ (1/3).m.h^2.W^2$		=	m.g.(h/2).(1-cosA)				
	W =	SQRT[(3g/h).(1-cosA)]						
Linear velocity V =		(h/2).W						
Horizontal linear velocity V_{horiz} =			V.cosA					
So								
	V horiz =	0.5.h.cosA.sqrt[(3g/h).(1-cosA)]						
	V horiz =	0.5 . cosA . SQRT[3gh(1-cosA)]						
The corresponding vertical initial velocity on leaving the edge of the roof is then used with								
the building height to estimate the fall time. The initial horizontal velocity on leaving the								
roof is assumed to be unaltered until the object hits the ground.								

In practice (as observed during building demolition and in earthquakes), masonry objects, and in particular slender ones such as chimneys, generally crumble and fall closer to the building rather than toppling as intact large masonry elements. In the Newcastle 1989 and Christchurch September 2010 and February 2011 earthquakes, for example, falling parapets generally fell immediately next to the facade on which they were mounted. Where the whole wall underneath collapsed out of plane, the hazard range extended to 4-5m, causing a number of deaths in Christchurch to people in road vehicles that were driving along roads rather than parked immediately next to the kerb.

In light of these observations we are confident in stating that the risk from falling non-structural building elements in the Groningen region is likely to be confined within 5m of building facades, and to be concentrated within 3m of building facades. For whole strong walls failing out of plane it is possible that the hazard range might be somewhat greater.

Figure A5.4 Hazard Ranges for Toppling Objects



These calculations for objects sliding and toppling from roofs corroborate our conclusions from the survey of real accidents, that

a. the hazard range for falling debris from non-structural building components is limited to the area within 5m of building walls, and

b. the risk is in the majority of cases concentrated within 3m of the building wall.

We therefore proposed defining the area at risk in front of a building as extending 5m from the building wall. For risk estimation in situations where people can walk close to buildings, we propose estimating the risk on the basis that the hazard is concentrated within 3m of the building wall.

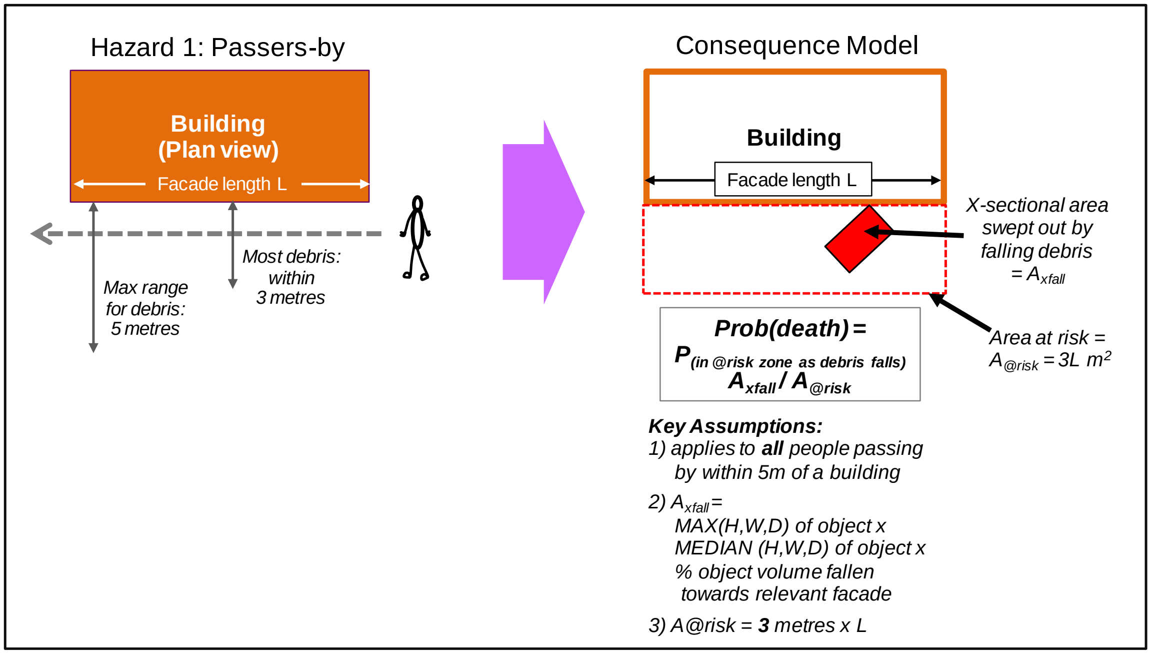
3. People Walking Past Buildings

The general approach is presented, followed by a discussion of different sources of footfall data and our conclusions as to which should be preferred for the Falling Hazards Risk Model.

3.1 General Approach for Exposure Outside Buildings

The situation being modelled is shown schematically in Figure A5.5.

Figure A5.5: Risk Exposure – Walking Past Buildings



The approach used is to estimate the number of people present in the at-risk area in front of buildings from the number who walk past per unit time. The consequences of such exposure are estimated based simply on the geometry of the falling object as shown on the right hand side of Figure 3. The assumptions made are:

1. The risk to passers-by is zero UNLESS there is public access to the space in front of the building wall adjacent to the street.
2. If there IS public access within 5m of the space in front of the building wall, then every passer-by is assumed to walk within the at-risk zone.
3. The width of the at-risk zone in front of the wall is estimated as 3m for risk estimation.
4. The probability of death is 1 if the object contacts the head of a person in the at-risk zone and zero otherwise (this is discussed in more depth in Appendix 6).

This approach builds in modest factors of pessimism, as it assumes someone walking past a building 4 or 5m away from the wall is at the same risk as someone walking past 2m from the wall, whereas in practice their risk is likely to be significantly smaller.

Buildings are classified in the Survey as “P” (denoting ‘public access’) if there is public access within 5m of the wall closest to the street. This classification is allocated manually by the surveyors and is effectively a yes/no evaluation (i.e. no attempt is made to measure and record the actual shortest distance from the facade to the point of closest public access; this would be too time-consuming). An exercise was carried out by NAM to measure this distance automatically using Kadaster data, but the difficulty in defining precise boundary locations and public access in relation to boundaries meant that the classification provided via the Survey was more reliable.

There is a second category of buildings where the public have access to the facade other than in walking down the street. Such buildings include public buildings such as schools, hospitals, churches, and numerous houses and apartment blocks which, though their address is on a given street, are actually built on side-spurs of the road or in blocks at an angle to the street. In many such cases the risk to passers-by may be minimal; the people at risk are those walking along the side-spur or along the building frontage which is “off road”. Such buildings are classified in the Survey as “P*”.

It is assumed that passers-by are at risk from falling debris for the whole of the time that they are directly in front of the facade of a ‘P’ or ‘P*’ building, and not otherwise.

Footfall is estimated using the best available data for P buildings using three methods as follows:

1. For Groningen Centrum (certainly the highest footfall area in the province), footfall data by street and shop is commercially available and has been purchased and used.

2. For other main streets with shops, data on the number, type and floor area of shops has been used to make estimates of footfall for the busiest streets in towns and villages outside the city of Groningen. (Note – at present these estimates are available only for whole streets and have not been split out into estimates appropriate to specific sections of streets and buildings; this remains as an opportunity for improvement in future versions of the risk model.)

3. For all other streets, the Survey allocates a rating based on the expected volume of pedestrian traffic. The rating scale ranges from 1 for an isolated building where no-one but the occupants and postman/delivery staff would ever be expected to walk past (few 10’s of persons walking past per week) up to 10 for the busiest street in Groningen city (Herestraat, where around 100,000 people walk up and down per week).

For P* hazards, a rating of H, M or L footfall is allocated during the Survey based on the situation and use of the building in question. H corresponds to “100’s of people may walk in front of the facade on a daily basis” (e.g. school & hospital buildings), M to “significant numbers regularly walk close to the building” (e.g. churches, theatres and other leisure amenity buildings), and L to “few people other than occupants/delivery staff regularly walk close to the building” (e.g. fire and ambulance stations, apartments or houses at the far end of a street side-spur or cul-de-sac).

The nature and pros and cons of the different data sources are discussed below.

3.2 Footfall Data Sources

3.2.1 Locatus measured footfall data

Footfall is a widely measured and used metric in retail planning and management in large towns and cities. The Netherlands is less developed in terms of footfall measurement than the UK (where there are some 500,000 automated footfall sensors in place across towns and cities), but footfall data is measured regularly in larger towns and cities.

The only commercially available data we could find for the Groningen region was for the centre of Groningen itself. This data was purchased from Locatus, who have a well-developed process for taking measurements on particular days and at particular times at sample measurement points within a shopping area, and then interpolating between those measurements to estimate footfall past each shop in a shopping area. Observations on footfall vs time of day, day of week and time of year across a very wide range of Netherlands shopping areas can then be used to translate the Locatus data (which provides estimated footfall outside each shop on an average Saturday) into average footfall per week or year.

Example measured/interpolated footfall for a randomly selected 3% sample of buildings in Groningen Centrum for which Locatus footfall data is available is shown in Table A2.1.

Table A5.3: Footfall at Example Groningen Shopping Street Locations

Street Address	PASSANTE
Gelkingestraat, 33	2500
Nieuwe Ebbingestraat, 6	3800
Nieuwe Ebbingestraat, 15	3800
Oude Boteringestraat, 5	10200
Carolieweg, 32	6800
Herestraat, 32	39000
Herestraat, 17	39000
Grote Markt, 35	12600
Folkingestraat, 3	14700
Oude Ebbingestraat, 61	7500
Oude Ebbingestraat, 61	7500
Oude Ebbingestraat, 89	7500
Stoeldraaierstraat, 54	11500
Vismarkt, 39	21300
Vismarkt, 3	26000
Steentilstraat, 33	3400
Steentilstraat, 16	3400
Zwanestraat, 23	9000
Folkingestraat, 39	10300
Oude Ebbingestraat, 48	11500
Herestraat, 33	39000

The footfall (Passanten) figures shown are average numbers of people walking past each building (in both directions/on both sides of the street) on an average Saturday. Locatus provide data (based on large numbers of surveys conducted all over the Netherlands) to help estimate footfall by time of day, day of week and time of year from the “average Saturday” footfall data, which is their standard format for supplying footfall information.

3.2.2 Estimated footfall in shopping streets based on shops data

Rakesh Paleja of Shell’s mathematics consultancy developed a simple method to estimate footfall in shopping streets by using ordinary least squares (OLS) and Poisson regression models to correlate footfall with total shop floor area and number of shops in particular (high footfall attracting) categories on each street. The data on shops, shop types and floor areas was that purchased from Locatus Netherlands and covers all shopping areas (defined as centres with 5 or more shops) in the Groningen region.

The Groningen Centrum area was used to find best-fit parameters for the models, and the parameters were then used to provide estimates of footfall for about 530 shopping streets in the region. Note that this method provides a single estimate for each street; the other methods used provide estimates on a building by building basis.

3.2.3 Estimated footfall during Falling Hazards survey

As part of the Falling Hazards survey carried out during summer 2015 by TTAC Ltd, the surveyors (largely university students and recent graduates) were asked to assign a footfall category to each building. The categories were defined as shown in Table A5.4.

Table A5.4 Footfall Categories used in Falling Hazards Survey

Footfall Categories	Footfall (typical) per day	Footfall/week		
		lower	**Footfall (typical), N/week**	**upper**
1	3	0	20	50
2	14	50	100	200
3	46	200	320	650
4	143	650	1000	1500
5	307	1500	2150	3100
6	657	3100	4600	6800
7	1429	6800	10000	15000
8	3071	15000	21500	31000
9	6643	31000	46500	68000
10	14286	68000	100000	200000

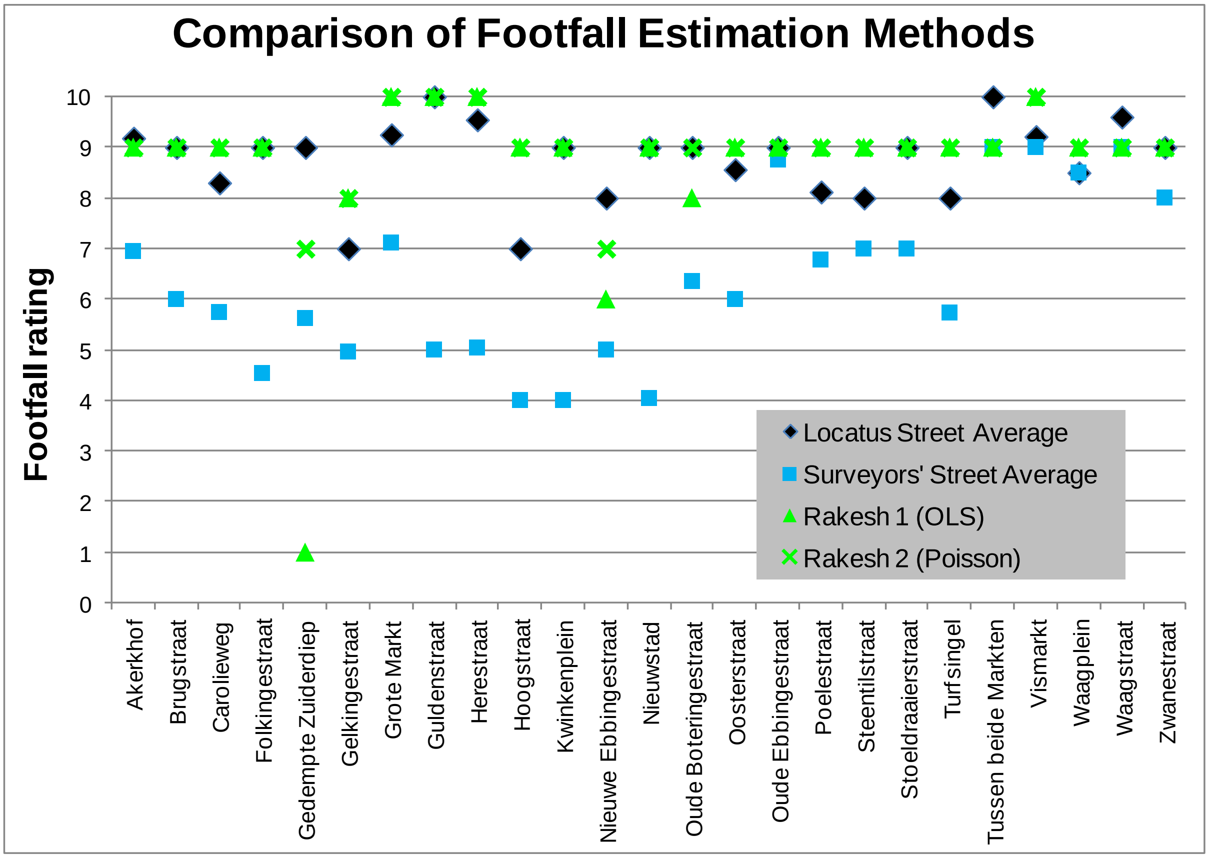
The surveyors were provided with a series of photographs illustrating different streetscapes from isolated houses through to busy city shopping streets, corresponding to the different footfall categories, looked like. They were asked, based on the population of buildings in the street and the vicinity, to estimate a footfall category based on their expectation for the street they were looking at, NOT on the people they could see in Street View. It is recognised that this is highly approximate.

A “second pass” review of all the footfall categories allocated to the High Priority Gemeenten surveyed up to the end of August 2015 (reviewing surveyors’ original ratings, and taking account of key “footfall magnets” such as shops and transport hubs) was carried out in order to check and refine the Surveyors’ estimates of population outside buildings which were delivered to NAM for incorporation into the V2 exposure database.

3.2.4 Comparison of footfall estimation methods, Groningen Centrum

Figure A5.6 shows a comparison of the average footfall rating (as in Table A2.2) for the streets in Groningen Centrum for which Locatus footfall data is available for one or more buildings.

Figure A5.6: Comparison of Footfall Estimates



Clearly, the falling hazards surveyors took insufficient account (on average) of the additional footfall to be expected in busy shopping areas. Paleja’s fit to the Locatus data is generally quite good, with the exception of one large outlier (Gedeempte Zuiderdiep). This street has a particularly high proportion of shops in the “special categories” used in the footfall simulation equation. The average difference (weighted for numbers of buildings with data available on each street) between ratings based on the Locatus data and those based on the other sources in the table are (positive denotes Locatus greater than other source):

- 2.4 (falling hazards surveyors)
- 0.05 (Rakesh 1 – OLS)
- -0.15 (Rakesh 2 – Poisson).

3.2.5 Conclusions – treatment of footfall in the falling hazards risk model

Our intention is to use the Locatus data were available, the Rakesh Paleja ordinary least squares estimates for other shopping streets (after checking for possible gross outliers based on streets with large numbers of special category shops), and the falling hazard surveyors' estimates for the rest of the region. The Paleja data is currently provided for whole streets only; as most shopping streets tend to be quite long with varied use along them it will be necessary to divide streets into sections for application of this data. This has not been possible within the timeframe available for the first issued version of the model but represents an opportunity for improvement in subsequent versions.

We note that for the vast majority of areas other than shopping streets, the footfall rating is likely to be too low for the contribution to community risk from passers-by to be significant in comparison with the risk associated with building occupants running out of buildings during earthquakes.

The uncertainty associated with these different methods of footfall estimation varies considerably; our judgment is that

a. The commercial data specific to Groningen centrum is likely to be accurate within a few 10's of % (the method used is very widely applied commercially and is relied upon for high value decision making in the retail industry).

b. The estimates for other main streets are considered accurate within a factor of 2 or 3 either side of the central estimate, while

c. The rating scales 1-10 and P*L,M,H are considered to provide a good relative indication of how busy the (generally quieter) streets outside main shopping and transport areas are, but not to provide a reliable absolute estimate of footfall.

It may be possible to calibrate the judgment-based assessments of footfall by adding together the implied annual km travelled on foot by the population of the region and comparing this with the annual km travelled on foot as revealed by the regular travel surveys carried out in the Netherlands and other EU countries. The key issue here would be the estimation of the distance walked from the surveyed footfall estimates. This has not been attempted at this stage but may merit further consideration if sensitivity studies show this to be a significant parameter.

Translation of footfall into population at risk in front of a building is carried out using the formula

Population at risk = Footfall x (Facade length) / (Walking Speed)

Walking speed is assumed equal to 3.5 km per hour except in busy shopping areas where it is assumed to reduce to 2.5 km/hr. Table A5.5 shows the resulting populations at risk for a typical facade length of 10m for the footfall categories that have been used to classify streets in the current falling hazards survey of buildings in the region.

Table A5.5: Footfall and Population at Risk in front of a 10m Building Facade

Footfall Category	Footfall (typical), N/week	Walk Speed kph	Ave people present, year round, within 10m facade length	Example relevant street situations
1	20	3.5	0.0003	Isolated building; occupants/postman only
2	100	3.5	0.0017	Quiet cul-de-sac or dead end
3	320	3.5	0.0054	Quiet residential street
4	1000	3.5	0.017	Busier residential street
5	2150	3.5	0.037	Village centre, town outskirts
6	4600	3.5	0.078	Smaller town centre
7	10000	3	0.20	Substantial town centre
8	21500	3	0.43	Large town/city shopping area
9	46500	2.5	1.1	Busy city shopping areas
10	100000	2.5	2.4	Busiest city shopping streets (Herestraat)

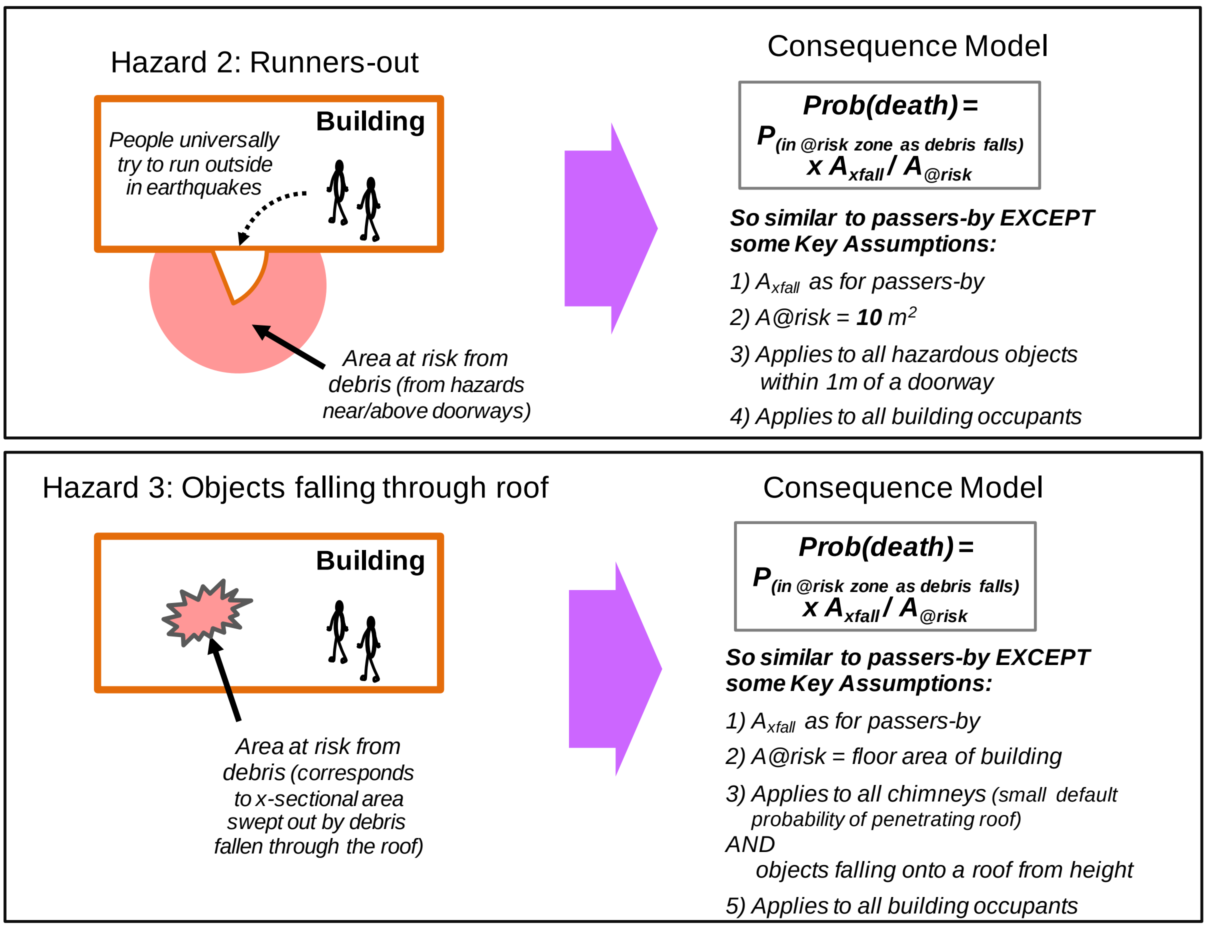
4. Building Occupants

Two risk exposure pathways are considered here:

- People running outside during earthquakes, and
- Objects falling through the roof of a lower, neighbouring building.

Figure A5.7 illustrates the approach to risk estimation used for each pathway.

Figure A5.7: Risk Exposure – Fleeing from Buildings



The Christchurch earthquake of 22/2/2011 led to 6 deaths and many injuries via each pathway. The Liège earthquake of 1983 led to 30 injuries via the first pathway (despite the earthquake being of very short duration and occurring in the middle of the night), and 1 death via the second. Both pathways are thus clearly important.

4.1 People Fleeing Buildings during Shaking

It is a universally observed aspect of human behaviour that people run outside buildings during significant earthquakes. Where falling debris is considered a greater risk than staying indoors (e.g. in New Zealand where houses are largely wooden and at very low risk of collapse in earthquakes), great effort is devoted to training people not to run outside during earthquakes. There is a strong argument based on earthquake experience in other areas with a large population of North European style masonry buildings that the area just outside the doorway of a masonry building is the worst possible place to be in an earthquake.

The population in the at-risk area outside a doorway can be estimated from the number of building occupants as follows:

N(at risk)	=	N (total number of building occupants)	
	x	P_1	Proportion of occupants who are in the building at the time
	x	P_2	Proportion of occupants able to leave the building
	x	P_3	Proportion of able occupants who flee the building
	=	N_3	No. of people attempting to flee the building
	x	P_4	Proportion of N3 who coincide with debris falling in the at-risk area in front of the building facade.

N x P_1 is the time-averaged population inside the building, which has been estimated by NAM for all buildings in the exposure database and is used as an input for the assessment of risk from falling objects to building occupants

Sensible estimates of P_2 and P_3 can be made based on whether people are awake and able to attempt escape or have some other condition preventing them attempting to escape (P_2) and in the knowledge that “attempting to flee a shaking building” is a universally observed instinctive human response to significant earthquakes (P_3). The most difficult parameter to estimate is P_4, the probability that people’s flight from a building will coincide with the time when debris is falling outside.

Annex 1 presents an analysis of the building damage and injuries sustained in the worst affected communities by the Roermond and Liege earthquakes of 1992 and 1983 respectively. It concludes that the values of P_4 in those earthquakes ranged from just over 1% (making the most optimistic assumptions for Liege) up to several 10’s of %. In light of the anticipated very short duration of shaking in man-made earthquakes in the Groningen region, it is suggested that a value of P_4 for risk assessment be adopted in the range from 1% to 10%.

This can now be used in conjunction with some simple assumed values for the other probabilities P_2 to P_4 to estimate overall populations at risk outside buildings as shown in Table A5.6.

Table A5.6: Proportion of Occupants At Risk Outside Buildings

Parameter	Daytime	Night	Average	Definition
P_2 (able)	90%	5%	50%	Proportion of people in building who are awake/able to run outside, should they want to try
P_3 (try)	70%	70%	70%	Proportion of awake/able people who try to run outside in a significant earthquake
P_4 (coincide)	3%	3%	3%	Probability that people running outside will coincide with the timing of any debris falling above a doorway
Overall	**1.89%**	**0.11%**	**1.05%**	Proportion of time-averaged occupants in the at-risk zone from debris falling outside a building

These are the values used in the V2.0 exposure dataset distributed by NAM on 27 August 2015; they can be scaled at will by appropriate variation of the parameters in Table 2 and will be adjusted as the Falling Hazards risk modelling work progresses in light of further evidence, comment and discussion during the “sense checking” of results.

4.2 Risk Exposure – Objects falling through Roofs

The Falling Hazards risk assessment model considers two particular hazards:

a. Every chimney is assumed to have a small probability (currently 3%) of falling through the roof of the building on which it stands.

b. Any potential hazardous object that could fall from height or at speed onto a roof is considered to have a substantially elevated probability (currently 30%) of falling through the roof.

In each case, the probability of death is estimated simply from the geometry of the falling object as shown in Figure A5.7. For case (b) the object is assumed to fall with the same shape profile through to ground level (i.e. no protection is assumed to be provided by any intervening ceilings/floors – this may be pessimistic for buildings whose upper storeys have concrete floors, but may be quite realistic for large objects falling through wooden floors/ceilings[3]). For case (a) the probability of death for building occupants whose head is in the path of the falling debris is reduced for lower damage states as follows, recognising that smaller objects are unlikely to penetrate ceilings unless they have fallen from some height:

- Damage state 1 (1-3% volume fallen) P(death) = 0
- Damage state 2 (3-10% volume fallen) P(death) = 0.1
- Damage state 3 (10-30% volume fallen) P(death) = 0.5

[3] The authors’ experience with wooden houses penetrated by boulders in Christchurch, NZ in February 2011is that the presence or absence of intervening wooden floors makes little difference to the area at risk from a heavy falling object – there is a degree of protective effect from slowing down the object, but many rooms where boulders came to rest showed evidence of damage beyond the boulder boundary as a result of wooden spars and boards being sent flying by the boulder impact, thus extending its hazard range. Further research into this issue is ongoing.

- Damage state 4 (30-70% volume fallen) P(death) = 0.7
- Damage state 5 (70-100% volume fallen) P(death) = 1

In the first case (a) above, the population at risk is taken simply as the time averaged population inside the building in question.

The second case (b) above may involve one of several scenarios:

i. An object falling from height through a lower roof on the same building (e.g. several chimneys falling from roofs towards conservatories were identified in the Survey)

ii. An object falling from height or at speed onto the (typically lower) roof of a neighbouring building, or

iii. A particularly tall object might fall at speed onto the roof of the building on which it stands.

These scenarios were the subject of much discussion in the early weeks of the Survey, which highlights potentially hazardous objects of all three types, but does not

- Distinguish between any of them in terms of likelihood of penetrating the roof
- Distinguish between the first and third scenarios, or
- Identify onto which neighbouring building the object would fall for the second.

Insufficient time was available for the risk assessment to map all the neighbouring buildings onto which objects might potentially fall. For the current falling hazards model, the simplifying assumption is made that neighbouring buildings are likely to have similar populations. Thus some crude and simple assumptions are used to characterise this risk:

a. Whichever building is at risk from an object falling from height, the population inside the building on which that object stands is taken as the population at risk, and

b. The same probability of roof penetration is used for all highlighted objects.

5. Comparison of Occupancy due to Passers-By and "Runners Out"

Table A5.7 provides a comparison between the number of people in the at-risk zone outside buildings as a function of footfall, using footfall categories as in Table 1, for a facade length of 10m and an average number of residents per house of 2.3 (the approximate Netherlands average).

Table A5.7: Passers-By and "Runners out" Numbers at Risk Outside Houses

Footfall Category	Footfall (typical), N/week	Average Passers-By present	Average Runners-Out present
1	20	0.000	0.024
2	100	0.002	0.024
3	320	0.005	0.024
4	1000	0.017	0.024
5	2150	0.037	0.024
6	4600	0.078	0.024
7	10000	0.198	0.024
8	21500	0.427	0.024
9	46500	1.107	0.024
10	100000	2.381	0.024

For a large majority of residential properties, the footfall category assigned in the Falling Hazards survey is between 2 and 4, suggesting that for most ordinary houses the number of people at risk close to buildings is likely to be dominated by building occupants running out, rather than by passers-by.

Given the relatively high importance of building occupants running outside, the derivation of the P_4 parameter in Annex 1 warrants particular review and discussion.

The situation regarding the third hazard, of people being struck by objects falling through their roof from taller neighbouring buildings, is more straightforward. The average number of people present inside a building where 2.3 people live is of order 1, which is much larger than all but the highest "Average passers by present" shown in Table A5.7. Though relatively few potentially hazardous objects have the potential to fall through roofs from height, such objects make up a substantial proportion of the higher Community Risk objects identified in the V1 Falling Hazards risk assessment. The crude assumptions and survey information used in their assessment thus also warrant further investigation.

6. Conclusions

The following conclusions are drawn:

1. The hazard range for non-structural objects such as chimneys, gables and parapets falling from around roof level is no greater than 5m (in the event of out of plane collapse of whole, strong walls the range could be somewhat greater).

2. People walking past buildings are thus not at significant risk from such falling debris unless their route past the building takes them within 5m of the building facade.

3. The risk is heavily concentrated in the 3m closest to building facades, which should be used as the basis for estimating risk to people walking past outside buildings where the public can approach within 5m of the facade.

4. Numbers of passers-by at risk outside buildings can be estimated with good reliability in relation to buildings (shops in Groningen Centrum) for which reliable footfall data is available.

5. For other buildings, and for estimation of numbers of building occupants at risk by virtue of running outside during earthquakes, reasonable estimates have been made, but the associated uncertainties are considerable.

6. Chimneys generally are considered, should they fall, to have a small chance of falling through the roof on which they stand based on observations from earthquakes.

7. The Falling Hazards Survey identifies and highlights objects considered to have a particularly high chance of falling through roofs (typically lower roof sections of the same or adjacent buildings). The risk assessment applies an elevated probability of falling through roofs for such objects but does not discriminate between them in terms of higher and lower probabilities of falling through roofs.

8. The best current assumption as to the number of people at risk in each building subject to elevated risk of an object falling through the roof is that it is equal to the average number present in the building on which the falling object stands (it is not possible, with the simple information collected in the Survey, to identify uniquely the neighbouring building onto which the object would fall).

There are considerable uncertainties associated with the characterisation of various aspects of the characterisation of numbers of people at risk as outlined above. To date this part of the risk assessment process has received less attention than the characterisation of fragility (probabilities of failure, and proportion of building elements failing). The importance of these uncertainties will be gauged via sensitivity studies on the falling hazards risk assessment results before recommending further work.

The key areas to be explored via sensitivity studies are:

1. Footfall estimates where not supported by shopping data analysis
2. Escape from buildings and its implications for numbers of building occupants at risk through running outside, and
3. Hazardous objects with an identified elevated risk of falling from height through roofs.

Annex 1: Coincidence of Building Occupants and Debris Falling Outside Buildings

Step 2	Estimate the number of people present in those buildings at the time, Nocc					
	Basis - Belgian & NL average of about			2.3	people per household	
	Proportion assumed at home (night)			95%	small % will have been out at work or away	
	Nocc (Liege) =		15160	to	34090	
	Nocc (Heinsberg) =		437	to	8740	
Step 3	Estimate overall probability each occupant was struck & injured by falling debris, based on reports of					
	30	related injuries at Liege, of which		90%	assumed to have been in St Nicolas/Flemalle, and	
	21	related injuries at Heinsberg				
	P(injured,overall, Liege) =		0.001781	to	0.000792	
	P(injured,overall, Heinsberg) =		0.061785	to	0.003089	
	Note - this assumes every contact with falling debris led to injury					
Step 4	"Reverse out" a value of the key parameter Ptim from these overall injury probabilities and sensible estimates of					
	the other parameters in Equation [1]					
	P(able) =		0.02	to	0.1	(both quakes in middle of night between 1 and 3 a.m.)
	P(try) =		0.3	to	0.7	(universally observed that most people try to run outside in quakes)
	P(injured overall) =		P(able) x P(try) x P(tim)			
	So	P(tim) =	P(injured overall) / [P(able) x P(try)]			
	Giving	P(tim) =	0.0113	to	0.297	(Liege)
			0.0441	to	1.000	(Heinsberg)
	(based on minimum P(injured overall) in combination with maximum [P(able & P(try)] and vice versa)					

This appendix provides a very rough and ready calibration of a simple model for the number of people present in the area outside doorways that is at risk from falling hazards, as a result of building occupants running outside in an earthquake.

The model is that the number of people present in the at-risk zone is given by

Nocc = P(able) x P(try) x P(tim) ***Equation [1]***

where	Nocc	is the number of occupants of the building
	P(able)	is the probability that an average person present in a building is awake and able to attempt to run outside
	P(try)	is the probability that an average person who is able to do so will try to run outside when a significant earthquake occurs
	P(tim)	is the probability that, if someone attempts to run outside, their presence in the at-risk area will coincide with debris falling (if this occurs)

P(able) can be estimated reasonably well simply as the ratio of (average time spent in bed) to (average time spent at home) - around 0.5

P(try) is also easy to estimate - this is a universally observed behaviour among a large majority of human beings globally - say 0.8 to 1

This leaves P(tim) as the key uncertain parameter we would like to estimate from observations of earthquakes where people ran out and were killed or injured by falling debris.

The record of injuries in badly affected communities in the Roermond and Liege earthquakes can be used to make some rough estimates as follows.

Step 1 Estimate N2, the number of houses where debris of some sort fell into the space outside a doorway:

N2 =	N1, the number of houses with a damaged chimney
x	M, a multiplier of N1 to scale up to "all fallen debris objects" (including more minor items such as glass fragments and roof tiles) that fell into the space outside doorways.

	For Liege (St Nicolas + Flemalle)			
N1 =	3469			(total DS2-3, Garcia Moreno & Camelbeeck for Liege)
M (multiplier for "all debris")	2	to	20	(assume many more smaller items than chimneys fell, with a high proportion above doorways)
N2 =	6938	to	15602	(no. buildings where debris assumed to have been present above doorways)
NOTE:	*The higher figure for N2 for Liege is truncated to the total number of buildings covered in the Garcia Moreno/Camelbeeck study*			
	For Heisenberg (post-Roermond)			
N1 =	100	to	200	(over 100 cars written off due to damage from fallen chimneys)
M (multiplier for "all debris")	2	to	20	(range found in Groningen falling hazards survey to date)
N2 =	200	to	4000	(no. buildings where debris assumed to have been present above doorways)

NOTE: *The higher the value assumed for M, the lower the value estimated for Ptim*

Appendix 6: Injury Impacts of Falling Masonry

Summary

This appendix provides estimates of the probability of fatal injury arising from impact of falling masonry objects on a person, in the context of the risk to people outside buildings in earthquakes. It is based on research carried out by Florence Pickup and Tony Taig of TTAC Ltd between November 2014 and January 2015, plus development of a related lethality risk model for application to large scale risk assessment of falling non-structural building elements during June to December 2015. The work has been carried out on behalf of Arup Europe and NAM.

Calculations were carried out, based on injury correlations found in a review of literature, to estimate the probability of death in different circumstances from masonry objects striking the human head. A set of incidents involving masonry falling into areas where people were present was identified and analysed to provide practical insight into circumstances that were more or less likely to result in fatality. Separate calculations were carried out to identify the extent of the space in front of a building within which the hazard from falling objects is concentrated.

Our conclusions are as follows

1. The primary fatal hazards associated with falling masonry are of inundation (leading to multiple injuries/crush) and impacts with the head (leading to fracture of the skull or contusion)

2. The hazard from falling masonry outside the wall of a building should be assumed to be uniformly distributed over a band of width 3m next to the building wall.

3. The probability of death as a result of being struck by falling masonry depends on
   - where on the body the impact occurs
   - the mass of the falling object
   - the height from which it falls, and
   - its orientation (edge/corner impacts are significantly worse than flat surface impacts).

4. Probabilities of death as a function of falling object mass and building height have been developed for objects of different sizes, averaged over all possible fall orientations and predicated on impact of any part of the falling object with the head.

5. A simplified model for use in risk assessment has been developed which provides good approximations to those derived using our more complex probabilities of death as a function of object size and fall height. The simple model is based on the assumptions that

    a. The probability of death if a falling masonry object strikes the head is 1, and

b. The area swept out by a falling object as it falls to the ground is calculated as the area swept out by the object based on its worst orientation of fall (such that the area swept out as it falls is equal to the product of longest x next longest sides), multiplied by the percentage of the object falling for a given damage state.

1. Introduction

This appendix supports the development of a model to assess risk to people outside buildings from detached non-structural building parts in earthquakes. The aim of this appendix is to understand the nature and severity of impacts of falling masonry on the human body, and in particular to be able to estimate the probability of death for a given impact or impacts. It has been prepared by Tony Taig and Florence Pickup of TTAC Ltd for Arup Europe and NAM based on research carried out from October 2014 to January 2016.

Detachment of non-structural building components such as chimneys, roof tiles, parapets, dormers, balconies and non-structural wall sections (such as facades, gable ends and the outer leaves of cavity walls) can occur at levels of shaking well below those required to collapse a building, and has caused many deaths and injuries in earthquakes in the past. This was the main cause of non-fatal injuries in the 1992 Roermond and 1983 Liege earthquakes.

To achieve our goal of being able to estimate the probability of death from a given impact, we have explored the nature and severity of impacts on the human body of different types and volumes of debris, falling from different heights, and impacting on different parts of the body. It proved difficult to assemble a large body of information from earthquakes in which these parameters could all be characterised for substantial numbers of people. We have therefore explored various other contexts in which the sensitivity of the human body to impact from hard objects has been studied or can be inferred, and have brought these together to produce a simple quantitative model for application in fatality risk assessment.

The appendix is presented in sections as follows:

- The approach and information sources are described first (Section 2), followed by
- An overview of other studies relating to ballistic impacts on the body (Section 3), and
- Direct anecdotal evidence of the impacts of falling masonry on pedestrians and people in motor vehicles (Section 4),
- A discussion of the findings and relevance of different evidence sources in the context of interest (Section 5), leading to
- Conclusions, in the form of a proposed quantitative model for the risk of death from falling masonry impacts (Section 6).

2. Approach and Information Sources

In the absence of direct information on the consequences of building parts falling from buildings in Groningen province, two main sources of evidence have been explored for this study:

a. A review of literature on the impacts of hard objects generally on the human body, with a particular focus on large blunt objects striking the head, and

b. Anecdotal experiences of situations in which reasonably well characterised masonry or similar materials have fallen in places where people were present either on foot or in motor vehicles.

There is a substantial literature on the injury consequences of contacts between the human body and hard blunt objects, in contexts including

- Road traffic accidents
- Impact of blast fragments
- Design of non-lethal weapons for crowd control
- Design of protective helmets (from sporting to military purposes)
- Causes and treatment of blunt trauma injuries generally
- Workplace accidents, and most recently
- Risk of impact of small remotely-controlled aircraft on people.

Relevant literature has been reviewed, and selected models have been applied to estimate the range of lethality that might be anticipated from the impact of masonry missiles on the head, which is clearly identified in all these studies as the most vulnerable part of the body. This material, which is not specific to masonry impacts on the body, is presented in Section 3 of the report.

In parallel, a more substantial piece of primary research has been carried out to identify and characterise incidents in which masonry or similar objects fell into spaces where people were present. Such incidents occur frequently in countries where masonry buildings are common, typically for reasons including storms, poor building maintenance, accidents during work on buildings, and of course earthquakes. This study involved using internet search engines with combinations of search terms relating to

The object that fell: *in combination with*	Brick, masonry, tile, dormer, parapet, concrete
Nature of event: *and*	Fall, falling, collapse, accident, incident, impact
Human outcome:	Death, injury, injured, killed, near-miss, lucky escape

The searches were carried out primarily in the English language using Google. Incidents were selected in which it was possible to characterise reasonably well

- the nature and scale of the object that fell
- the height from which it fell
- who was present in the vicinity of the fall
- where on the body any impact occurred, and
- the resulting outcome in terms of injury severity or death.

More limited searches were then carried out using Spanish, German, Italian and French phrases, from which it was clear that, given sufficient time, a very much larger body of anecdotal material could be collected if desired. A similar secondary search was conducted of incidents involving people in motor vehicles to provide a complement to the (pedestrian-dominated) incidents identified in the initial search.

A dataset of 156 incidents, representing 97 fatalities, 165 other injuries and 24 near-misses, was collected in this way and is described and analysed in Section 4.1 of the report. Clearly, the anecdotal nature of this search means that there can be no expectation of being able to estimate the frequency of different types of incident via this process. What does emerge are some interesting observations on the link between the scale of the falling object, the height from which it falls, the part of the body impacted and the lethality of the event (probability of death).

Two further, smaller datasets were available from previous studies in New Zealand carried out by one of the authors (T Taig). These were

a. An analysis of the fatalities occurring as a result of failures of unreinforced masonry (URM) buildings during the 22 February 2011 Christchurch earthquake, compiled from the Royal Commission hearings into each building which caused fatalities, and

b. An anecdotal internet survey of the impacts of rockfall onto motor vehicles carried out in the context of assessing the risk of rockfalls in the Port Hills area of Christchurch onto local roads.

The information gained from these studies is also described in Sections 4.2 and 4.3 of the report.

Finally, during checking of the Google-based survey for Section 4.1, another anecdotal list of incidents in which masonry components had fallen from buildings was discovered. This had been prepared by the UK-based property consultancy TPS (a subsidiary of Carillion plc) in the context of demonstrating the importance of building maintenance in avoiding dangerous incidents, and covered 77 incidents, including 9 fatalities, occurring in the UK from 2000 to 2014. Section 4.4 of the report provides a high-level overview of the TPS dataset and a capture-recapture analysis (carried out on the assumption that it and the TTAC dataset described in Section 4.1 were completely independent of each other) from which a rough estimate has been made of the frequency of serious incidents involving falling masonry in the UK.

The information presented in Sections 3 and 4 of the report is discussed in Section 5 in the context of lethality of detached non-structural masonry components of buildings in earthquakes, and a simple quantified model for the lethality (probability of death) resulting from a given masonry impact on a person in the path of such an object is presented.

3. Non-Masonry-Specific Impacts on the Body

Deaths and injuries from falling masonry in earthquakes largely appear to involve either inundation of the whole body by building debris (responsible for most of the deaths associated with URM building failure in the Christchurch February 2011 earthquake for example), or head and upper body injuries resulting from falling roof tiles, bricks and smaller sections of masonry (responsible for most of the injuries in the Liège 1983 and Roermond 1992 earthquakes for example).

There is little uncertainty surrounding the fate of people unfortunate enough to be overwhelmed or inundated by masonry debris in the event of major building collapses or out of plane failure – their chance of survival are remote unless they are sheltered in some way from the falling debris. Of more interest in the context of falling hazards associated with non-structural building components is the fate of people struck on the head or upper part of the body by smaller fragments of masonry. This has therefore been the focus of a brief review of literature described below (3.1) and of example calculations using published correlations between the attributes of moving objects striking the head and death or serious injury (3.2).

3.1 Overview of Literature

Blunt trauma injuries account for a large proportion of accident and emergency admissions to hospitals, arising from falls, road accidents, sports injuries, violence and other accidents, so are extensively studied. In the context of falling masonry impacting on the head and upper parts of the body, major areas of study including road accidents and falls were not reviewed in detail. The major sources of information reviewed relate to

- Traumatic brain injury generally,
- The effects of fragments produced by blast,
- Non-lethal kinetic weapon projectiles,
- Design of combat or sports helmets, and
- Impact of small unmanned aircraft.

The lethal effects of the impacts reviewed are generally associated with impacts either on the head or on the thorax (as the context in most of these situations is that of missiles impacting people from the side or front rather than, or as well as, from above). The head is considered much the more likely source of serious injury in the context of falling masonry so is the primary focus of the following brief review.

3.1.1 Head injury from hard object impacts

A good overview of traumatic brain injury is provided by the US National Institute of Child Health and Human Development[1]. The two types of injury of relevance in the context of blunt object impacts are skull penetration and contusion (where the brain is damaged by impact with the inside of the skull). The outcomes range in either case from concussion to serious permanent injury to death.

The scale and severity of such injuries in the Netherlands is addressed in a recent (2013) Veiligheid NL factsheet[2]:

- About 85,000 people in the Netherlands suffer traumatic brain injury annually, of whom
- About 20,000 are admitted to hospital with brain injuries resulting from an accident or violence, and
- Just over 1,000 die from such injuries each year.

About a third of all the hospital admissions are associated with road accidents, most of which involve impacts with relatively massive bodies. But nearly half involve falls (largely among elderly people and young children), and a further 10% involve sporting impacts, where the momentum involved corresponds to that of a human body moving relatively slowly in comparison with the speed of a brick falling from a house.

The simple observation from the Veiligheid NL factsheet is that in comparison with most other types of injury associated with accidents, traumatic brain injury is of relatively high lethality (over 1% of all victims of any such injury, and around 5% of the numbers admitted to hospital, dying annually). To find correlations between what strikes the head and health outcomes we need to explore some of the other more context-specific sources.

3.1.2 Blast fragments

Falling building debris is identified in a review for the UK Health & Safety Executive[3] as the second largest cause of death (after bomb blast and shrapnel impacts) in air raids involving the bombing of occupied buildings. The same review notes that in the event of people surviving the immediate impact of being buried by debris, their chance of survival fall rapidly with the time for which they remain buried.

This HSE review notes that there is very limited data available on the impact of blunt missiles on the human body, but links speed of direct impact of a blunt 10lb (about 4.5 kg) projectile on the head to effects as shown in Table A6.1, from an earlier publication[4]:

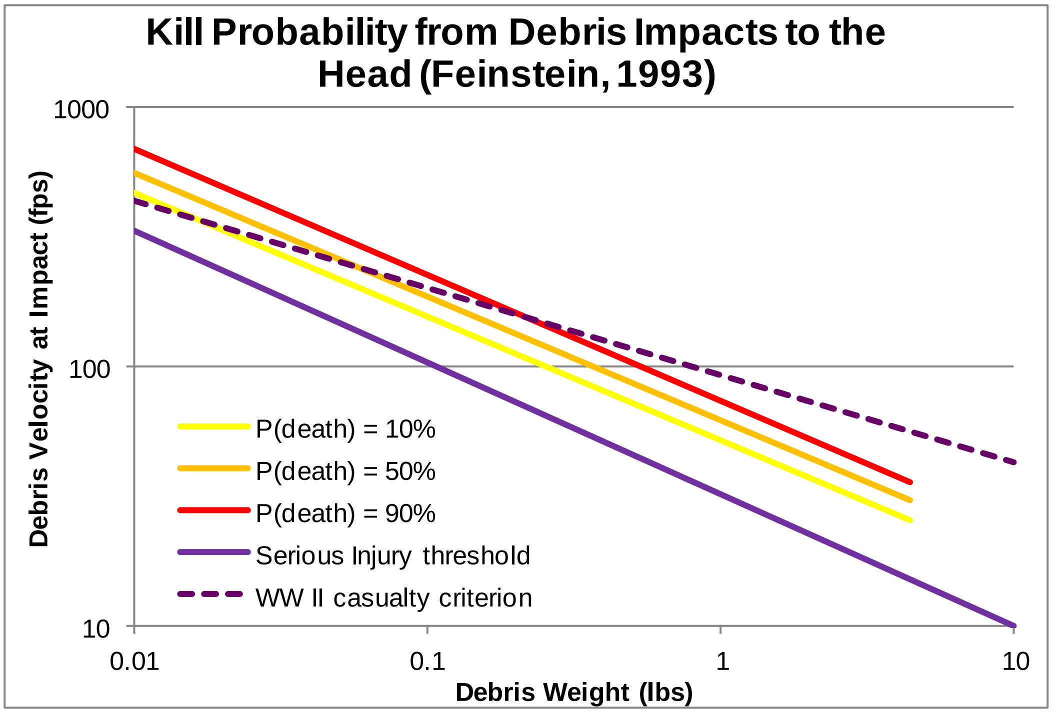
Table A6.1: Injury Outcomes – Direct Impact of a Blunt 10lb Missile on the Head

Injury Outcome	**Impact Velocity (feet/s)**
Cerebral concussion – mostly safe	10
Cerebral concussion – threshold for lasting/lethal effects	15
Skull fracture – mostly safe	10
Skull fracture – threshold for lasting/lethal effects	13
Skull fracture – nearly 100% mortality	23

10 lb is about the weight of a very large brick (as used in some large older buildings such as churches); a typical brick used in house construction in the Netherlands would be somewhat lighter (typically around 2kg or a little more). The impact speeds in the Table A6.translates into heights from which a 10lb projectile would have to fall to cause fatality from just under 1m (threshold to fracture) up to about 2.5m (near 100% mortality).

Feinstein[5] reviewed available experimental evidence (dating from the early 20th century to 1966) based on the impacts of blast debris on dogs and human cadavers) and produced correlations between missile mass, speed and injury outcomes for impacts on various parts of the body. His findings for impacts on the head are shown in Figure A6.1, with the inclusion (as in the Feinstein paper) of a casualty criterion used during the 2nd World War. (Note the US Imperial units in Figure A6.1 – feet per second on the vertical and pounds weight on the horizontal).

Figure A6.1: Lethality of Blast Fragment Impacts on the Head



Note that the upper weight limit of Feinstein's correlations (the yellow, orange and red lines in Figure A6.1) is about 2kg, so application of these correlations to bricks is close to the limit for which this was intended. These correlations are used in Section 3.2 to provide a possible basis for estimating the probability of death from a falling brick.

3.1.3 Non-lethal kinetic weapon projectiles

In recent decades there has been great interest in the development of non-lethal weapons for crowd control, and much associated concern over the possibility of projectiles used in such weapons causing death or serious injury. While the projectiles involved are typically lighter and smaller than typical masonry fragments, there has been considerable attention paid to how best to scale results of experiments on human cadavers, animals, and both mechanical and mathematical models of the human head to cover a wide variety of projectile weights and impact velocities.

Oukara et al[6] recently reviewed different approaches for predicting the lethality of a projectile impacting on the human head. Their starting premise was that further direct experimental evidence on human cadavers (beyond that obtained by Raymond et al – see below) or animals was unlikely to become available for various ethical and practical reasons, so they set out to compare different alternative ways to estimate particle lethality.

The methods compared were

- a French approach involving measuring the forces involved when a projectile impacted on a flat wall
- the Strasbourg University Finite Element Human Head Model (a mathematical model), and
- the Ballistics Load Sensing Headform (a mechanical surrogate model of the human head, available commercially).

The conclusion was that the results from all three models were comparable and (with appropriate calibration) should provide a good way forward for estimating lethality probabilities for risk assessment.

Within the time and resources available for this assessment it was not considered feasible or worthwhile acquiring the relevant mathematical or mechanical models in order to estimate injury impacts of falling masonry on the head. Instead, a correlation based on the Blunt Criterion was used, based on the work of Raymond et al[7]. This team carried out direct experiments involving impacts of a 38mm projectile weighing just over 100g with the heads of human cadavers post-mortem. A range of impact velocities was explored and different possible correlations were explored as predictors of whether skull fracture (which occurred in 7 out of 14 tests) would occur.

The best correlation was found to be obtained using the Blunt Criterion (BC), which is defined by the equation

$$BC = LN \{ (mv^2) / (2M^{1/3}TD) \} \qquad [1],$$

where m is the mass of the projectile (kg)

v is the projectile velocity at impact (cm/s)

M is the mass of the head (kg)

T is the thickness of the soft tissue and skull at the impact location (cm), and

D is the projectile diameter (cm).

The Blunt Criterion is based on US military research dating back to the 1970's (see 3.1.4 below). It combines the kinetic energy of the projectile (the numerator of equation [1]) with a term accounting for the energy-absorbing impact of soft tissue and bone (the denominator of equation [1]). It is predicated on the assumption that the projectile mass is very much less than the mass of the target object, so that the impact stops the projectile without accelerating the target.

The Blunt Criterion was applied in the study of impacts on the body of small unmanned aircraft (see 3.1.5 below) and is used in Section 3.2 to provide an estimate of the probability of impact from a falling brick leading to fracture of the skull.

3.1.4 Design of helmets and armour

There is an extensive literature on the more effective design of helmets and armour for protecting against head injury in the context of sport, motorcycling, combat and law enforcement. Blackman et al[8] provide a very readable overview of traumatic brain injury and what is involved in it, and explain the evolution of the helmet industry's approach to attempting to mitigate the acceleration vs time profile of impacts (building on parallel work in the motor industry). A number of curves are provided relating acceleration/deceleration and duration to the thresholds for and probability of brain injury, and different criteria used and proposed for serious brain injury.

Initial attempts were made to apply acceleration/duration criteria to masonry impacts on the head, but the difficulty in estimating realistic acceleration profiles led to this approach being excluded from the example calculations presented in Section 3.2.

It is notable that the Blunt Criterion evolved from a comprehensive review of animal and human blunt impact data carried out in the context of the design of armour[9].

3.1.5 Impact of Small Unmanned Aircraft

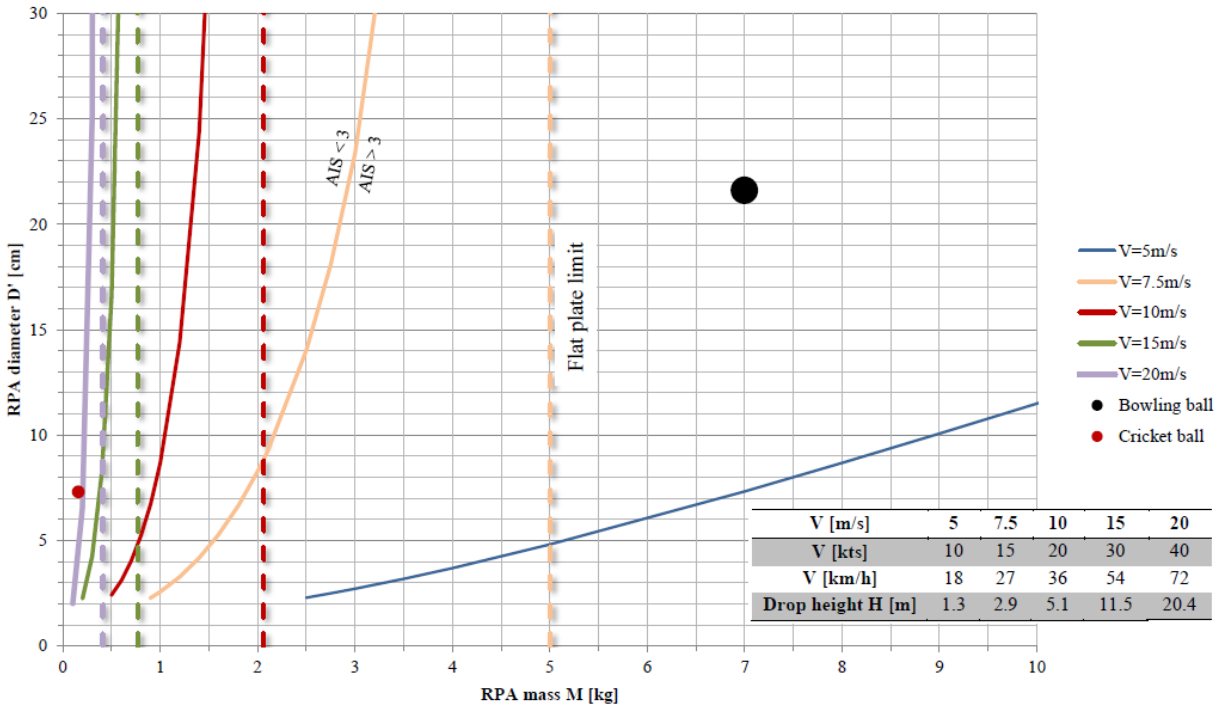
A single relatively recent paper in this area, prepared by the Australian Civil Aviation Safety Authority[10], addresses the injury hazard presented by small unmanned aircraft, which are increasingly being used and proposed for a wide variety of civilian as well as military applications and could be particularly attractive in the context of communication and delivery of small items over large distances to remote communities. This paper was of particular interest as it considers impacts from blunt objects weighing from about 0.5kg up to several kg, moving with velocities comparable with those achievable by masonry falling from buildings (5-30 m/s).

This paper reviews models that have been developed for predicting the lethality of blunt impacts on the thorax and head. It compares

- the automotive crash testing approach (heavy moving objects – crash dummies – with high momentum, and criteria based on forces, moments and acceleration) with
- the approach used for non-lethal projectile weapons (small moving projectiles, criteria based on projectile energy).

The latter is considered more appropriate in the context of small unmanned aircraft. The Blunt Criterion as applied by Raymond et al, see 3.1.3 above, was adapted for this situation to allow for the mass of the impacting object being comparable with that of the part of the body that is impacted. The adapted Blunt Criterion is then used to assess the impact diameter of a moving object that would produce a 50% probability of skull fracture as a function of projectile mass (0-10 kg) for different impact speeds (5-20 m/s) onto the head. The results are shown in Figure A6.2 (note – RPA = Remotely Piloted Aircraft; the RPA diameter is based on a sphere of the given mass impacting onto the head).

Figure A6.2: CASA Results – Impact Diameter vs Impacting Mass on Head (reproduced from reference 10)



The dotted lines in Figure A6.2 show the flat plate limit corresponding to the head being struck by a flat plate of the given mass at the given speed. This provides a bounding case (any other geometry will lead to fracture at lower speed or mass of impacting object).

Figure A6.2 suggests that the probability of skull fracture if impacted by a hemispherical object weighing 1-3kg (the typical range of weights of Netherlands housing bricks) is relatively low, but highlights the sensitivity of skull damage to all three of the parameters (mass, velocity and impact area) of the impacting projectile.

For a large flat object (the limiting case) the CASA model predicts 76 Joules as the maximum tolerable (i.e. without skull fracture) deformation energy of the head during impact with a flat surface. This is considered conservative in relation to experimentally determined values of the kinetic energy required for skull fracture in impact with flat surfaces (a relatively commonly measured parameter in the context of motor vehicle accidents), which are broadly in the range 100-200 Joules.

The CASA approach, with a simplified adaptation of the Blunt Criterion, is used in Section 3.2 to estimate the probability of skull fracture resulting from the impact of different weights of masonry objects falling from different heights and with different orientations.

3.2 Example Calculations

Three groups of calculations are presented here:

a. estimation of the impact speeds of falling masonry with people underneath, and of the range beyond the wall of a building to which this hazard extends

b. use of a simple kinetic energy comparison to provide a rough indication of the range of fall heights that are likely to be more or less lethal, and

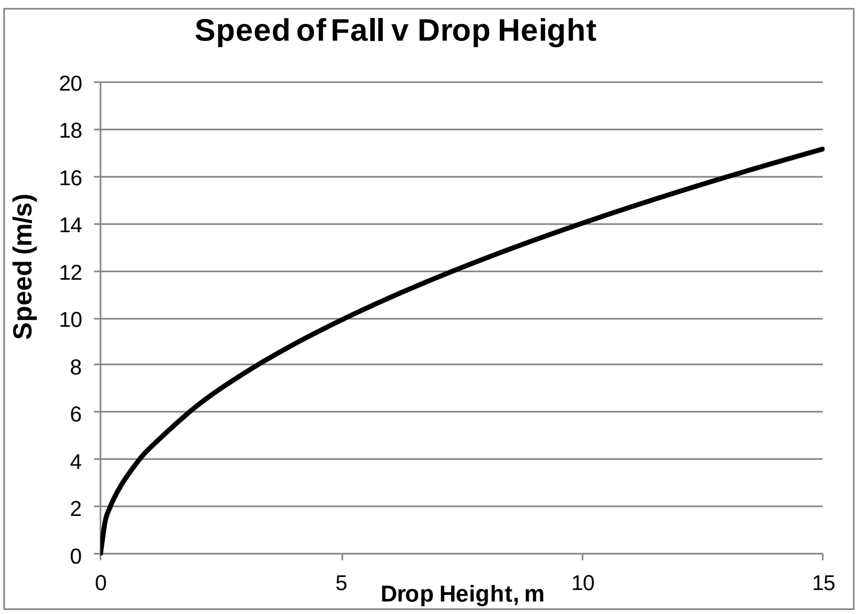
c. comparison of estimated probabilities of various health outcomes using the Blunt Criterion and other criteria discussed in Section 3.1

3.2.1 Masonry fall speeds and hazard range vs height of drop

The speed of fall V reached by an object as a function of the height H from which it is dropped is given (ignoring air resistance, which seems reasonable for falling masonry) is given by

$V^2 = 2\ g\ H$ (as shown in Figure A6.2).

Figure A6.3: Speed of fall vs Drop Height



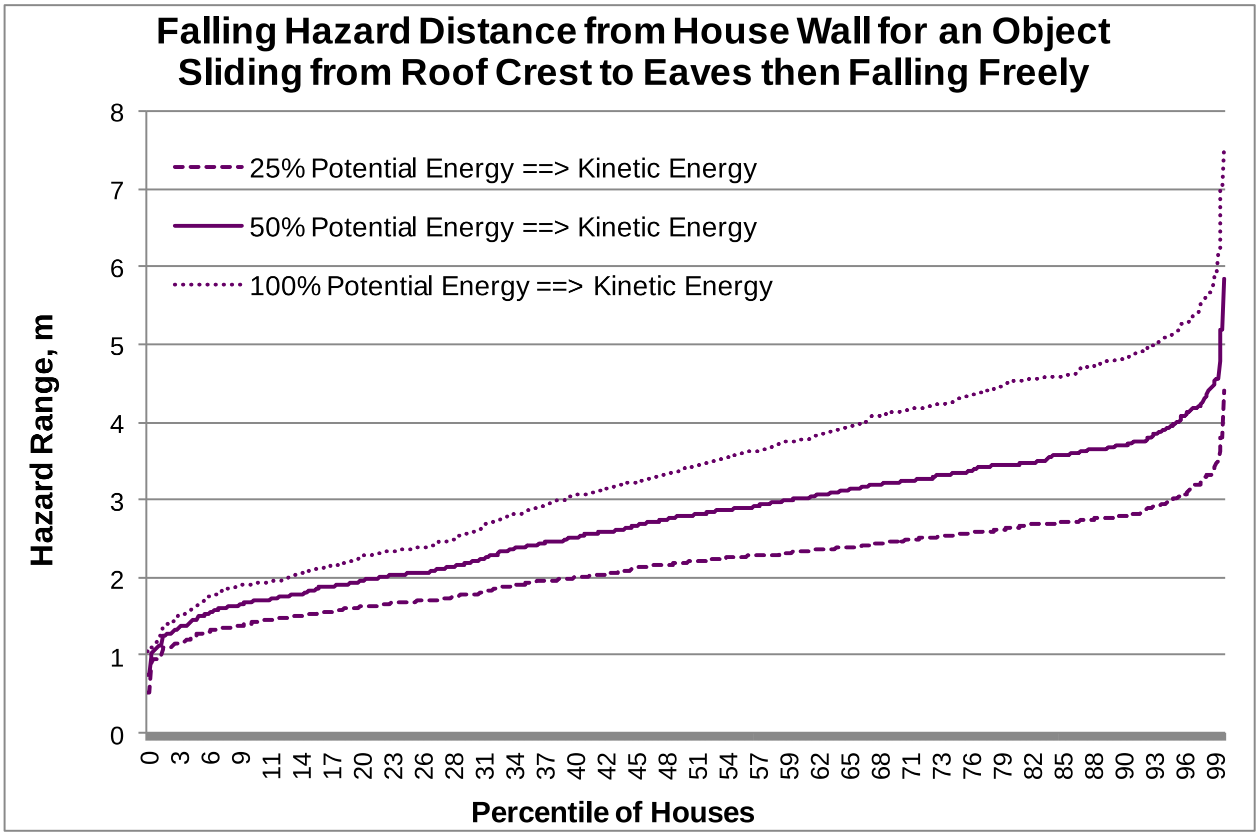
The range outward from the wall of a building for which the hazard of falling objects could extend has been estimated using two approaches:

a. by calculating the dynamics of an object sliding down from a roof crest, then falling freely to the ground once it reaches the eaves, and

b. by calculating the dynamics of an object that topples from the top of a building.

The calculations are described in Appendix 5. Figure A6.4 shows the range of results calculated for about 5000 buildings that had been subject to Rapid Visual Screening (RVS) and for which pairs of values for the difference between roof crest and facade height (i.e. the height of the roof above the facade) and the length of the orthogonal facade were available[4].

Figure A6.4: Falling Hazard Distances for Objects Sliding from Rooves



These calculations are all based on the falling object sliding from the roof crest. The upper curve, assuming perfect conversion of potential into kinetic energy of the sliding object, is clearly pessimistic; the lower curves are considered more realistic, suggesting a hazard range of around 2-3 metres out from the wall or somewhat higher for some buildings.

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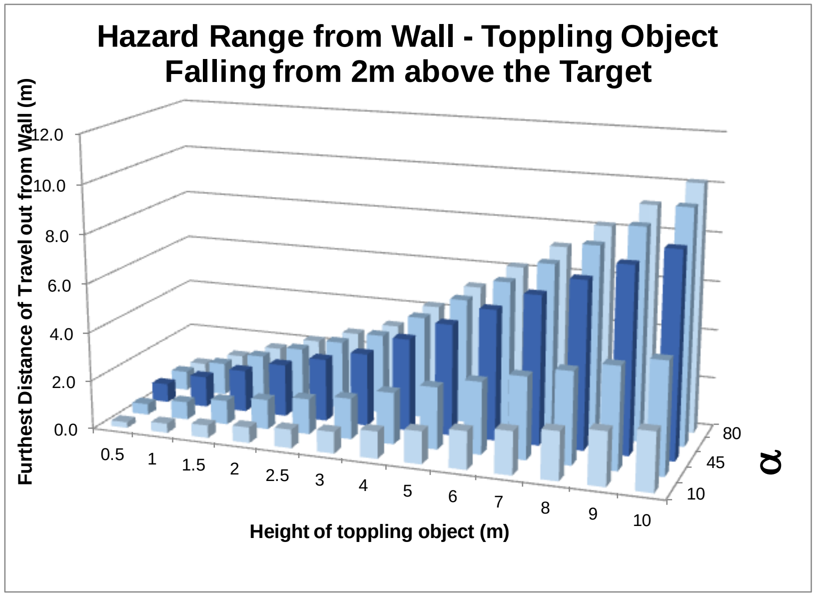
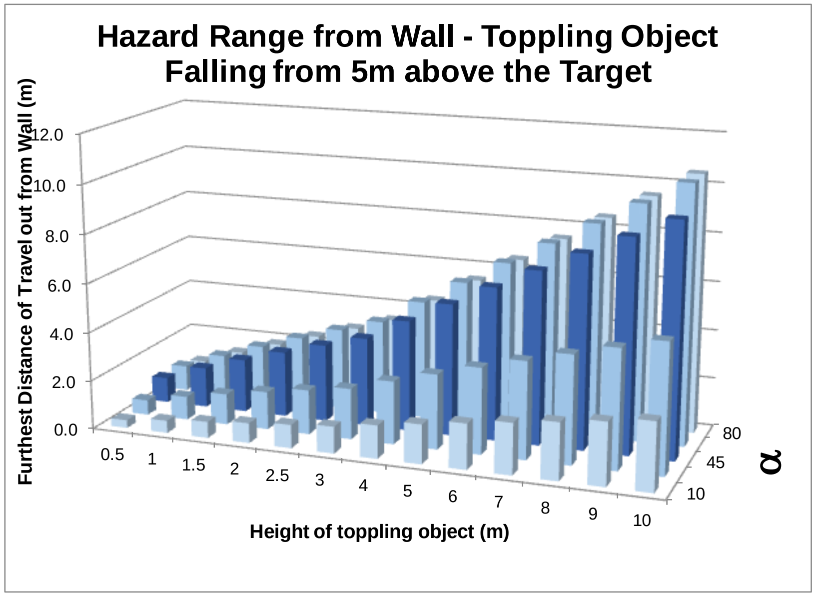
[4] NOTE – there are just 709 of these. The data used takes the roof height (eaves to crest) as the difference between building height and facade height, and the length of the slope of the roof as one half of the length of the facade to right or left of the given facade, ASSUMING the roof is always sloping towards the facade in question. The RVS does not at present record which way the roof is sloping – so this estimation is extremely rough and ready, with 2 main sources of error a) in the assumed dimensions and b) in the assumed roof shape (always sloping towards the facade in question). The proposed revised specification for screening data collection would provide this data; in the meantime this is considered adequate to provide an indication of the likely range of possible travel of falling masonry.

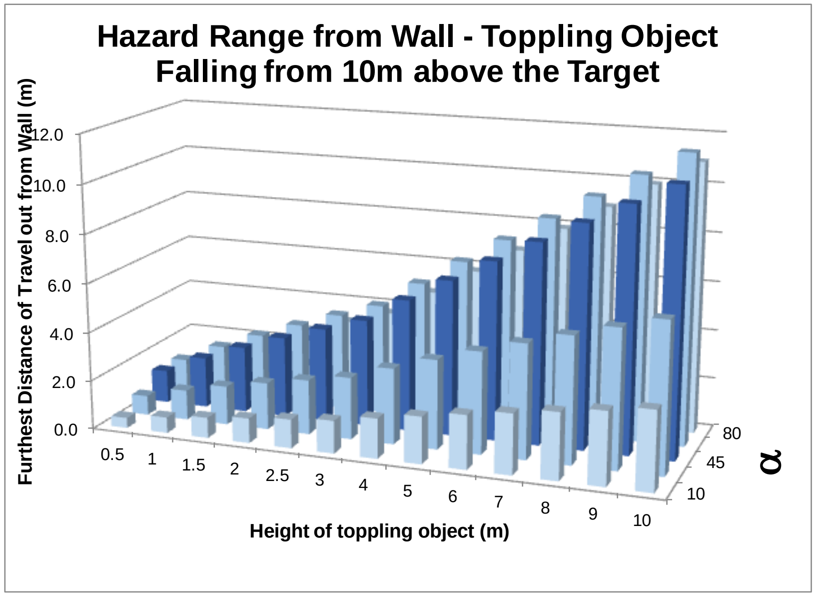
Figure A6.5 shows the hazard ranges calculated for an object of a given height toppling from the edge of a roof, as a function of the height of its base from the ground before falling and the angle of topple α (degrees to the vertical) at which it parts company from the building.

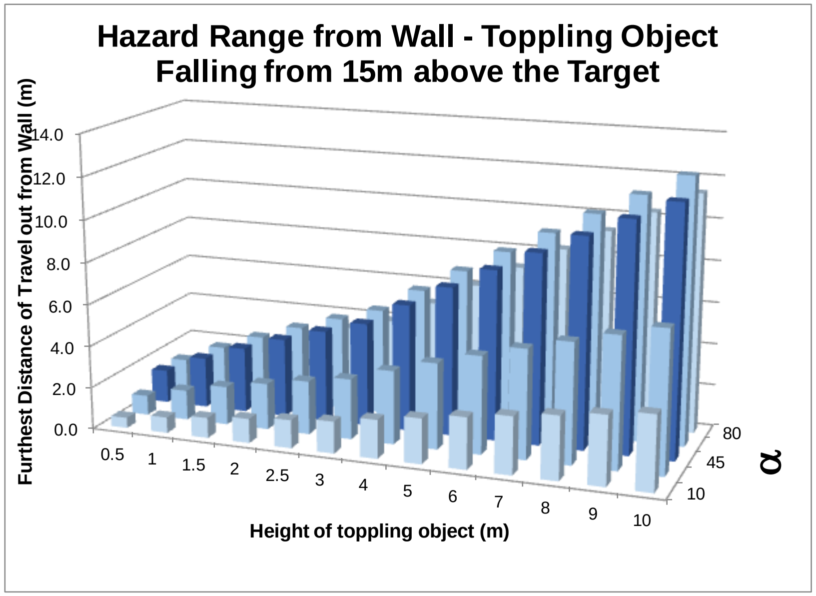
However, to provide a simplified initial basis for modelling the risk from falling hazards our recommendation, based on Figures A6.4 and A6.5 and typical falling object heights, is to assume that the whole of the falling hazard is concentrated within a space extending 3m outward from the building facade of interest.

Figure A6.5: Hazard Range for an Object Toppling from a Building Edge





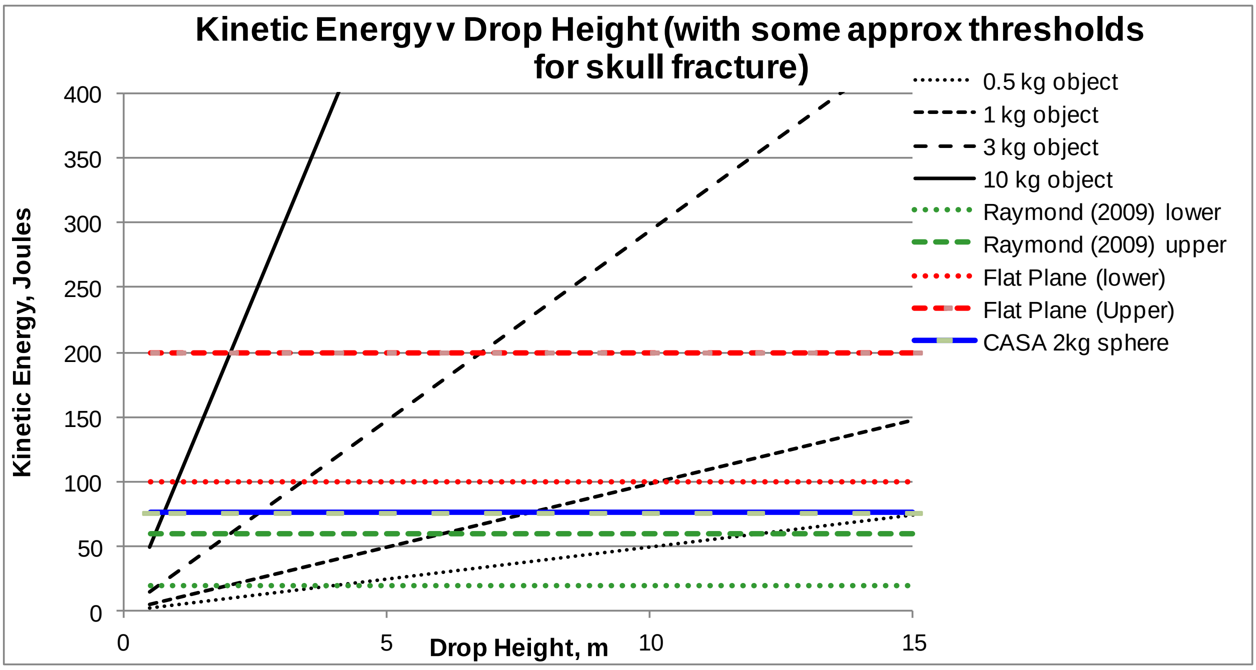




3.2.2 Kinetic energy as an indicator of injury potential

Figure A6.6 shows the kinetic energy of various objects of different mass as a function of the height from which they have fallen, in comparison with some very approximate ranges within which skull fractures have been found to occur.

Figure A6.6: Some Kinetic Energy Comparisons



The sloping lines show the energy of different mass objects as a function of fall height. The horizontal lines show the ranges of kinetic energy required to cause skull fracture:

- in the experiments of Raymond et al, using small diameter projectiles (20-60 Joules, green lines),
- in experiments involving impact with a flat plane shaped object, as reported in the CASA report (see Section 3.1.5 above; 100-200 Joules, red lines), and as estimated by CASA for a 2kg spherical object using the Blunt Criterion.

A masonry object might be expected to behave more like a small projectile if a corner or edge impacts on the skull, and more like a flat plane shaped object if a flat face of masonry impacts on the skull. On the basis of the figure, it appears that

a. an object weighing 0.5kg (smaller than a brick, possibly the size of a small roof tile or fragment) would need to fall from a few metres or more to have significant risk of fracturing the skull even if it fell on edge

b. a 0.5kg object would be unlikely to cause skull fracture even if falling from several storeys height if it impacted with a flat face against the head

c. objects around the weight of a brick or larger tile (1-3 kg for most Dutch bricks, ~1kg for tiles) might pose a significant risk of skull fracture if impacting on the head edge or corner-on from a few metres height, and if impacting face-on against the head having fallen from more than one storeys' height.

3.2.3 Blunt criterion & other injury criteria

The Blunt Criterion was used to estimate the probability of skull fracture for a given mass of masonry object falling onto the head either face-on, edge-on or corner-on (worst case). The probability of skull fracture was interpreted from the results of Raymond (2009) as described in Section 3.1.3, using parameters for the human head as adopted by the Australian Civil Aviation Safety Authority:

- Effective head mass = 6kg
- Effective thickness of skull and soft tissue = 1.3 cm
- Effective diameter of head = 18cm

Effective impact diameters were assumed as follows based on simple calculations of the geometry of a face, an edge or a corner of a rectangular sided object impacting on a sphere of 18cm diameter with a tough covering layer 1.3cm thick:

- Face-on impact: 9 to 15 cm
- Edge-on impact: 3 to 7 cm
- Corner-on impact: 1 to 3 cm.

The resulting estimates of probability of skull fracture vs drop height are shown in Figure A6.7 for objects weighing 1, 3 and 10 kg.

Perhaps the first point of note is the wide range of uncertainty based on applying the data from Raymond et al, as indicated by the 5-95% confidence intervals shown by the lilac bars on the charts.

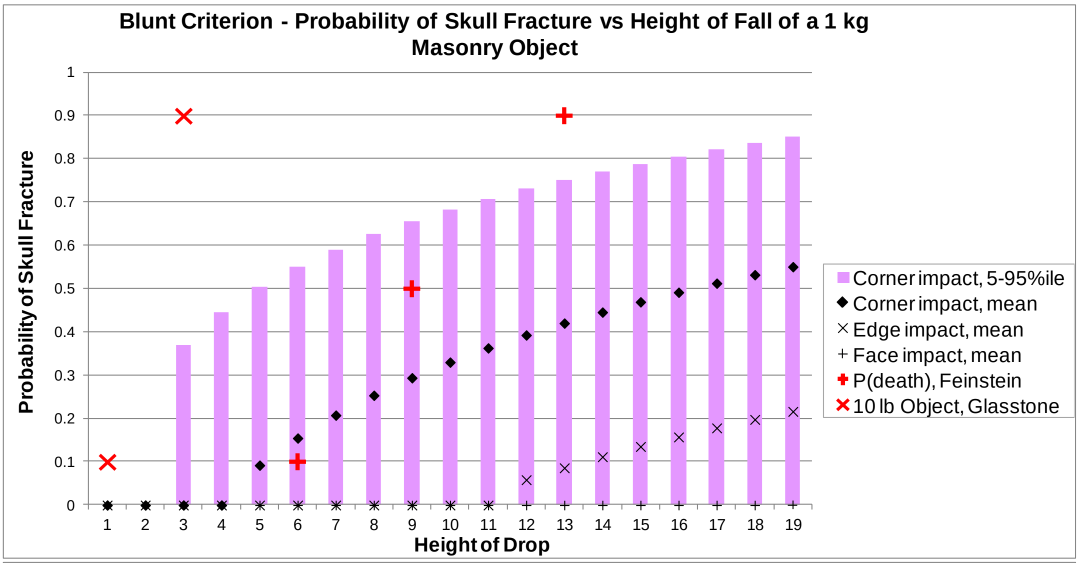
Prediction of skull fracture is not the same as prediction of death, but is considered a reasonable indicator thereof. Not all skull fractures are fatal, but this is compensated for by the proportion of fatal impacts that do not involve fracture.

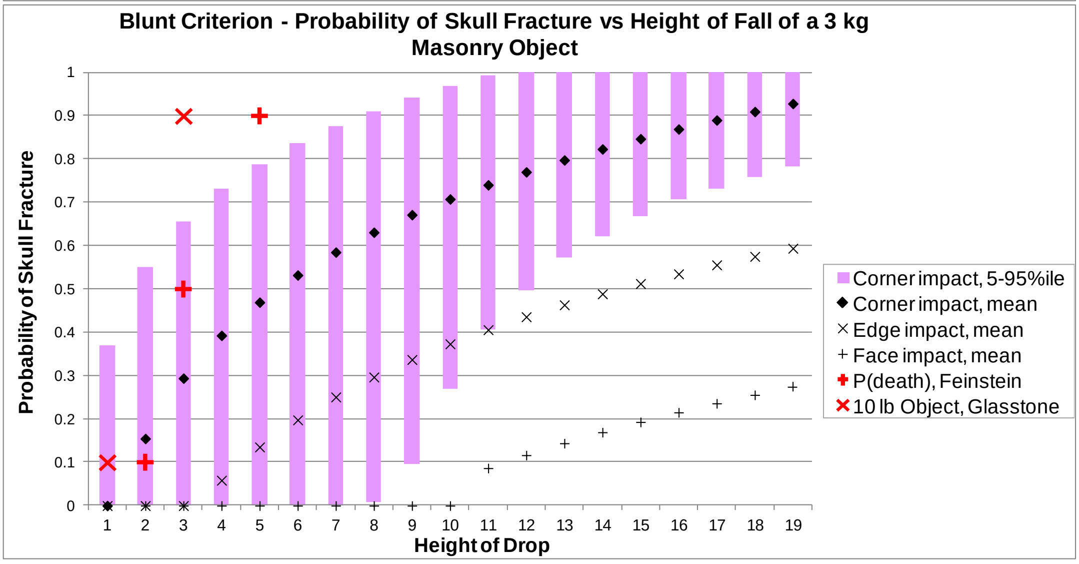
The correlations of Feinstein, which were developed largely from data on small projectiles, are more conservative than those based on the Blunt Criterion, but given the large uncertainties associated with all the criteria illustrated, the results appear reasonable consistent with each other and support the following general conclusions:

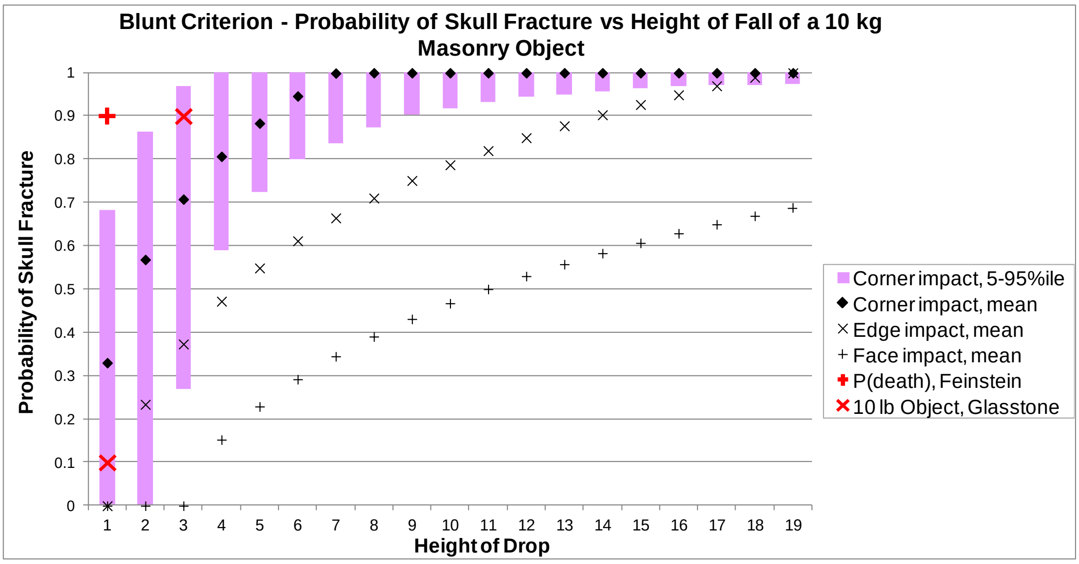
1. Lightweight masonry items of order 1kg or lower are unlikely to prove lethal in worst-case (corner-on) impacts when falling from heights less than 2 storeys, but have up to a few 10's of % probability of causing fatality if impacting edge or corner-on having fallen from multiple storeys height. They are unlikely to be fatal if impacting face-on even having fallen from several storeys height.

2. An object of the weight of a more typical house brick (3kg) could be lethal even in a face-on impact if falling from several storeys, has a good chance of proving lethal if impacting edge or corner-on from more than 1 storey height, and the possibility of being lethal in such impacts even if falling from as little as 1-2m height.

Figure A6.7: Comparison Probabilities of Head Impact Outcomes







3. A heavier object weighing 10kg has a high probability of proving fatal in an edge or corner-on impact even from a few metres height, and a substantial probability of proving fatal in a face-on impact if falling from a height of 2 storeys or more.

These conclusions are reconsidered below in light of observations from real incidents involving injuries sustained from falling masonry.

4. Masonry (& similar) Incident Information

The largest part of this report has involved the collection and analysis of a substantial set of incidents in which people were exposed to falling masonry or similar debris. This analysis is presented in Section 4.1. The other parts of this section provide briefer summaries as follows:

- Of a review of fatalities caused by URM building failure in the Christchurch February 22, 2011 earthquake carried out by T Taig (4.2)
- Of a smaller survey of incidents involving rockfall impacts on vehicles carried out by T Taig in the context of the assessment of rockfall risk for road users (4.3), and
- Of a listing of UK incidents involving debris falling from buildings compiled by TPS Consulting in the context of illustrating the pitfalls of poor building maintenance (4.4).

4.1 Survey of Relevant Incidents

An internet search was carried out and incidents were classified as described in Section 2. Figures A6.8 to A6.11 show how the incidents were distributed in terms of country, worst injury outcome, cause, debris volume and height of fall of the debris. A clear limitation of a survey such as this is that it relies on what has been reported publicly; it is thus expected to become progressively more incomplete for more minor incidents.

As can be seen from Figure A6.8, the search was conducted primarily in the English language; a quick-look scan in several other languages suggested that a comparable set of incidents could be produced for other European countries or other countries where masonry is a common construction material.

Figure A6.8: Incidents Classified by Country and Outcome

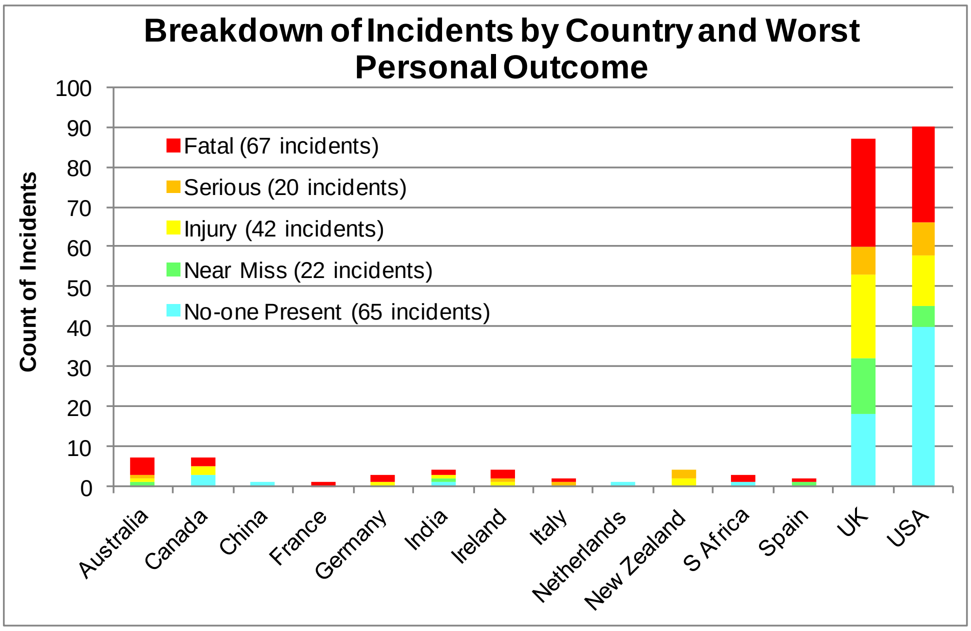


Figure A6.9: Incidents Classified by Cause and Debris Source

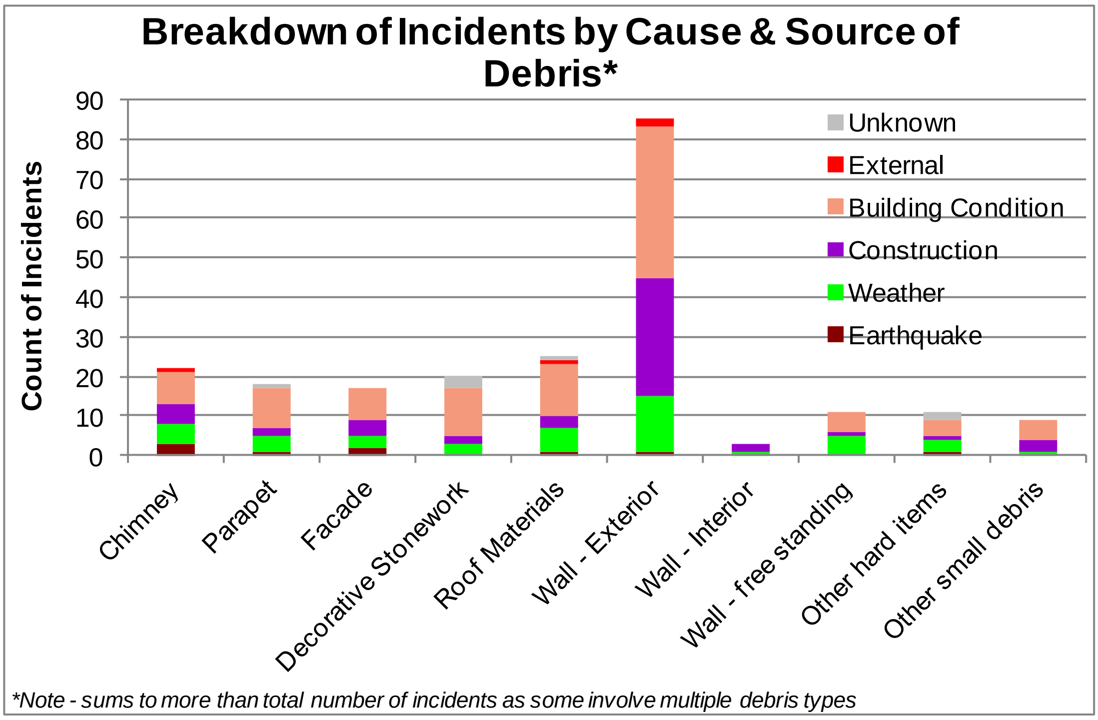


Figure A6.10: Incidents Classified by Debris Sources and Volume

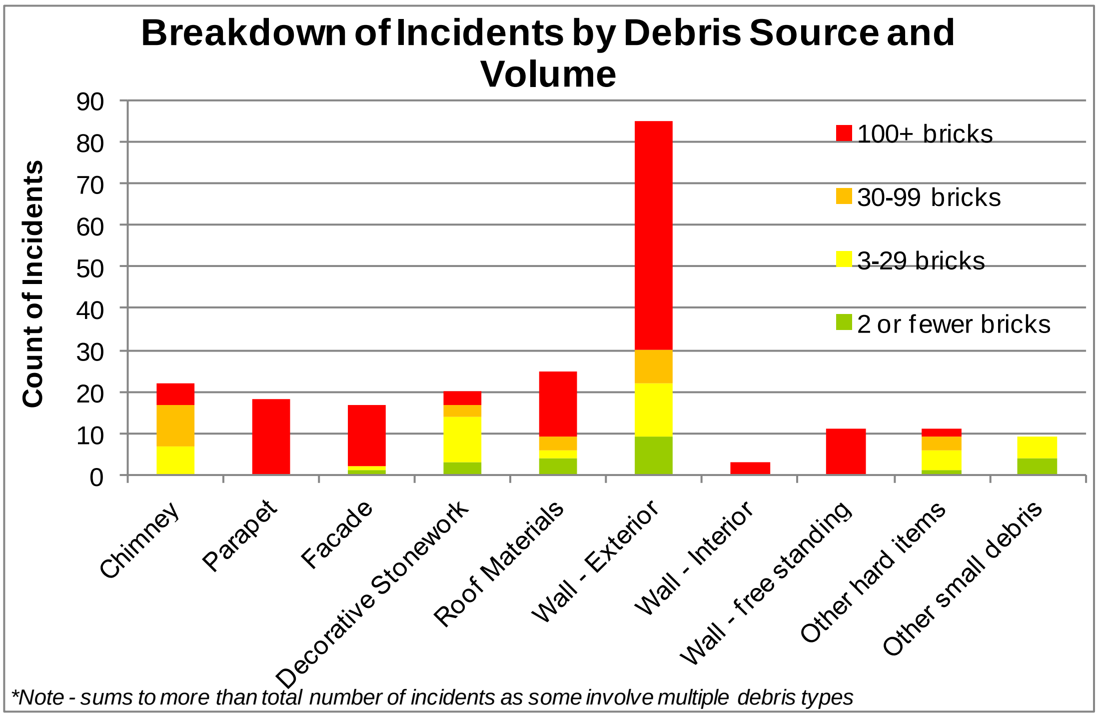
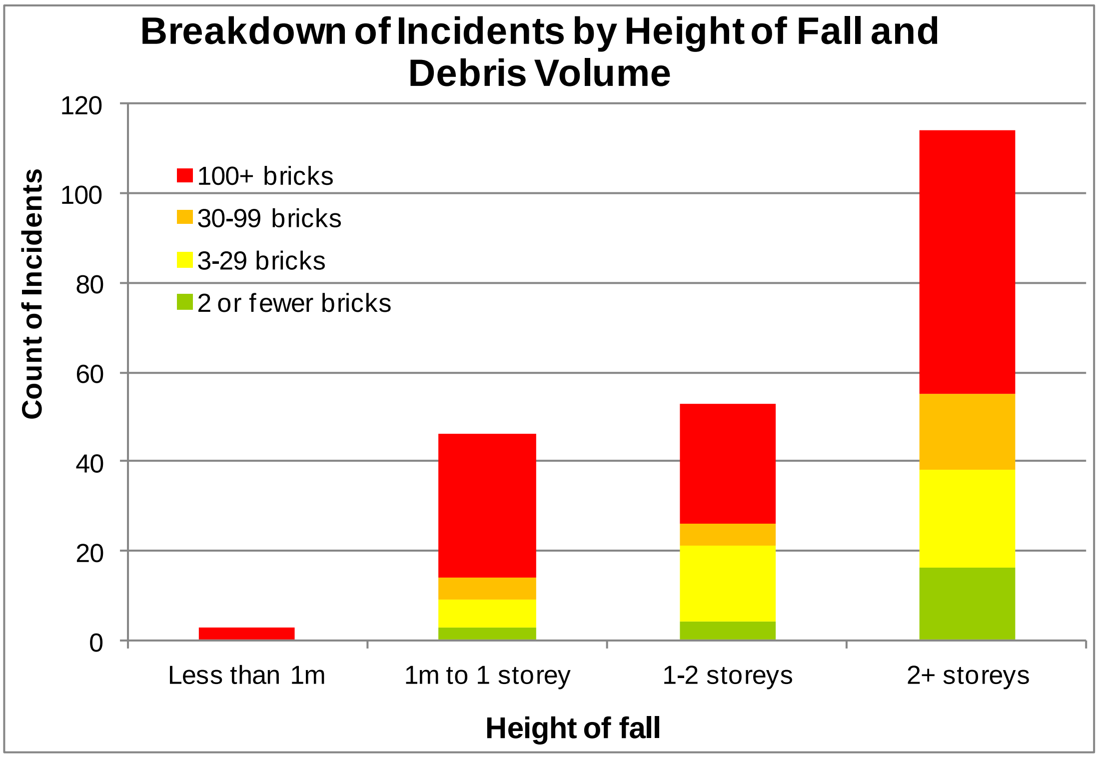


Figure A6.11: Incidents Classified by Height of Fall and Debris Volume



Selected case studies, illustrating the types of incident categorised in various terms, are provided in Annex 1.

The main interest in this survey lies in comparing injury outcomes arising from different types of impact. Figure A6.12 shows the distribution of fatal injuries by volume of debris and where on the body the person was injured (note – this may not always be where they were originally struck by the falling debris – a few cases involved secondary injuries associated with falls after impact).

Figure A6.12 shows clearly that reported fatal accidents are dominated by those involving people being inundated by large volumes of debris, whether on foot or in vehicles. There were no incidents found where injuries to the arms or legs had caused a fatality; this might reflect a greater propensity for incidents to be reported when they took place in busy urban situations than in remote areas where emergency medical care may have taken longer to arrive. Fatal accidents caused by injury to a specific body part were split 20:5 between the head and the torso.

Among the 5 fatal injuries due to impact on the torso, all but one involved large volumes of masonry. The one exception was an incident in which a construction worker was struck by a single brick that had fallen from 4 storeys up whilst bending over, exposing his back to the falling hazard.

Figure A6.12 thus appears to support placing the primary focus of risk assessment from smaller fragments of masonry on impacts to the head, and to support the simple hypothesis that inundation by very large volumes of masonry is very likely to prove fatal.

Figure A6.12: Fatalities by Debris Volume and Location of Injury on the Body

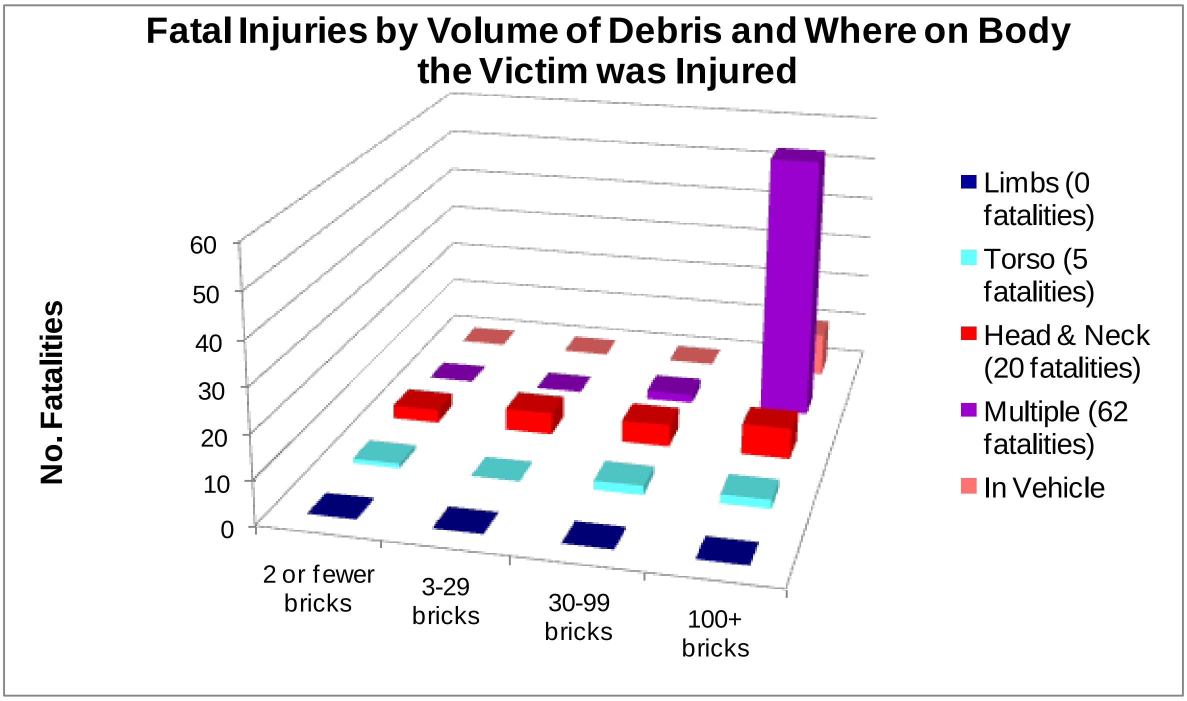


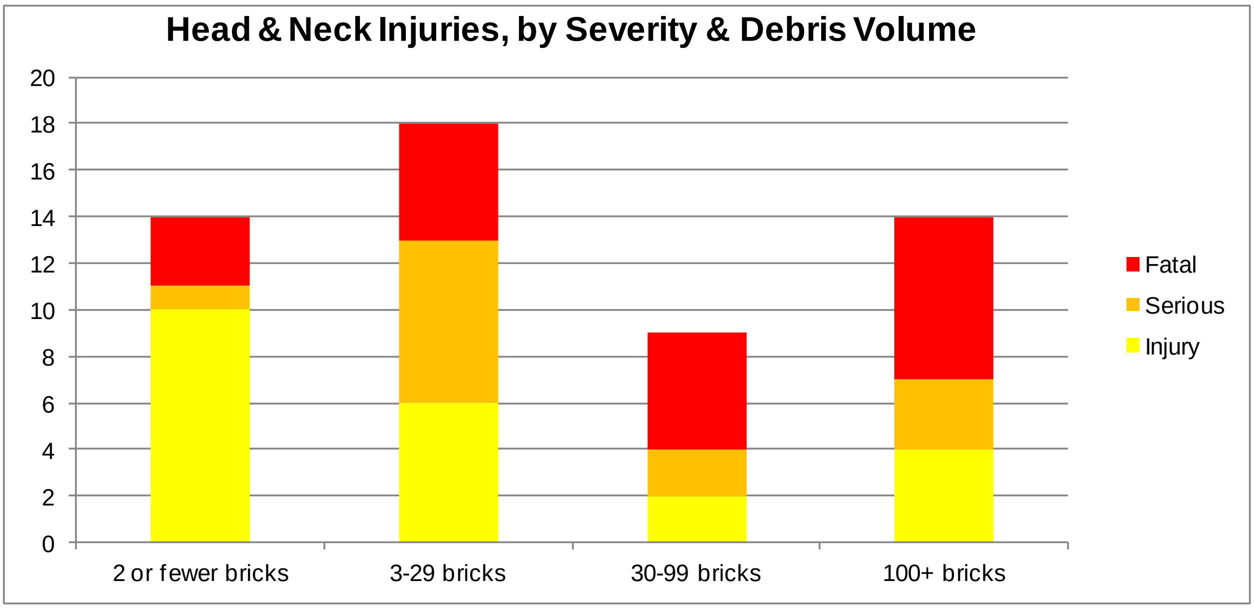
Figure A6.13 shows how injury severity varies with debris volume for injuries to the head and the torso. Note that in many cases it was not possible to establish the severity of injuries from the reports found. “Severe” is used to correspond to “Specified Injuries” in the UK RIDDOR Regulations (2013), of which the relevant categories are

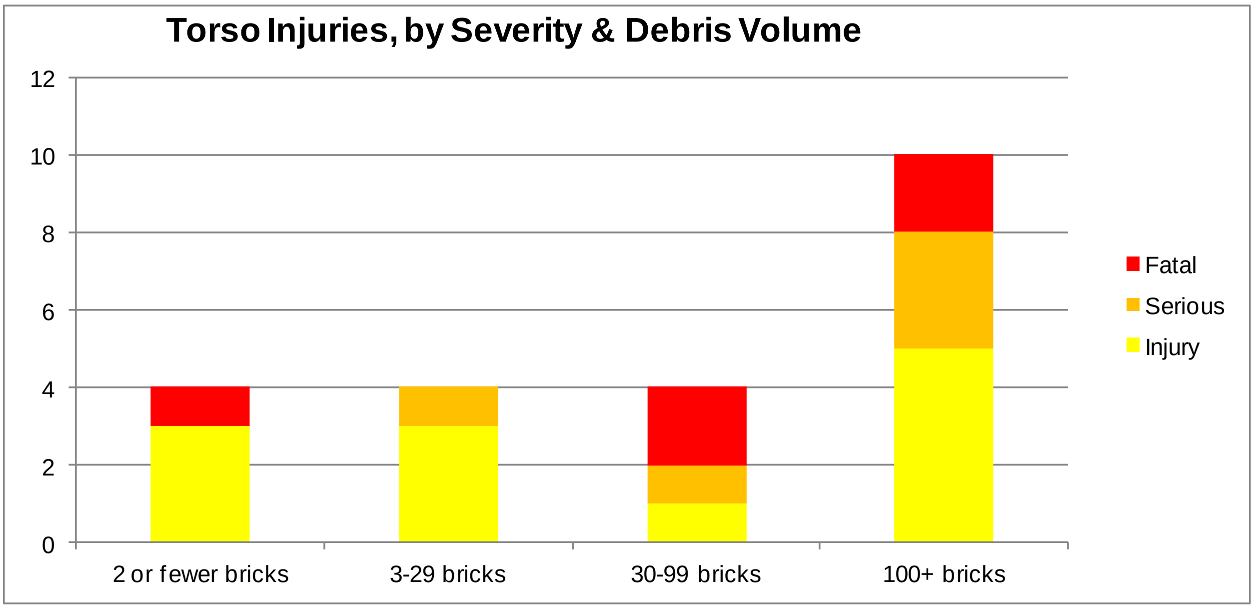
- fractures, other than to fingers, thumbs and toes
- amputations
- any injury likely to lead to permanent loss of sight or reduction in sight
- any crush injury to the head or torso causing damage to the brain or internal organs
- any scalping requiring hospital treatment
- any loss of consciousness caused by head injury or asphyxia.

Figure A6.13 shows an apparently significant difference between injuries to the torso and injuries to the head in terms of the proportion of reported events that are fatal. For head injuries, the proportion fatal increases fairly smoothly with debris volume, from about 20% for impacts with 1 or 2 bricks up to about 50% for very large debris impacts.

It is relatively easy to understand how substantial impacts on the torso could be non-fatal, but less obvious, particularly in light of the discussion in Section 3, how impacts of the larger categories of masonry (the categories are based on UK standard bricks which weigh just over 3 kg, so the ‘3-29 bricks’ category corresponds roughly to 10-100 kg) could be non-fatal. Brief descriptions of the incidents involving masonry in the ‘3 or more bricks’ categories leading to non-fatal impacts on the head are as follows.

Figure A6.13: Relative Severity of Head & Torso Injuries vs Debris Volume





a. A 10m wall collapsed and caused a man to fall down an embankment, where he was found surrounded and part covered by bricks. It is not clear what injuries were caused by direct impact of falling debris and what by the subsequent fall down the embankment.

b. A man smoking outside his home was struck by bricks from a failed chimney which were deflected by impact with sloping roof "otherwise he would have been dead"; he was hospitalised for nearly 2 weeks but recovered.

c. A woman was struck by a brick as walking with fiancée and was paralysed from waist down. Very close to fatal; may never walk again. The masonry block was over 1m long and weighed 70kg (direct impact on head would certainly have been fatal).

d. A student struck by a 1.5kg block that had fallen 15m received life threatening head injuries and spent 20 days in a drug-induced coma after major surgery to remove fragments from his head. He left hospital after 9 months of treatment but will almost certainly suffer long-term brain impairment.

e. A construction worker suffered severe injuries after being hit on the head by a 10kg piece of masonry; he was not wearing a hard hat. The incident was described as "tragic" and his injuries as "life changing".

f. A worker was buried under bricks when a wall collapsed on him. Emergency services responded very rapidly; the man was found unconscious. Outcome not known

g. A 3-month old baby received a fractured skull and was “fighting for his life” after a piece of stone balustrade was detached by council workers erecting Christmas decorations. According to a passer-by the baby’s life was saved by the pram hood which shielded him from the full impact of the debris.

These cases all involve one or other of

- Partial screening or other factors meaning the individual did not bear the full brunt of the impact on their head (a, b, g)
- Severe long-term disability, with their life saved by rapid and intensive medical intervention (c, d, e), or
- Longer term outcome not known (f).

This analysis suggests that it would be mildly, but not unduly, pessimistic to assume that impact of large masonry items (10 kg and upwards) directly onto the head will prove fatal.

The effect of fall height is illustrated in Figure A6.14, which shows fatalities distributed across fall height and volume of debris. Figure A6.15 then shows the proportion of all impacts that were fatal, broken down in exactly the same way.

Figure A6.14 shows that fatal accidents associated with very short fall heights are rare. There were just two such events identified: both involved collapse of a wall. In the first a toddler was killed when a 1.5m long section of wall 1m high fell on him in a garden. In the second a construction worker was killed when a wall and stonework collapsed on him.

A large majority of fatal accidents involved inundation by large volumes of debris (Figure A6.14). Among the fatal accidents not in the ‘100+ Bricks' category, Figure A6.15 suggests there is relatively little difference in lethality (the proportion of impacts that are fatal) between different debris volumes and fall heights.

Figure A6.14: Fatalities by Debris Volume and Height of Fall

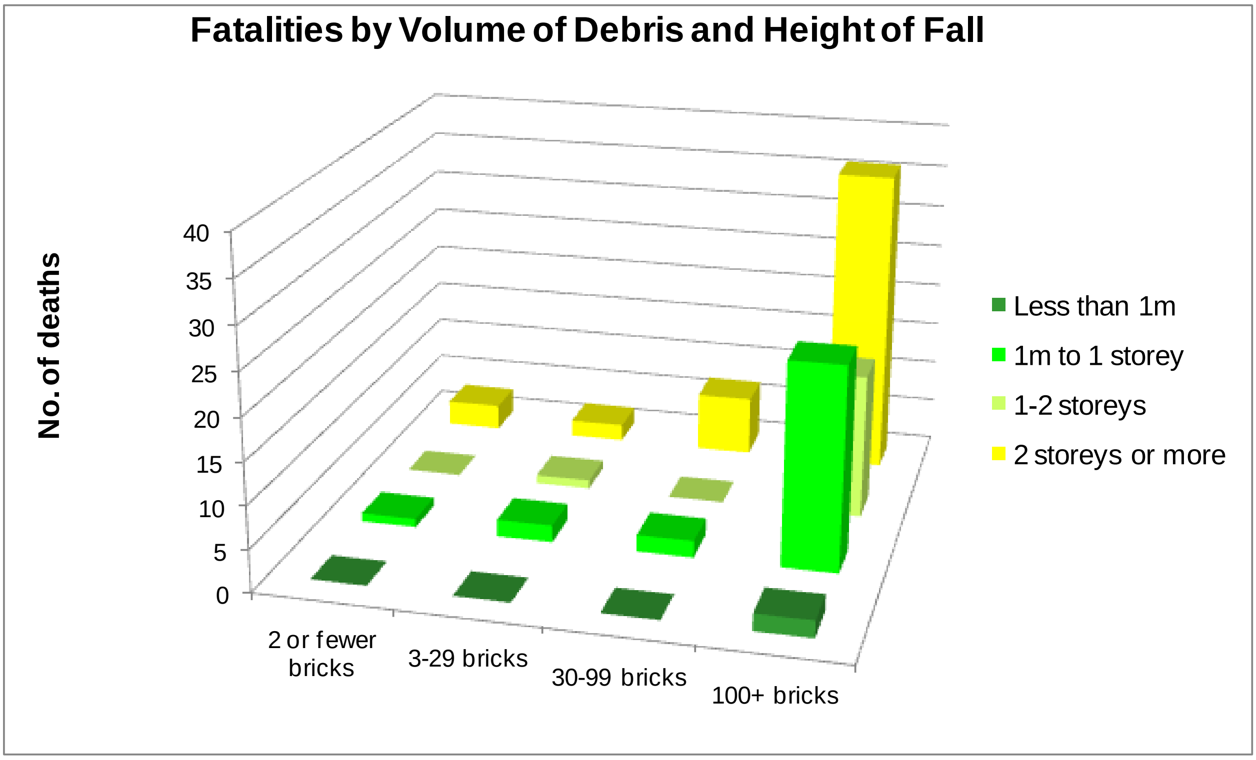
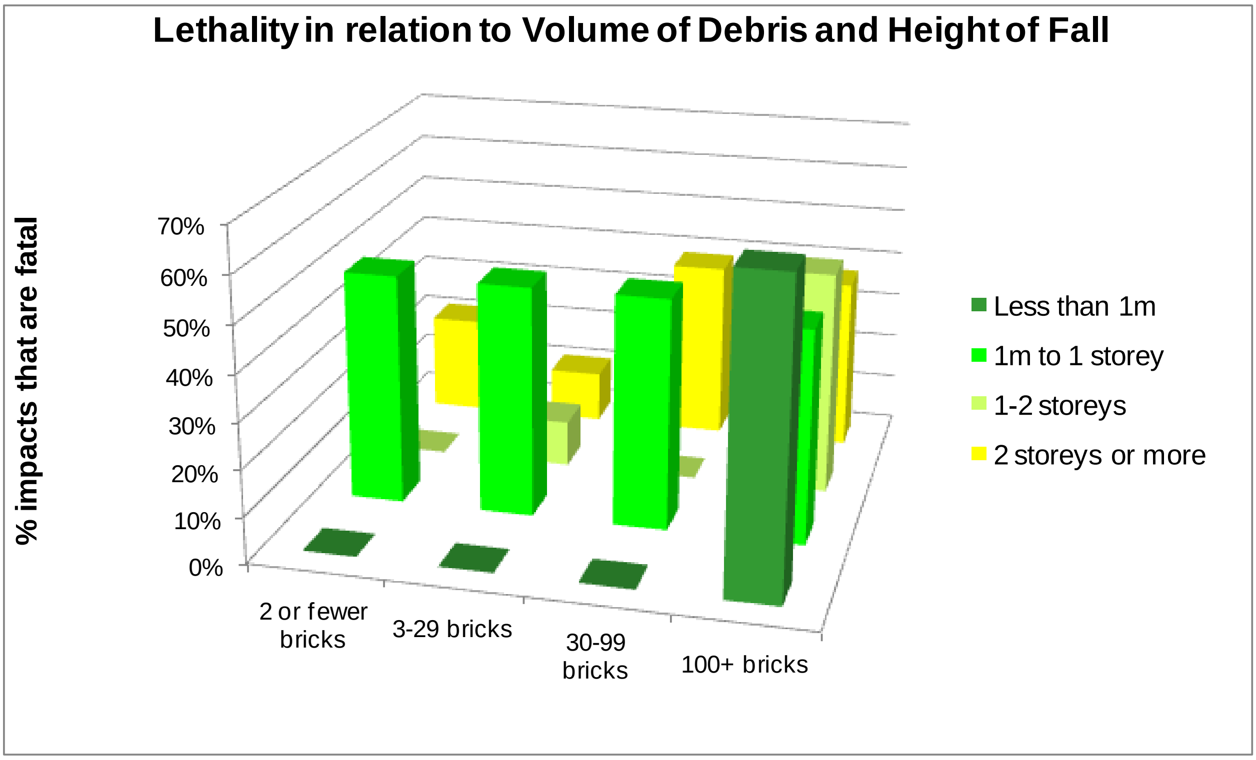
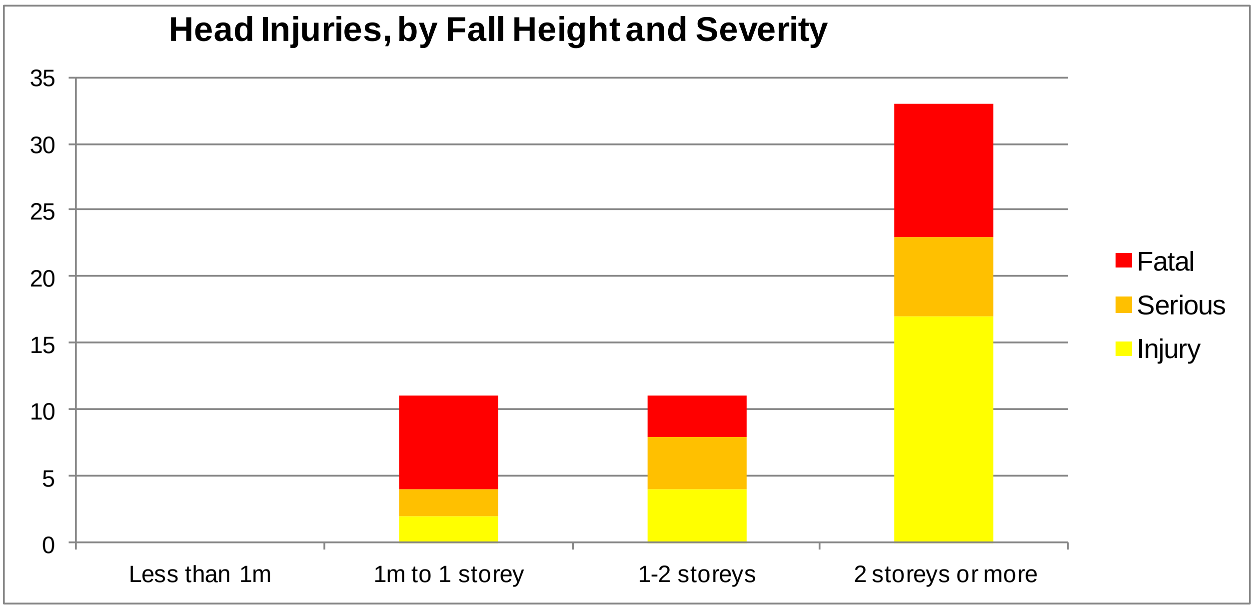


Figure A6.15: Proportion of Impacts that are Fatal, by Debris Volume & Height of Fall



This lack of dependence on fall height is notable again in the breakdown of injury severity with fall height for people struck on the head, as shown in Figure A6.16.

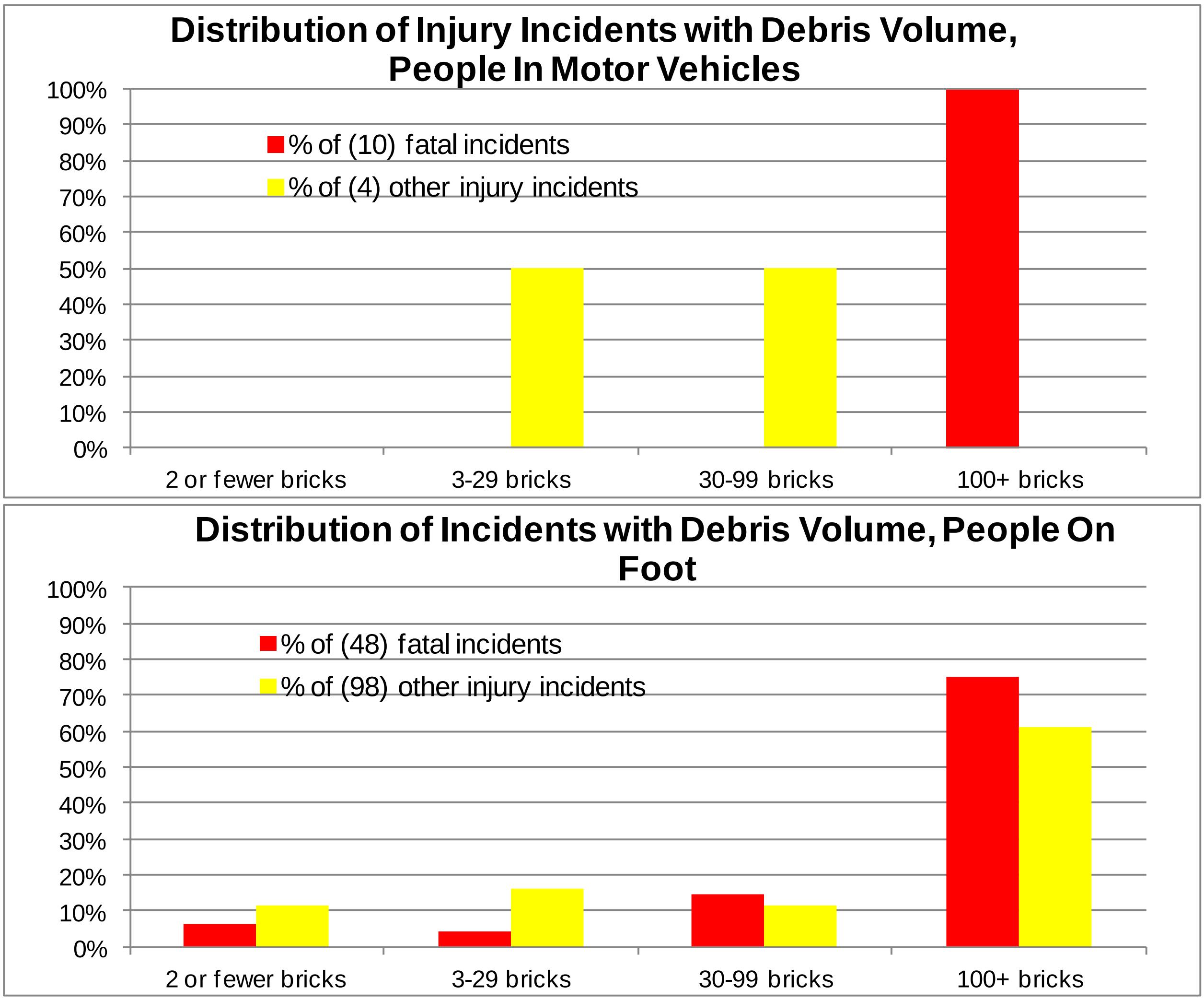
Figure A6.16: Head Injuries by Fall Height and Severity



Although this set of incidents is anecdotal rather than in any sense being "complete" or "definitive", these observations tend strongly to support the conclusions of Section 3, that for falling objects above a few kg in weight, the likelihood of fatality if the head is directly struck is high, so the scope for increase with building height is limited.

Finally, Figure A6.17 shows the distribution of fatal and of other injury incidents across debris volumes, both for people in motor vehicles and for people on foot. Though the number of incidents involving motor vehicles is very small, the absence of fatalities for the smaller debris volumes tends to suggest that motor vehicles may provide some degree of protection against smaller masonry impacts.

Figure A6.17: Injury Distribution with Debris Voume – Motor Vehicles vs Pedestrians

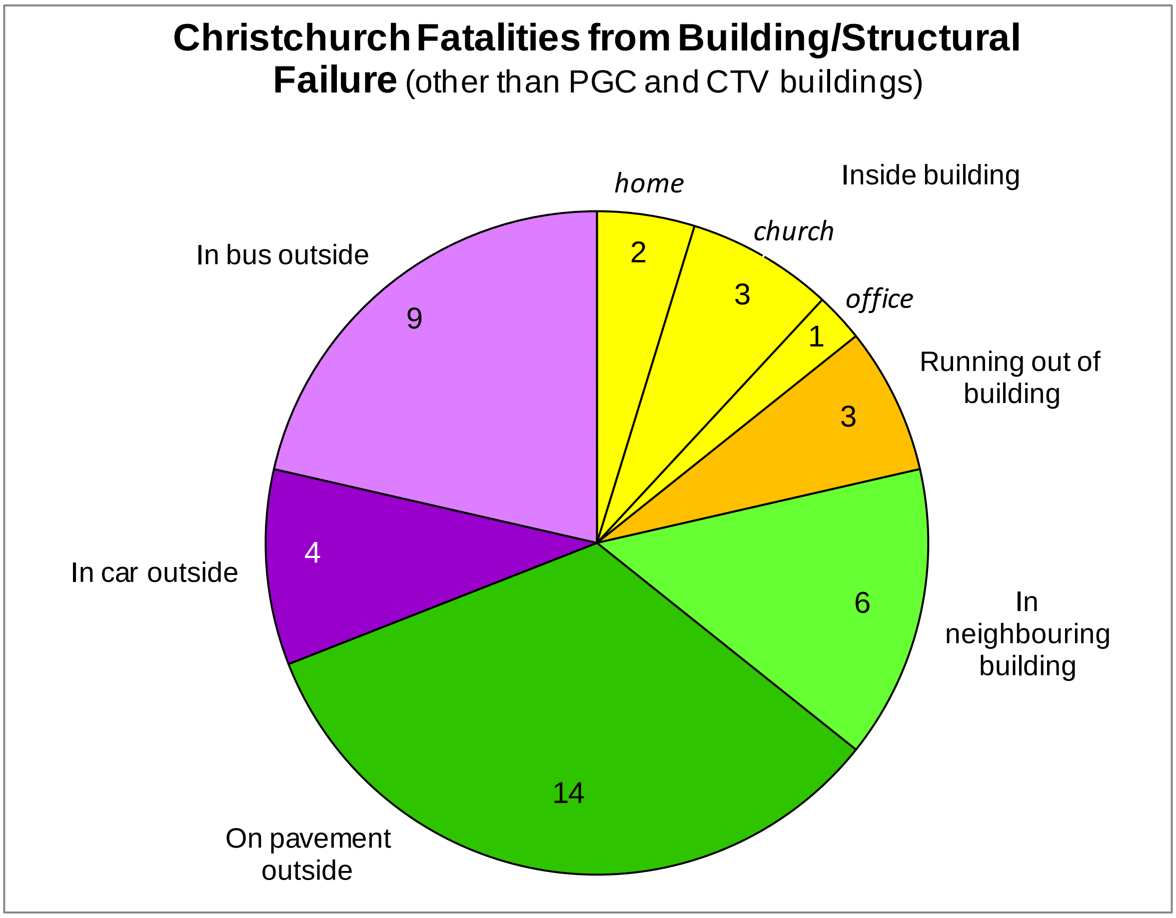


4.2 Christchurch 2011 Fatalities from URM Building Failure

As part of a review of earthquake-prone building policy in New Zealand[11], one of the authors (Tony Taig) carried out a review of the fatalities associated with building failures during the 22 February 2011 Christchurch earthquake. Most of the victims were outside the buildings at the time and were struck by falling masonry, as summarised in Figure A6.18. 41 of the 42 buildings involved were constructed from unreinforced masonry.

Unfortunately, though assiduous steps were taken to record full histories of all the buildings whose collapse led to fatalities along with the histories and experiences of the victims of fatal accidents, no such systematic effort was made to document non-fatal injuries and near misses. Thus the Christchurch information is of limited value in providing further insights to differentiate between situations that are fatal and those that are not.

Figure A6.18: Christchurch 22/2/11 Fatalities from Building/Structural Failure



The Christchurch experience does, though, provide a number of useful insights relevant to this report and the falling hazards risk model to which it contributes. In particular

- Falling hazards as described here (including in particular non-structural masonry elements, facades and wall sections failing out of plane) made a significant contribution to the total burden of fatalities associated with out of plane failures (at least 7 of those shaded green in Figure A6.18).
- All the victims of those falling hazards were located on the pavement (footpath) outside buildings, either as pedestrians walking in the street outside or as building occupants rushing to escape. All were within 3m of the building at the time of being struck.
- Out of plane collapse of whole building walls can have a hazard range significantly greater than 3m, as instanced by the fatalities that occurred to people in vehicles (shaded purple and lilac in Figure A6.18).
- For both pedestrians and people in motor vehicles, the falling masonry hazard (in these large scale failures at least) is extremely localised. One lady in Red Bus 702 survived while the other 8 passengers were killed. A brother was killed running out of a bar while his sister, who was holding his hand, survived. A mother and the baby in her arms were killed while the baby's father and his sister, walking a pace in front, survived.

This last point strongly suggests that what is falling through the air in these large scale failures of building facades and walls consists of discrete, large sections of masonry (with gaps between them enabling some of those exposed to survive), rather than a more homogeneous "rain" of bricks and smaller masonry pieces (which is what is often observed on the floor afterwards).

4.3 Google Survey of Rockfall Impacts on Vehicles

A survey not dissimilar to that described in Section 4.1 of rock fall impacts on people in road vehicles was undertaken by Tony Taig in connection with the assessment of rock fall risk to road users in the Port Hills area of Christchurch[12]. 26 incidents were identified, in which 14 people were killed, 13 injured, and 22 were uninjured beyond minor scratches or bruises.

Key findings of this survey were

1. As was observed in the Christchurch earthquake, the effects of large boulder impacts on cars are extremely localised. Cases included
    a. A pregnant woman killed by a large boulder while travelling as a car passenger in France; her husband who was sitting next to her driving was unharmed.
    b. A New Zealand woman, also a front seat passenger, was killed by a large rock fall in 2014 while her sister who was sitting next to her driving was unharmed.
    c. The French driver of a Mitsubishi Shogun which photographs show appearing to have been completely crushed in 2012 by a large boulder escaped without injury, thanks to the fortuitous coincidence of his driving position avoiding direct impact with the boulder
2. In the event of direct impact of a large boulder with the part of a car where a person is sitting, death is almost certain, as evidenced by the first two incidents above and several others.
3. Unsurprisingly, car crashworthiness is far greater in respect of frontal impacts than impacts from above. Incidents where cars ran into or fell onto rocks included
    a. In New Zealand in 2009 a car was knocked off the road by rock fall and fell down a drop of 5-10 metres. The driver was uninjured.
    b. Also in 2009 a couple's car was knocked off the road and fell 30ft into the Frying Pan River in Colorado, USA. Both were unhurt.
    c. In 2014 a man was driving in excess of 90 kph when "about 2000 cubic yards" of rock and debris fell on and around his car, crushing the front. He stopped, got out, hopped over the barrier at the side of the road and was unharmed.

The conclusion reached after this survey was that for large boulder impacts the presence or otherwise of a car is almost immaterial to the prospects of survival of its occupants – if they are personally in the path of the boulder their probability of dying is high, otherwise it is low.

4.4 TPS Consulting List of Relevant Incidents

In the course of checking the incident sources for Section 4.1 of this report, an independently prepared list of incidents involving significant masonry items falling from buildings in the UK from 2000 to 2014 was discovered[13]. The list was prepared by TPS, a property and construction consultancy owned by the Carillion Group.

This list comprised 77 incidents of which 9 were fatal. The incidents on the list corroborated the findings in Section 4.1 above.

The overlap between the TTAC incident list described in Section 4.1 has been used to carry out a capture/recapture analysis[5] to estimate the total incidence of falling masonry incidents and fatal falling masonry incidents in the UK, on the assumption that each list represents a random sample of the whole “population” of relevant UK incidents over the period covered (1/1/2000 to 30/11/2014). The results are shown in Table A6.2.

Table A6.2: Capture-Recapture Estimate of UK Incidence of Falling Masonry Incidents

Source	**UK Incidents 1/1/00 to 30/11/14**		
	All	**Fatal**	
TTAC Study	98	22	
TPS List	77	9	
Overlap (both)	16	6	
Capture/Recapture Analysis ==>			
Total Incidents	472	33	
in	14.9	14.9	years
equals	**32**	**2.2**	per year

Clearly these two lists are far from independent; both will clearly understate incidents as many incidents occurring when no-one is present or in quieter locations are likely to go unreported or even un-noticed. Both are likely to have identified incidents that gained the most publicity. But Table A6.2 provides an interesting very approximate estimate of significant incidents and of numbers of fatalities annually which may help set risk associated with falling masonry due to Slochteren earthquakes in perspective. It would be interesting to see the Netherlands equivalent.

[5] The capture/recapture method is widely used to estimate populations of wild animals, birds etc. In the “capture” stage, N_1 members of the species of interest is captured, ringed and released. After a suitable interval a second population sample of N_2 members is captured. The number N_{12} of ringed animals recaptured in the second sample is then used to estimate the total population N. The assumption is that the proportion of ringed animals in the second sample equals the proportion of ringed animals in the whole population. Thus $N_1/N = N_{12}/N_2$, and the whole population $N = N_2 \times N_1 / N_{12}$

5. Discussion

We consider first the general observations and conclusions from this research (5.1), and then a simplified model for application in large-scale risk assessment for many thousands of buildings at once (5.2).

5.1 General Observations

Our companion report "A Model for the Risk in the Groningen Region from Non-structural Falling Hazards in Earthquakes", along with the experience of the Christchurch earthquake (Section 4.3), supports the view that the falling hazard when non-structural components detached from buildings is likely to consist in most cases of a relatively small number of large masonry elements falling through the air, and then more or less fragmenting on the ground.

There are two exceptions to this rule. The first is provided by older chimneys (in particular those dating before about 1920) which were not lined with metal or ceramic liners. In these cases mortar is expected to be particularly fragile, and what falls onto and from a roof, and then through the air, is better characterised as a pile of loose bricks. The second is provided by detached roof tiles, which are not generally mortared together and, like brickwork from older chimneys, are likely to behave on falling as a shower of individual items rather than as a coherent whole.

This means that for older chimneys and roof tiles we are interested in predicting the probability of fatality if struck by an item as small as a brick or a roof tile (generally in the mass range 1-3.5 kg, or as large as the whole of the failed building element.

The starting premise in approaching this project was that for masonry objects falling from above, the main hazards of concern would be

a. Inundation of the whole body by large falls of masonry (with a very high probability of death unless circumstances provide protection against impact or crushing), and for smaller masonry falls

b. Impact onto the head, which can cause death either via skull fracture or by the impact of the brain against the skull.

These presumptions were borne out by the literature surveyed and the incidents of falling masonry analysed for this report.

Simple physics calculations of the mechanics of objects sliding down or toppling and falling from roofs suggest, consistent with the observations of where pedestrian fatalities occur outside buildings in earthquakes, that the main hazard to life is associated with a space about 3m wide immediately adjacent to a building facade. Exceptions where the hazard range may extend further include

a. Roofs of specific geometry (particularly on taller buildings) where objects might acquire sufficient momentum in sliding down the roof to project it out as far as 4-5 metres,

b. Tall non-structural elements mounted immediately above the facade edge toppling outward, extending the hazard range to their own height plus typically 1-2 metres, and

c. Larger scale out of plane wall collapse, where a whole wall section toppling can extend the hazard out beyond a 2-3 metre footpath and several metres into a roadway, as illustrated by several of the building failures in the Christchurch 22/2/11 earthquake.

The potential for lethal impacts of objects within the weight range of interest has been explored on the basis of simple, approximate criteria that have been described in the literature and used in other contexts. A simple kinetic energy criterion (100-200 Joules required to fracture the skull in impact with a flat planar object; 20-60 Joules required to fracture the skull in impact from a small projectile) and the Blunt Criterion (considered a superior basis for estimating skull fracture since it takes into account the resistive capacity of the soft tissue and bone as well as the energy of the impacting object) lead to the conclusions summarised in Table A6.3.

Table A6.3: Summary of Results of Applying Literature-Based Injury Criteria

Falling Object Mass	**Probability of Fatality - Flat face impact on head**	**Probability of Fatality - Edge/Corner Impact on Head**
Kinetic Energy Considerations:		
Up to ~ 1 kg	Little possibility of skull fracture/fatality for any fall height	Possible for fall heights above 2 storeys
~ 3 kg	Remote for fall from 1 storey; Significant possibility for 2 storeys; Increasing with building height	Significant possibility for 1 storey; Probable for falls from 2+ storeys
~ 10 kg+	Significant possibility from 1 storey; Probable for fall from 2+ storeys	Probable for fall heights as low as 1-2 metres
Blunt Criterion Considerations:		
Up to ~ 1 kg	Little possibility from any fall height	Rising from ~10% to perhaps ~50% from 2 storeys fall height upward
~ 3 kg	Little possibility for eaves height <~10m	Significant possibility (~10%) for fall from 1 storey; rising from ~40% for 2 storeys up to maybe 80%+ for tall buildings

~ 10 kg+	Low for 1 storey; ~10-20% for 2 storeys; rising to perhaps ~50%+ for tall buildings	Of order 50% for 1 storey; Virtual certainty for 3 storeys+

The review of actual incidents in Section 4 suggests that:

a. The probability of death when struck on the head by masonry objects is roughly independent of fall height of the object (but note that data on smaller objects causing death is sparse), and

b. The probability of death increases fairly smoothly with the weight of the falling object, from around 20% for objects of size 2 bricks or less, up to around 50% for very large objects.

These probabilities are almost certainly an overestimate for the lower probability (because large numbers of incidents involving smaller fragments of masonry falling and non-lethal injury are likely to go unreported), and an underestimate for the higher probability (because the non-fatal incidents involving head injury via a large object impact can mostly either be explained by some form of sheltering of the head from the worst of the impact, or led to such serious permanent disability that the outcome might be regarded by many people as of comparable severity to death).

Taking all these factors into consideration, along with the large variability of injury outcome depending on the orientation of masonry items when they strike the head, we propose probabilities of fatality from falling masonry striking the head as shown in Table A6.4.

Table A6.4: Proposed Probabilities of Fatality from Falling Masonry

Object Mass (examples)	**Fall from 1 storey roof**	**Fall from 2 storey roof**	**Fall from 3+ storey roof**
Less than 0.5 kg	0	0	0
0.5 to 1.5 kg (e.g. typical roof tile or Lilliput brick)	0	1-5%	5-10%
1.5 to 5 kg (e.g. typical house brick)	1-5%	5-10%	10-20%
5 to 15 kg (small multi-brick masonry sections)	5-10%	20-50%	50-90%

Greater than 15 kg (larger masonry or concrete sections)	20-50%	50-100%

These values are applicable if any part of the falling masonry item contacts the head of a person within that range, and are based on average orientation of objects as they fall. The proposed probabilities for larger items recognise the possibility of death resulting from inundation or impacts with other parts of the body.

For the purposes of risk assessment we proposed that falling hazards should be considered to be randomly distributed within a range up to 3m outward from the building wall.

5.2 Simplified Model for Wide Scale Risk Assessment

Our risk model for falling hazards calculates the Local Personal Risk (LPR) in an at-risk space from a falling object as

$LPR = \Sigma_i \,.\, P1_{ik}\, \Sigma_j\, P2jk \,.\, P3_{jk}$ ***Equation [1]***

Where

$P1_{ik}$ is the probability of failure of an object of type k in shaking within PGA band i

$P2_{jk}$ is the probability, in the event of object failure, of it failing to damage state j, and

$P3_{jk}$ is the probability of death for a person in the path of the object as it falls.

The third probability, P3jk, is the product of two factors:

P3jk = P(head in path of object, given damage state j)

x P(death occurs if head in path of object) ***Equation [2]***

The former probability depends on both

a. the dimensions of the particular object involved
b. its orientation as it falls, and
c. the area of the at-risk space into which it falls.

The latter probability is that contained in Table A6.4 above.

The combination of the probabilities of death from Table A6.4 with the object and situation-specific geometric factors to do with someone in the at-risk area's head being in the path of the falling object makes the calculation of $P3_{jk}$ a quite complex one which is specific to each individual object.

In discussing this issue, NAM suggested a drastic simplification of the lethality model for wider scale application of the risk model. This was, instead of using Equation [2] above to estimate probability of death, simply to assume that if someone's head was in the path of a masonry object their probability of death would be one, and otherwise it would be zero.

Taken on its own this would clearly be a potentially quite significantly conservative (tending to overstate risk) assumption. But in combination with another simple assumption about the cross-sectional area of different damage states of falling masonry items, it can be made less so. Damage states for the falling hazard risk model are defined in terms of the percentage of the masonry element that falls to the ground:

- DS1 1-3% (average 2%)
- DS2 3-10% (average 6.5%)
- DS3 10-30% (average 20%)
- DS4 30-70% (average 50%), and
- DS5 70-100% (average 85%).

The key assumption we have used for each damage state to compensate for the increasingly conservative nature of the "Probability of death if in path = 1" assumption is that the cross-sectional area swept out by the object as it falls is simply that of the whole object multiplied by the appropriate average percentage of its volume falling as debris for the damage state in question. This tends to maximise the area swept out by the object as it falls for high damage states, but to minimise it for the lowest damage state.

This is perhaps best illustrated with a simple example. Suppose we have a chimney 1m high, 0.4m wide and 0.4m deep. If the WHOLE chimney snaps off and falls, then we would make the the worst case assumption that the area it sweeps out as it falls through the air would be 1m x 0.4m = $0.4m^2$.

Now suppose that instead of failing in its entirety the chimney fails in damage state 1. In reality this would mean perhaps 1-2 bricks had fallen for an average chimney. In our simplified lethality model, though, we assume that the area swept out as this DS1 object falls through the air is equal to 2% x the area swept out if the whole object fell through the air. That is, 0.02 x 0.4 = $0.008m^2$. We are effectively assuming that a thin slice of the chimney (still 0.4x0.4m width x depth) falls through the air in the orientation that minimises area swept out, but maximises the hazard presented by the object (as discussed in previous sections, a brick is likely to have very different consequences depending whether the head is struck by a flat face of the brick, an edge or a corner).

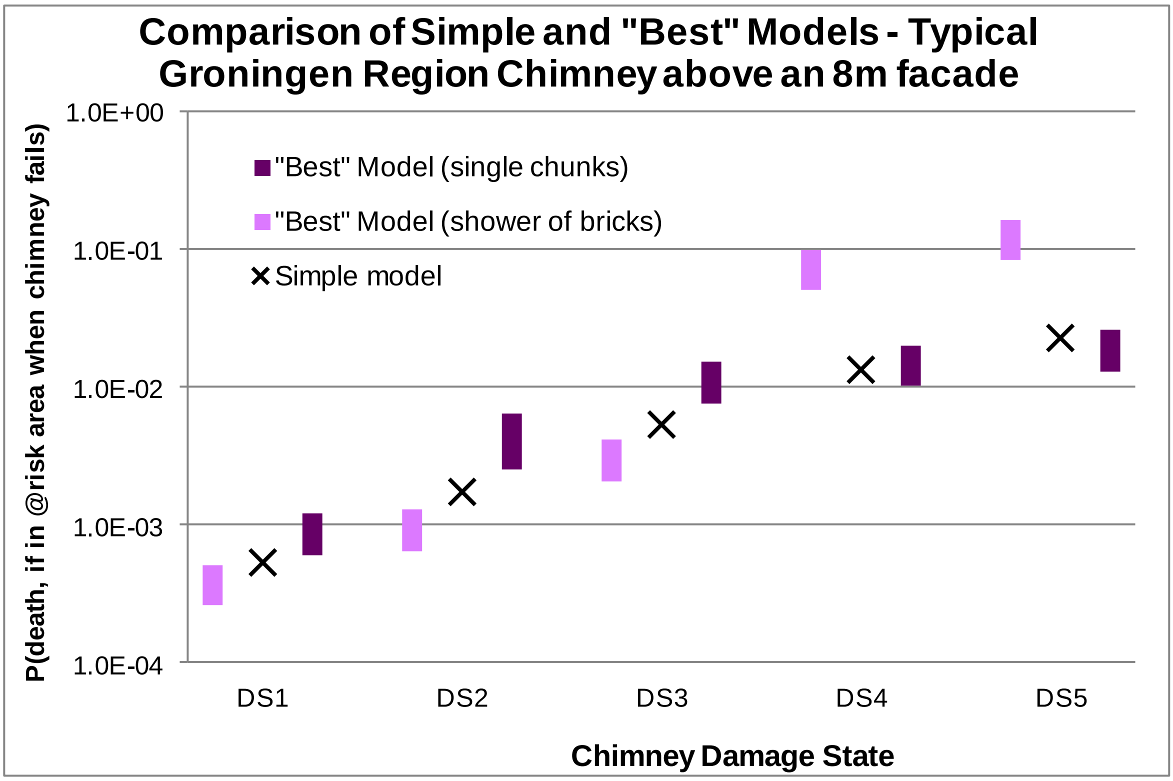
The overall probability of death has been calculated for each damage state of a Groningen region chimney of average dimensions, based on our "best estimate" model (Table A6.4, combined with average orientation of the falling object) and then on our simplified model. Two versions of the best estimate model have been used. In the first, the object (whatever its damage state) is assumed to fall as a single discrete "chunk" of debris. In the second, the object is assumed to fragment and fall as a "shower" of individual bricks. The calculations of orientation-averaged swept out area and probability of death are described in Annex 2.

The results, comparing the "best estimate model" with the simplified model, are shown in Figure A6.19. The simplified model result lies within the range covered by the "shower of bricks" and "single chunk" versions of the more complex model for all damage states.

In fact, it has the rather attractive property of being closer to the “shower of bricks” estimate at low damage states (which are more likely to involve individual bricks and small groups of bricks shaking loose), while being closer to the “single chunk” estimate for high damage states (where complete snapping of a large part of the object is more feasible).

Another interesting feature of the calculational results presented in Annex 2 is that for the WHOLE object, the average swept-out area over all orientations is very close to that calculated from the simple product of (maximum x median dimension). The orientations where the swept-out area is increased are compensating for those where it is decreased. This means that the simplified model is providing a good approximation for high damage states as well as for lower ones.

Figure A6.19: Comparison of Lethality Models: Typical Groningen Region Chimney



Our conclusion is that this simplified model is eminently suitable for use in risk assessment. It moreover has the very attractive property that in Equation [1] above, the ratio of (Area swept out by the whole object as it falls) to (Area at risk) can be taken outside the sums over damage states and shaking bands. This means that a set of those summation terms can be calculated off-line for each PGA contour and object type (as explained in Appendix 1 describing the Risk Model), and looked up in a reference table. This simplification makes the difference between it being feasible or not feasible to carry out risk calculations in spreadsheets containing 5,000 or more buildings/hazardous objects.

6. Conclusions

Our conclusions are as follows

1. The primary fatal hazards associated with falling masonry are of inundation (leading to multiple injuries/crush) and impacts with the head (leading to fracture of the skull or contusion)

2. The hazard from falling masonry outside the wall of a building should be assumed to be uniformly distributed over a band of width 3m next to the building wall.

3. The probability of death as a result of being struck by falling masonry depends on
   - where on the body the impact occurs
   - the mass of the falling object
   - the height from which it falls, and
   - its orientation (edge/corner impacts are significantly worse than flat surface impacts).

4. Probabilities of death as a function of falling object mass and building height have been developed for objects of different sizes, averaged over all possible fall orientations and predicated on impact of any part of the falling object with the head.

5. A simplified model for use in risk assessment has been developed which provides good approximations to those derived using our more complex probabilities of death as a function of object size and fall height. The simple model is based on the assumptions that

   a. The probability of death if a falling masonry object strikes the head is 1, and

   b. The area swept out by a falling object as it falls to the ground is calculated as the area swept out by the object based on its worst orientation of fall (such that the area swept out as it falls is equal to the product of longest x next longest sides), multiplied by the percentage of the object falling for a given damage state.

7. References

1. US National Institutes of Health, “Traumatic Brain Injury (TBI): Condition Information”, available at http://www.nichd.nih.gov/health/topics/tbi/conditioninfo/Pages/default.aspx

2. Veiligheid NL Factsheet, “Traumatisch Hersenletsel”, available at http://www.kennispleingehandicaptensector.nl/gehandicaptenzorg/factsheet-traumatisch-hersenletsel-veiligheidnl

3. K Galbraith, “Review of Blast Injury Data and Models”, HSE Research Report RR192/1998, produced by the Defence Evaluation & Research Agency for HSE.

4. Glasstone S & Dolan P J, “The Effects of Nuclear Weapons”, Castle House Publishers, UK, 1980

5. D.I. Feinstein, “Fragment Hazard Criteria”, US Department of Defence Explosives Safety Board, Alexandria VA, 1993

6. A. Oukara, Nsiampa N, Robbe C, Papy A, “Injury Risk Assessment of Non-Lethal Projectile Head Impacts”, The Open Biomedical Engineering Journal, 2014, Vol 8, pp 75-83

7. D. Raymond, Van Ee C, Crawford G, Bir C, “Tolerance of the skull to blunt ballistic temporo-parietal impact”, Journal of Biomechanics, 2009 Vol 42, pp 2479-2485

8. E.G. Blackman, Hale M E, Lisanby S H, “Improving TBI Protection Measures and Standards for Combat Helmets”, University of Rochester, NY, 2011.

9. V. R. Clare et al, “Blunt trauma data correlation”, US Law Enforcement Assistance Administration report AD-A012 761, Edgewood Arsenal, 1975

10. A. Radi, “Human injury model for small unmanned aircraft impacts”, Civil Aviation Safety Authority & Monash University, 2013

11. T. Taig, “A Risk-Based Framework for Earthquake-Prone Buildings Policy”, TTAC Report (with GNS Science) for NZ Ministry of Business, Innovation & Employment, November 2012

12. C. I. Massey, T. Taig et al, “Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Risk Assessment for Dean’s Head”, GNS Science Report 2014/77, July 2014 (and related reports available at http://www.ccc.govt.nz/homeliving/civildefence/chchearthquake/porthillsgeotech/porthillsmassmovement.aspx

13. Schal (TPS Consult), “Safe as Houses ... Masonry Fall List”, Available at http://www.tpsconsult.co.uk/schal/our-services/building-surveying.aspx

Annex 1: Case Studies from Internet Survey

X1.1 Illustration of different debris volume incidents

1) <3 bricks

An elderly man was walking down a high street in Troon, Scotland with his wife when he was hit on the shoulder by a piece of masonry. He pushed his wife into a doorway and they managed to avoid the rest of the debris. He suffered bad bruising and pain to his shoulder. His wife commented that if it had been an inch to the left it would have hit his head.

A woman walking with her fiancé past a church in Chicago was hit on the head by part of a dislodged gargoyle and died before the ambulance reached the hospital. Knowing that the victim was walking with her fiancé, and reading his account of the incident, we know that they were walking in very close proximity to one another. This case highlights how deadly small pieces of masonry can be for someone standing directly in the at risk area.

Photos available at http://www.dailymail.co.uk/news/article-2744517/Engaged-mother-two-tragically-killed-hit-gargoyle-head-fell-three-stories-historic-church.html

2) 3-29 bricks

A man standing outside a store in Bristol was hit on the head by a piece of masonry that had fallen 15 meters. He needed 7 hours of surgery to remove fragments of stone from his head, followed by a 20-day drug induced coma. He spent 9 months recovering in hospital and was left with permanent brain damage.

A piece of stonework fell from above a busy restaurant patio in Battersea, London. It hit a man directly on the head causing a skull fracture; he died at the scene. No one else on the patio was hit.

Photos available at http://www.dailymail.co.uk/news/article-2024714/Peter-Westropp-27-killed-falling-masonry-Le-Bouchon-Bordelais-restaurant.html

3) 30-99 bricks

Blocks of masonry fell from the roof and through an awning over a busy bar’s patio. The debris caused multiple injuries, including a broken leg and left one man in a serious condition. 1 person was killed due to a head injury; she was hit directly on the head.

A 65-year-old woman walking past a row of shops in Ruby was struck on the head by falling debris when the roof collapsed. She had a fractured skull and a blood clot in her brain. Doctors were not expecting her to survive but she recovered from the incident, although with some lasting impairments. It affected her sight, hearing and walking.

4) >100 bricks

The roof of a building on a busy shopping street in Cork, Ireland collapsed, pushing out 3 rows of bricks onto the street below. The debris covered a large area but fell in small fragments, 1 person died and 7 were taken to hospital where 1 was left paralysed from the waist down. Of those injured some were saved from a more serious injury, as they were able to get out of the way, or were pushed away from the danger. The one fatality was due to her location in relation to the falling debris, she was hit directly by a large volume of masonry causing the following injuries: broken leg, multiple rib fractures, a broken breastbone, a shoulder fracture, neck fractures & internal bleeding.

A changing room wall collapsed in Monmouth Leisure Centre when school pupils were getting changed for a PE lesson. The wall collapsed onto a 15-year-old boy; he was given a 50% chance of survival. He suffered serious internal bleeding and urgent surgery was needed to repair a torn artery and serious liver damage. He had two fractured ribs, a punctured lung, damaged bowel, one leg was broken in five places and his hip and pelvis were broken. He was put into an induced coma and had several pins and a frame inserted into his leg. He managed a full recovery, and after extensive physiotherapy, can now walk without a limp. No head injuries were reported.

X1.2 Examples of different injury outcome severity

1) Fatal injuries

A freestanding brick wall situated directly next to a pavement collapsed during windy weather killing all 3 people walking next to it at the time. The weight of the wall killed 2 people at the scene. The third died later in hospital because her brother, who died at the scene, tried to protect her when the wall fell by using his body as a shield. It softened the blow but did not shield her completely; she died from severe head injuries. The wall was 2 meters high and debris covered the entire pavement and part of the road.

In Montreal, a block of concrete fell from an external wall towards the patio of a sushi restaurant. It landed on a woman's head, killing her instantly; the man sat opposite her suffered a hand injury. No one else was injured. Had the block fallen in smaller fragments it is highly likely that more people would have been seriously injured and woman may have survived. However, due to the nature of the block that fell it did not break up.

Photos available at http://montreal.ctvnews.ca/falling-concrete-slab-kills-woman-at-montreal-restaurant-1.417370

2) Serious Injuries

A man was seriously injured during an attempted robbery when he tried to squeeze through a hole in the wall of a shop. He suffered a ruptured spleen and other serious internal injuries when masonry, from inside the two-skinned wall, collapsed onto his torso when he was halfway through the hole. He was taken to hospital in a critical condition but recovered from his injuries. It is not known how far the masonry fell or how heavy it was.

In Folkestone, Kent, a woman was walking along the high street with her fiancé when a 70 kg piece of masonry fell from above a shop. She was the only one hurt; no one else was hit by debris. It was initially reported as a head and shoulder injury however her injuries were later discovered to be more severe. She was left paralysed from the waist down.

Video showing object and source available at http://www.itv.com/news/meridian/story/2013-07-18/woman-hit-by-falling-masonry/

Other Injuries

Three people suffered minor injuries when a roof collapsed causing bricks and debris to fall into the high street in Norbury, London. Only two were taken to hospital, one man with a head injury and one woman with a foot injury. Others with minor injuries, cuts and bruising, were treated at the scene. The head injury was not life threatening.

Photo available at http://www.standard.co.uk/news/london/three-people-injured-after-being-hit-by-falling-bricks-as-roof-collapses-in-south-london-9390224.html

The parapet of a house collapsed, falling on people sat on the veranda. In this incident the debris fell in a shower-like fashion, not in a large slab. One man was resuscitated at the scene by a neighbour and taken to hospital in a serious condition. A woman had a toe amputated and another man injured his knee causing him to have trouble walking for a short time after the accident.

Photo available at http://www.nj.com/hudson/index.ssf/2014/06/several_injured_in_west_new_york_partial_building_collapse.html

[end of Annex 1]

Annex 2: Swept Area and Lethality Comparisons

X2.1 Calculation of area swept out in falling

Suppose a rectangular object is oriented so that its longest and next-longest axes are both horizontal.

(Imagining a chimney) - if H is the longest axis length, W the next longest and D the shortest then

A swept (this situation) = H x W for the whole chimney, or
(H+R)x(W+R) to add in the human head radius

where A swept is the plan view cross-sectional area swept out by the object as it falls through the air.

Now tilt the long axis of the object at angle α to the horizontal and the next longest axis to angle β

The new effective H & W to calculate A swept are now given by

$H_{new} = H.\cos\alpha + D.\sin\alpha$

$W_{new} = W.\cos\beta + D.\sin\beta$

For different α and β we can now work out the revised A swept as (Hnew+R) x (Wnew+R)
(Note that the angle of rotation around the vertical axis does not matter, as it makes no difference to the area swept out as the object falls through the air).

The product (Hnew+R) x (Wnew+R) was calculated for each combination of the orientation angles α and β in one degree intervals from 0 to 90o, and the average resulting area was assumed to be the average swept-out area of a typical Groningen region chimney as it fell through the air in each of the 5 damage states considered in the

Average chimney parameters were derived from the Falling Hazards Survey data as follows:

	H	W	D	
Average for Gemeente Loppersum	0.79	0.44	0.56	(average of all chimneys in the Survey)
Average for Groningen Centrum	0.97	0.44	0.55	
Assumed average for illustration	0.88	0.44	0.56	

The resulting calculations of the area swept out in falling are shown below, both on a "best estimate" basis (averaged over all falling angles) and on the simplified model basis (with H reduced pro rata to the % fallen in each damage state)

	Parameter	Whole chimney	DS1	DS2	DS3	DS4	DS5	Units
	% Fallen	***100%***	2.0%	6.5%	20%	50%	85%	(none)
H	Longest	***0.88***	0.018	0.057	0.176	0.439	0.747	m
W	Median	***0.56***	0.56	0.56	0.56	0.56	0.56	m
D	Shortest	***0.44***	0.44	0.44	0.44	0.44	0.44	m
	R (human head radius)	***0.1***	0.10	0.10	0.10	0.10	0.10	m
A(swept), average of all fall angles		***0.688***	0.287	0.306	0.361	0.484	0.627	m2
A(swept), simplified model		***0.641***	0.013	0.042	0.128	0.321	0.545	m2

X2.2 Calculation of probability of death

The following calculation is predicated on a chimney of typical Groningen region dimensions, above an at-risk area of 24m^2 (8m facade length x 3m at-risk area in front of facade).

"BEST" MODEL (shower of bricks)	DS1	DS2	DS3	DS4	DS5
% chimney falling	2.0%	6.5%	20.0%	50.0%	85.0%
N bricks	2	5	16	40	68
N bricks per object	1	1	1	1	1
Actual A swept/object	0.062	0.062	0.062	0.062	0.062
P death/object (lower, in path)	0.05	0.05	0.05	0.5	0.5
P death/object (upper, in path)	0.1	0.1	0.1	1	1
N objects	2	5	16	40	68
P(in path), per object	0.003	0.003	0.003	0.003	0.003
P death/object (lower, in @risk area)	1.3E-04	1.3E-04	1.3E-04	1.3E-03	1.3E-03
P death/object (upper, in @risk area)	2.6E-04	2.6E-04	2.6E-04	2.6E-03	2.6E-03
P death/N objects (lower, @risk area)	2.6E-04	6.5E-04	2.1E-03	5.0E-02	8.4E-02
P death/N objects (upper, @risk area)	5.2E-04	1.3E-03	4.1E-03	9.8E-02	1.6E-01
"BEST" MODEL (chunks)	**DS1**	**DS2**	**DS3**	**DS4**	**DS5**
N bricks	2	5	16	40	68
N bricks per object	2	5	16	40	68
Actual A swept/object	0.287	0.306	0.361	0.484	0.627
P death/object (lower, in path)	0.05	0.2	0.5	0.5	0.5
P death/object (upper, in path)	0.1	0.5	1	1	1
N objects	1	1	1	1	1
P(in path), per object	0.012	0.013	0.015	0.020	0.026
P death/object (lower, in @risk area)	6.0E-04	2.5E-03	7.5E-03	1.0E-02	1.3E-02
P death/object (upper, in @risk area)	1.2E-03	6.4E-03	1.5E-02	2.0E-02	2.6E-02
P death/N objects (lower, @risk area)	6.0E-04	2.5E-03	7.5E-03	1.0E-02	1.3E-02
P death/N objects (upper, @risk area)	1.2E-03	6.4E-03	1.5E-02	2.0E-02	2.6E-02
SIMPLE MODEL	**DS1**	**DS2**	**DS3**	**DS4**	**DS5**
Assumed A swept	0.013	0.042	0.128	0.321	0.545
Assumed P(death) if head in path	1	1	1	1	1
Assumed (Pdeath)	5.3E-04	1.7E-03	5.3E-03	1.3E-02	2.3E-02

[end of Annex 2]

Client: Nederlandse Aardolie Maatschappij

Arup Project Title: Groningen Earthquakes Structural Upgrading

Risk Assessment of Falling Hazards in Earthquakes in the Groningen region: Appendix 7

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PO Box 57145
1040 BA
Amsterdam
The Netherlands

ARUP

Contents

Appendix 7: The Falling Hazards Survey

Summary

This appendix describes the Falling Hazards Survey carried out by TTAC Ltd for Arup and NAM over the summer and autumn of 2015, and presents the final version of the survey results for the 160,000 buildings surveyed. The survey covers all buildings with addresses within the Municipality of Appingedam, Bedum, Delfzijl, Eemsmond, Groningen, Haren, Hoogezand-Sappemeer, Loppersum, Menterwolde, Oldambt, Slochteren, Ten Boer, Veendam and Winsum.

The purpose of the survey and the risk assessment it enables is twofold:

a. to help prioritise areas within the Groningen region for “on the ground” inspection and surveying in support of decisions on upgrading, and

b. to help develop evidence to support risk-based rules for decision making on prioritisation of potential falling hazard objects for upgrade.

Pilot studies in Bedum and Groningen Centrum demonstrated the feasibility of a desk-based survey using readily available internet data sources (Google Street View and Google Earth) to identify and characterise non-structural building elements with potential to fall into streets, above doorways or onto roofs in earthquakes.

The strength of this approach is that it enables information directly relevant to risk (object dimensions and location in relation to doorways, public spaces and roofs through which objects might fall) to be collected quickly for large numbers of buildings by people without specialist expertise. The weaknesses of the approach are that

a. some buildings cannot be viewed in Street View (the primary information source) as they are either obscured or were built since the latest Street View photographs were taken), and

b. the condition of objects cannot generally be assessed from the relatively low resolution photographs available from the sources used.

The measures taken to devise the survey format and data collected, to recruit and train the survey team, and to check and quality assure the survey outputs, are described in the report.

The results are presented in aggregate across the whole area surveyed and in more detail at individual Municipality level. Key summary statistics (rounded to the nearest 1000) include

- 160,000 buildings surveyed in just over 4 months by a team of 20 surveyors

- 120,000 potentially hazardous objects identified, with the largest numbers comprising chimneys (47,000), gables (29,000 including Dutch gables), canopies (16,000) and parapets (8,000)
- Were these hazardous objects to collapse in an earthquake,
  - just over 2/3 could fall within 1m of a doorway,
  - just under 2/3 could fall into publicly accessible space in front of or around buildings,
  - just under 4% could fall from height onto the roof of an occupied building.

1. Introduction

This appendix is the report of a survey of non-structural building components that constitute potential falling hazards in the event of earthquakes in the Groningen region of the Netherlands. The survey was carried out between June and November 2015 by a team consisting largely of students and recent university graduates working under the management of Florence Pickup and the direction of Tony Taig of TTAC Ltd, using Google Street View and other freely available online databases. Arup provided considerable assistance in

- clarifying the initial scope of buildings to be covered
- extracting building data files as a starting point for the survey, and
- checking of sample results both of the survey and of the risk assessments built on its results.

This report explains the survey approach and the results for the Municipality surveyed: Appingedam, Bedum, Delfzijl, Eemsmond, Groningen City, Haren, Hoogezand-Sappemeer, Loppersum, Menterwolde, Oldambt, Slochteren, Ten Boer, Veendam and Winsum.

The purpose of the survey was to facilitate a rapid assessment of falling hazard risk with two objectives:

1. to enable prioritisation of large groups of buildings for upgrade and
2. to support the development of practical rules for decision making about upgrading of potential falling objects.

It was recognised from the outset that a survey of this nature could never hope to make definitive evaluations of risk for single objects/buildings. The risk of objects failing is highly dependent on their condition, which cannot be gauged from the low resolution photographs, many of them taken 5 years ago or more, which are available on Street View. It was also recognised from the outset that to complete this survey in the allotted time (survey plus risk assessment to be completed within 6 months from the end of June 2015) it would be necessary to make a single, high speed pass through all the surveyed buildings. Checking results for each building and object was not possible. The survey results thus inevitably contain inaccuracies and inconsistencies. The aim of checking and QA has been to quantify the implications for risk of those inaccuracies and inconsistencies, rather than to identify and remove them all.

The appendix covers

- the background to the survey and development of the overall approach (Section 2)

- the information collected in the survey, the survey process and checking and QA arrangements (Section 3), and
- the survey results (Section 4)

Annex 1 provides details of the pilot survey results and of survey results by Municipality. The Survey Handbook used by surveyors is available as a companion document.

2. Survey Background and Approach

This section of the appendix explains the background to the survey, the pilots undertaken in Bedum and Groningen Centrum, and the development of the survey format and team.

2.1 Survey Background

The starting point for the survey was an ambition to prioritise falling hazards for upgrade based on quantitative assessment of the associated risk to life.

The Rapid Visual Screenings (RVS) undertaken to date as the first step in evaluating buildings for upgrade were explored as a basis for such risk assessment but were not suitable for this purpose for several reasons:

1. The set of "High Risk Building Elements" (HRBEs) identified in the RVS did not include several categories of potential falling object considered potentially significant (e.g. gables were included only when some significant deficiency in the wall was identified; the set of objects covered was based on those found in the Loppersum Municipality where the RV process began and did not include many of the object types found in more urban areas).
2. Much of the information needed to estimate risk from falling objects, both a) in relation to the object itself (e.g. shape, dimensions, construction material) and in particular b) in relation to its likely direction of fall in relation to locations occupied by people, is not collected and recorded in a systematic way in the RVS outputs.
3. To complete the RVS process for the whole region would take many years; it would be highly desirable to be able to form a rapid overview of risk and the areas in which it is concentrated so as to prioritise "on the ground" surveying and upgrade activity.

We therefore explored a number of other, more rapid routes to collect falling hazard data with NAM and Arup. In particular, we noted that a large majority of objects such as chimneys, gables and parapets could readily be identified and characterised via Google Street View. As a proportion of objects above main doorways and public rights of way that majority is particularly high, though clearly (as indeed is often the case for RVS) it is not usually possible to inspect the rear facade of buildings.

Feasibility studies were therefore carried out into the collection of falling hazard object data via internet-based, desk surveys.

The intent of such a survey is NOT to replace RVS – some form of on-the-ground screening will always be essential to inform decisions on upgrading. The intent is to help prioritise areas on which to focus such on-the-ground screening, by providing the information to support risk assessment to evaluate the mix of

- More/fewer objects present
- Higher/lower risk of objects falling, and
- More/fewer people in at-risk areas

to be evaluated in a systematic way.

An ancillary benefit of such risk assessment is to support decisions on setting of norms or standards in relation to the risk of falling hazard objects. The current NEN-NPR draft standard addresses risk to building occupants from building structural failure, but does not address risk to people outside buildings. The development of the falling hazards risk model, and of a database of what sorts of potentially hazardous objects are present and where they are, is a valuable adjunct to the development of such norms.

2.2 Feasibility Studies

Two pilot studies were carried out to explore the feasibility of collecting falling object data via internet-based surveys. The first covered the village of Bedum and was carried out in January 2015 in anticipation of it being possible, within a few weeks, to compare what was found via the pilot survey with what was found during RVS of the same area. After this showed promise, a second pilot was carried out in Groningen Centrum in June 2015, to assess whether it would still be feasible to identify and characterise falling hazard objects in an urban environment with narrower streets and taller buildings.

A paper describing the pilot studies and comparing their results with RVS (Bedum) and direct first-hand observation (Groningen Centrum) is included in this appendix as Annex 1.

Initial examination of the first (Bedum) pilot results in comparison with RVS appeared to show that the survey via Street View had missed many of the HRBEs identified via RVS. It quickly became clear, though, that the major reason for this was differences in scope, focus and interpretation of what was recorded in the Street View survey, rather than items being missed. In particular the Street View survey focused on masonry objects, on and around roof level, with potential to fall into the space outside doorways or into publicly accessible space next to buildings. Dutch Gables, and gables in general, had not been systematically recorded.

The Groningen Centrum pilot demonstrated that, though it may take a little longer (in order to examine buildings from different standpoints), the proportion of buildings unable to be surveyed was no greater than, and possibly less than, that in Bedum. A key finding of this pilot was that for an urban environment the set of "potentially hazardous falling objects" needed to be expanded to include a greater variety of heavy items attached to the outside of buildings such as decorative stonework, signs, canopies and large areas of architectural glass.

It was agreed that any future Street View survey should

- Include all the regularly occurring non-structural objects attached to the outside of buildings, noting their construction material wherever possible
- Include Dutch Gables and (on discussion of the importance of gable end failures in earthquakes) gable ends generally that were above doorways or public space, but
- Continue to focus on recording objects above doorways or publicly accessible space in order to save time on items likely to involve several orders of magnitude lower risk.

It was recognised that there were likely to be perhaps around 10% of buildings that would be impossible to survey via Street View because they were either obscured or had not been covered (or had not yet been built) in the most recent Street View photographic surveys.

Finally, it was noted that the Bedum pilot exercise took 2 people about 3 weeks to complete, with the rate of working accelerating modestly as it progressed. A major rate-limiting step was the need to identify building addresses via Street View, as these often took considerable time to trace or to infer from adjacent buildings, and could not always be established with confidence. The Groningen Centrum pilot was a little slower; although buildings were easier to identify, more time and effort was required to move up, down and across streets in order to be able to see features on and around building roofs.

A rate of working of 100 buildings per person per day was considered a reasonable benchmark for estimating what would be involved in any future such surveys.

A proposal was then developed for a large scale survey to cover as many of the buildings in the area at risk of significant seismicity over the summer and early autumn of 2015, to take advantage of the availability of students on their summer vacation or who had recently completed their degree studies. The target was to complete a minimum of 50,000 buildings where falling objects, if present, could put at risk people running out of doorways or in publicly accessible space outside the building[1]. Training of the survey team commenced on 21 June 2015.

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[1] Based on the pilot studies, it was hoped (but by no means known with any confidence) that this would be sufficient to cover of order 80 to 100,000 total buildings in Municipalities identified as higher priority.

2.3 Developing the Full Scale Survey

The key steps involved in moving to a full scale survey were

- Development of a standard spreadsheet template for capturing and recording building and hazardous object features
- Recruitment and training of the team of surveyors
- Agreement with Arup and NAM as to the precise scope of buildings to be covered and the prioritisation for surveying of different parts of the Groningen region, and
- Extraction of relevant building data by Arup as the starting point for the survey.

The spreadsheet template was a vital part of the survey. In addition to establishing the data fields and definitions of what was to be identified and recorded (see Section 3), it built in easy to use arrangements for the QA, checking and progress monitoring of the work. Each surveyor used a simple one letter code to state after each building and hazardous object whether they were confident with their assessment or would like a colleague to check it. The initials of the surveyor and date of the assessment were attached to each building and object surveyed, so that at the end of each session the surveyor could enter their initials and date into a summary sheet along with their hours worked. This then generated a summary of buildings surveyed, hazardous objects identified and hours spent that was collated every evening throughout the survey.

The team of surveyors was recruited on the basis of intelligence, integrity and commitment from individuals known personally to the Survey Director and Manager and their families. No special skills were considered necessary; graduate level intelligence and capability to maintain focus and speed of thought (and mouse action!) were the prime attributes sought. 23 surveyors were trained over the course of the project, initially in a group of 12, with additional surveyors being recruited and trained as the work progressed. All surveyors spent sessions surveying in pairs after completing training before being allowed to work on a solo basis.

It was agreed with Arup and NAM that the survey would work in units of whole Municipalities (split into individual Wijks for the city of Groningen for convenience). After some discussion the scope of buildings was agreed to be:

All buildings within the 0.1g PGA contour on the 2013 KNMI map (1 in 475 year exceedence frequency), excluding "notverblijfsobjecten" of less than 10m^2 in plan area.

The main points of discussion here were how far out from the most seismically active areas to try and survey, and how far to go among the large population of unoccupied buildings. On the former the 0.1g contour on the KNMI 2013 map was chosen as a threshold beyond which the risk of falling objects might safely be assumed to be very small. On the latter, it was hoped that by including buildings above 10m^2 we would capture most potentially risk-creating buildings (for example school outbuildings or storage buildings where people regularly play or walk close to one or more facades of the building).

Arup then extracted basic information on the buildings within this scope (see Section 3) from the V1 exposure database (as at 21 June 2015) and provided a set of spreadsheets to TTAC Ltd, one for each Municipality except that the files for Groningen City were split into individual Wijks for convenience. Some of the larger files were split before or during surveying to facilitate managing both the files themselves and the surveyor rostering.

With this scope, the total of buildings to be covered was over 280,000, which was considered an unrealistic goal to achieve over the summer vacation period for which the surveyors were known to be available. After discussion with Arup and NAM, buildings without addresses were excluded as being likely to entail very low risk, which reduced the total to 195,000.

Municipalities were then prioritised into high (H), medium (M) and low (L) priority groups. The primary objective was to complete the survey of the H priority Municipalities with the best practicable QA and checking (see Section 4), then to complete the survey of the M priority Municipalities with lighter touch QA and checking. For the L priority Municipalities no survey was anticipated – if risk assessment revealed any significant possibility of falling hazard risks within an order of magnitude of any levels of possible concern then the risk in these areas would be assessed using a typology approach such as has been applied for collapse risk assessment by NAM and other parties.

The numbers of buildings involved by Municipality are shown in Table 1.

Table 1: Buildings within 0.1g PGA Contour (2013 KNMI map), by Municipality

GEMENTEE	Total number of buildings	Number of buildings with no address	No. of buildings WITH an address	Priority
Aa_en_Hunze	5378	2034	3344	L
Appingedam	7752	2620	5132	H
Assen	8	4	4	L
Bedum	6144	1734	4410	H
Bellingwedde	42	34	8	L
De_Marne	5326	2084	3242	L
Delfzijl	18169	6928	11241	H
Eemsmond	12910	5448	7462	M
Groningen	64036	8700	55336	H
Grootegast	8	4	4	L
Haren	12184	4279	7905	M
Hoogezand_Sappemeer	20092	6535	13557	M
Leek	853	405	448	L
Loppersum	8029	3310	4719	H
Menterwolde	9338	3809	5529	M
Noordenveld	4300	1782	2518	L
Oldambt	25689	9017	16672	M
Pekela	8268	3122	5146	L
Slochteren	13562	6718	6844	H
Ten_Boer	3994	898	3096	H
Tynaarlo	23291	9306	13985	L
Veendam	16809	4722	12087	M
Winsum	9191	2979	6212	H
Zuidhorn	8550	3030	5520	L
Total	**283923**	**89502**	**194421**	

Sub-Totals by Priority Category

Priority	Total Bdgs	Bdgs without address	Bdgs with address
H	130877	33887	96990
M	97022	33810	63212
L	56024	21805	34219
TOTAL	**283923**	**89502**	**194421**

3. Survey Data Fields and Process

This section of the report explains what data was collected in the survey (3.1), how this was done (3.2), and the arrangements for quality assurance and checking of the results (3.3).

3.1 Survey Data Fields

These are described in Tables 2 to 4below covering

- Basic building data provided from the Arup buildings database
- Building and street properties
- Hazardous object characteristics

Further information is provided in the companion Survey Handbook. No explanations are provided for fields which are already self-explanatory. Additional fields were provided for QA purposes including initials, dates, comments and a code indicating confidence in the assessment for both surveyor and checker.

Table 2 Basic building data

Field	**Explanation**
BAG Building ID	Unique building identifier
Year of construction	
PGA contour	From KNMI 2013 map
BAG Address ID	Unique address identifier
Street Address	
Postcode	
Municipality	
Primary Use	e.g. residential, retail, office, educational
No. addresses in bldg	Particularly useful e.g. for apartment blocks

Adjacency	e.g. detached, semi-detached, terraced, apartment block
Building height (m)	
Street View link	

Table 3 Building and Street Properties

Field	**Explanation**
Footfall category	Rating from 1-10 (see Section 3.6)
Survey classification	P – any building with one or more facades within 5m of public space
	D – not P but has at least one hazard within 1m of doorway
	N – facades clearly visible; no identifiable hazards
	O - obscured or otherwise not visible
	T - not built at time of StreetView photo
	X - out of scope building type
	Z – building without BAG ID, not visible on the BAG Viewer web site
Facade lengths (where public access)	F – length of facade facing the (address) street
	L – length of facade facing to left of front facade
	R – length of facade facing to right of front facade

It should be noted that the list of hazardous objects identified in the survey (see Table 4) includes many types for which we have little or no empirical data from other earthquakes on performance in earthquakes. In the current version of the model, these have been treated by reference to other types of hazardous object (for example balustrades and free standing walls have been assumed to behave similarly to parapets).

The selection of which of the three object types for which we do have empirical data (parapets, chimneys and gables) to use as a comparator, and the relativity to be assumed between a given class of object and its comparator, are discussed in the companion reports on risk assessment of the surveyed buildings.

The spreadsheets supplied by Arup were sorted (by City, then Street Name, then Number to facilitate rapid moving through a sheet). A template set of column headings was added for information to be collected by the surveyors. A sheet with lists of permitted data field entries was added along with Excel data validation for relevant cells, to ensure that key fields could not be populated with misspelt “chimeys” or “chinmies”. Conditional formatting was incorporated into the sheets to be populated so that, once a building had been given a high level classification, fields not requiring to be filled in would be shaded out. A progress sheet was included into which surveyors posted details of their time spent each day so that progress could be monitored.

Table 4: Hazardous Object Characteristics

Field		Values/Explanation
Hazardous object type		Chimney
		Parapet
		Gable
		Balcony
		Balustrade
		Bay window (upper floor)
		Brick infill panels
		Canopy - supported
		Canopy - unsupported
		Decorative stonework
		Dutch Gable - parapet
		Dutch Gable - gable
		Flagpole (on building)
		Free standing wall
		Industrial object
		Large glass area/structural glazing
		Pinnacle
		Sign - vertical
		Sign - horizontal
Dimensions (H, W, D)		
Hazard category		
	D	above doorway (within 1m)
	D*	presumed above doorway
	P	above public space on street
	P*	above public space, off street
	R	particular fall through roof hazard
Direction of fall		
	%	towards each facade (F,R,L,B)
	F	extra risk of fall thru' own roof
	N	risk of fall thru' neighbouring roof
Shape (from menu)		
Construction material (from menu)		
Special features		
	E	extended potential area at risk
	R	restraints in place
	T	wall ties in place
Condition (by exception only)		

3.2 Survey Process

Surveyor induction included

- Signing of TTAC contract of employment and NAM non-disclosure agreement
- Overview of the background to seismicity in the Groningen region
- Falling hazards and risk observations based on earthquake experience to date
- Key risk-determining factors for falling hazard objects
- Specific objectives of the survey, and
- The survey process and handbook (companion document to this report).

After this induction the surveyors were introduced to the spreadsheets within which they were required to collect survey data and the Handbook explaining how they were to work. The spreadsheets were based on those provided by Arup for each Municipality in the region (each Wijk within the City of Groningen), providing basic information on each building: a unique BAG identifier, the street address, year of construction, primary use, adjacency (detached vs terraced etc.), PGA contour on the 2013 KNMI map and a link to Street View.

Surveyors were then walked through the survey process and the main tools used for the survey:

- Google Street View & Google Earth
- BAG viewer (https://bagviewer.kadaster.nl/lvbag/bag-viewer/index.html - invaluable for precise determination of which building has which address)
- PDOK viewer (http://pdokviewer.pdok.nl/index.html - useful for more accurate measurement of distances along facades and/or from facades to public space).

Surveyors then spent typically 2 days working in pairs before starting to "work solo" on the surveying. As part of the process, the surveyor initialled each building and hazardous object identified, and gave a code to each to state whether they were confident with their assessment or would like a colleague to review it. The Team Leader (Florence Pickup) reviewed requests for review each evening and provided the Team Director (Tony Taig) with a summary of issues arising and proposals for resolution. In the early weeks of the survey the Handbook was updated daily. Weekly meetings were held throughout to discuss tricky issues arising and exchange good practice ideas for surveying – an interesting mix of gamers with lightning keyboard skills teaching keyboard short cuts to some steadier team members, and in return being trained themselves in how to maintain concentration and reduce error.

The initial team comprised 12 surveyors, but it became clear that more would be needed to complete the H and M priority Municipalities in a timely manner. The team was rapidly expanded to 20 and, as students left for university in September, additional new graduate members were recruited to maintain a smaller but viable (8 people) team to complete the M priority Municipalities and assist with the application of the risk assessment process to the surveyed buildings.

Surveying of the last H priority Municipality was completed on 20 August, at which point the entire team was switched into checking (see 3.3 below) before resumption of survey work on M priority Municipalities in September. Surveying and the (agreed) limited checking of the M priority Municipalities was completed on 14 November 2015.

3.3 Survey QA & Checking

It was appreciated from the outset that this was a rapid, approximate process for screening large numbers of buildings quickly, and that it would be impossible to check the results for every building and hazardous object. The main elements of the assurance processes built into the survey to assure its fitness for purpose were:

During the Survey Process:

1. Design of the survey spreadsheet template with standardisation of data fields to prevent inadvertent mis-keying of entries and conditional formatting to guide surveyors as to which fields required completion, dependent on initial inputs for a whole building
2. Surveyor selection and training
3. Self-assessment by surveyors of each building and hazardous object, enabling the Team Leader to appraise the judgment and reliability of individual surveyors
4. Daily review of a large sample of surveyors' work and updates to the Survey Handbook
5. Weekly meetings to discuss difficulties and share good practice
6. Sharing of survey files with Arup Groningen office and spot checks of sample buildings against RVS reports where available.

On Completion of a Surveyed File:

1. ***For H priority Municipalities only:*** Random selection of 20% buildings for peer review by fellow-surveyors (plus extension of any modifications made to similar buildings in the same street – providing coverage to 30%+ buildings for most Municipalities/Wijken).
2. ***For M as well as H priority Municipalities (this and subsequent steps):*** Application of Risk Assessment to the checked file (this reveals various anomalies that may be missed during checking, in particular as risk fields that fail to compute because other fields are entered incorrectly or in the wrong place).

3. Random selection of 2% of buildings for final TTAC review by trusted surveyors, with the aim of quantifying the error still embedded in the checked files.

4. Repetition of the Risk Assessment for the 2% checked buildings and evaluation of the difference to risk associated with any changes made as a result of the final 2% TTAC checks.

5. Random selection by Arup Groningen office staff of a 10% sample of all TTAC's 2% checked buildings to provide independent verification of the quality of the final TTAC checks.

6. Workshops held with Arup Groningen staff both before and after risk assessment of the survey files, to discuss and qualify differences revealed in the checking process and to "sense check" the risk assessment results (and thus the survey data which underpinned them).

The survey was, by design, a once-through, high-speed process for which it was impossible to re-survey and check every building. It is inevitable that there will be inaccuracies and inconsistencies within the final Survey spreadsheet files. The purpose of points 3-7 above (on completion of a surveyed file) is to quantify how much difference those inaccuracies and inconsistencies have made to the estimated risk per building.

In the course of the survey we have identified for each Municipality the number of buildings that could not be surveyed because they were either obscured or not built at the time the latest Street View photographs were captured. After completion of checking of the H priority survey results, one of the team spent a week at the Arup office in Groningen to survey a sample of such buildings using the RVS files, rather than Street View, as his information resource. A sample of 245 buildings was surveyed in this way.

The intent of these QA arrangements is that, on completion of the risk assessment of the buildings surveyed, it should be possible to estimate the overall impact on aggregate risk across the building population of

a. Inaccuracies and inconsistencies in the final spreadsheet files (as revealed by before and after risk assessment of the 2% sample of buildings checked by our surveyors)

b. Inaccuracies captured by Arup's more detailed survey of a sample of our 2% checks, based where possibly on the superior building and HRBE information available in RVS reports (from the checking completed by Arup at the time of writing it seems clear that the net effect of this will be to establish the degree by which our survey underestimates risk because of the building elements missed in the Street View survey), and

c. Incompleteness associated with buildings obscured, not covered in Street View or not built at the time the Street View photographs were taken.

4. Results

An overview of the survey results for the High priority Municipalities is provided in tables and charts as follows:

- Table 5: Overview of building classifications by building primary use, summed over all Municipalities
- Figure 1: Count of object types, summed over all Municipalities, and Table 6 (same information, with additional information on numbers of each object type creating potential risk exposure above doorways, public space, and through building roofs)
- Figure 2: Hazardous objects by type and exposure route (doorways, public space, through roofs), all Municipalities
- Figure 3: Hazardous objects by group and Municipality.
- Key summary statistics include
- 160,000 buildings surveyed in just over 2 months by a team of 20 surveyors
- 120,000 potentially hazardous objects identified, with the largest numbers comprising chimneys (47,000), gables (29,000 including Dutch Gables), canopies (16,000) and parapets (8,000)
- Were these hazardous objects to collapse in an earthquake,
  - just over 2/3 could fall within 1m of a doorway,
  - just under 2/3 could fall into publicly accessible space in front of or around buildings,
  - just under 4% could fall from height onto the roof of an occupied building.

IMPORTANT NOTE – these numbers are NOT classified here as "High Risk Building Elements". The existence of a chimney or gable does **NOT** of itself mean it is high risk. The risk assessment of identified potentially hazardous objects is presented in the Main Report. No conclusions about the numbers of high risk objects likely to require upgrade can be drawn from this appendix.

Table 5: Buildings Surveyed, by Primary Use and Building Category

Primary Use	**P**	**P No Hazard**	**D**	**N**	**O**	**T**	**X**	**Z**	**Total**
Accommodation	114	14	0	5	436	9	1	0	**579**
Educational	179	137	9	15	79	4	0	0	**423**
Gathering Place	649	280	40	56	312	22	19	0	**1378**
Healthcare	87	59	14	23	46	3	0	0	**232**
Industrial	756	1053	146	422	853	136	498	0	**3864**
Office	642	348	61	80	123	33	6	0	**1293**
Other utilitarian	159	3078	21	171	2885	98	4831	0	**11243**
Residential	49325	31352	24210	23752	9473	1130	131	0	**139373**
Retail	1071	304	12	33	122	17	6	0	**1565**
Sports	46	63	5	10	85	4	8	0	**221**
Blank	32	0	12	0	0	0	0	14	**58**
TOTAL	**53060**	**36688**	**24530**	**24567**	**14414**	**1456**	**5500**	**14**	**160229**

Building Categories allocated during the Survey are as follows:

P Building with 1 or more facades within 5m of publicly accessible space

D Building with 1 or more hazardous objects above a doorway

N Building clearly visible and survey able which is neither P nor D

O Building or significant parts obscured or otherwise not visible in Street View

T Building not yet built when most recent Street View photographs taken

X Out of scope building (sheds, garages, small unoccupied buildings that are not P)

Z Buildings not present in the BAG database

Table 6: Hazardous Objects by Type and Exposure Route, All Municipalities

Object Type	Total	Above doorways	Above public space	Elevated above roofs	Object group (for Fig 3)
Balcony	3472	2326	2567	1	Other
Balustrade	4285	2759	3306	50	Other
Bay window	2034	1365	1893	0	Other
Canopy-supported	1683	1399	1025	2	Other
Canopy-unsupported	14005	12704	7346	6	Other
Chimney	47371	30109	27367	4776	Chimney
Decorative feature	706	475	613	11	Chimney
DG-gable	709	528	651	9	Gable
DG-parapet	709	514	651	15	Parapet
Dormer	2244	1793	1995	4	Parapet
Flagpole	1086	500	1049	4	Other
Free standing wall	1507	1101	685	72	Parapet
Gable	28139	14515	17966	1187	Gable
Industrial object	77	24	54	17	Other
Large glass area	537	390	436	4	Other
Other	108	63	90	4	Other
Parapet	7557	5255	6390	218	Parapet
Pinnacle	363	174	335	26	Chimney
Sign - horiz	2406	1309	2244	17	Other
Sign - vert	1181	561	1138	1	Other
Walkway	39	15	36	0	Other
TOTAL	**120218**	**77879**	**77837**	**6424**	

Note that the totals by exposure route sum to more than the total number of objects, as some objects involve exposure by more than one exposure route. The right hand column shows the grouping to which each object type is allocated in Figures 3.

Figure 1: Total Hazardous Objects Recorded, by Type of Object, All Municipalities

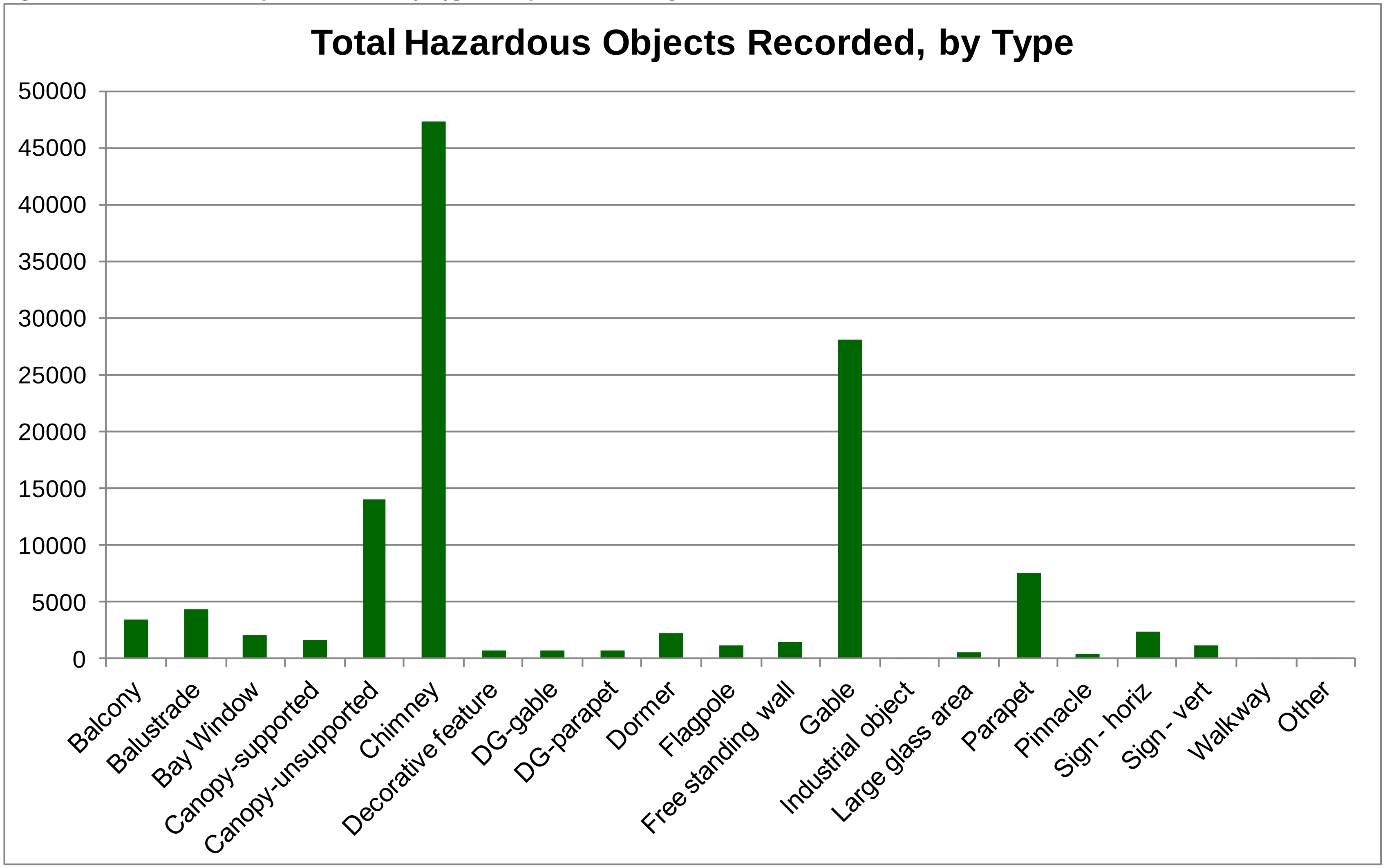


Figure 2: Hazardous Objects by Type and Exposure Route, All Municipalities

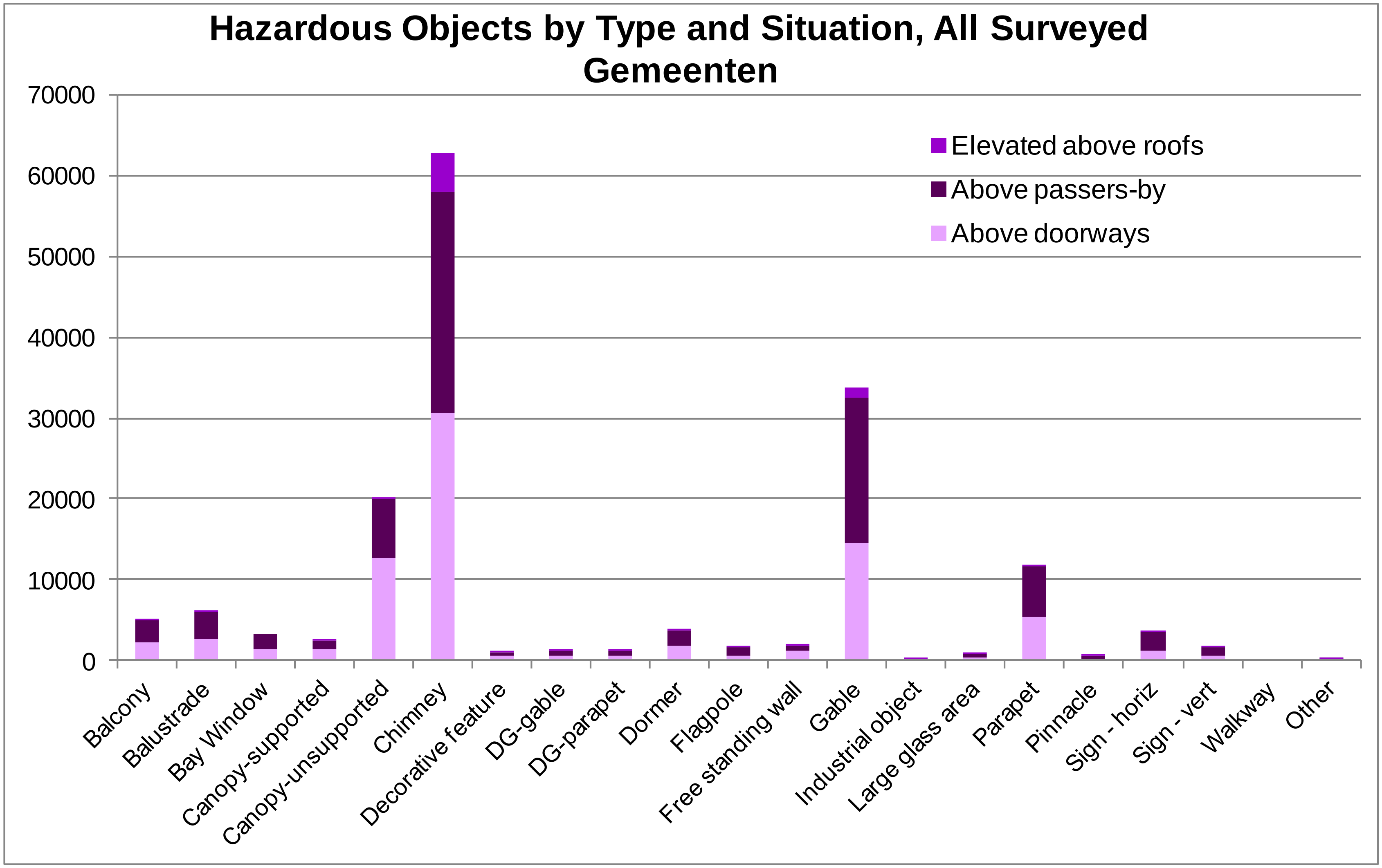
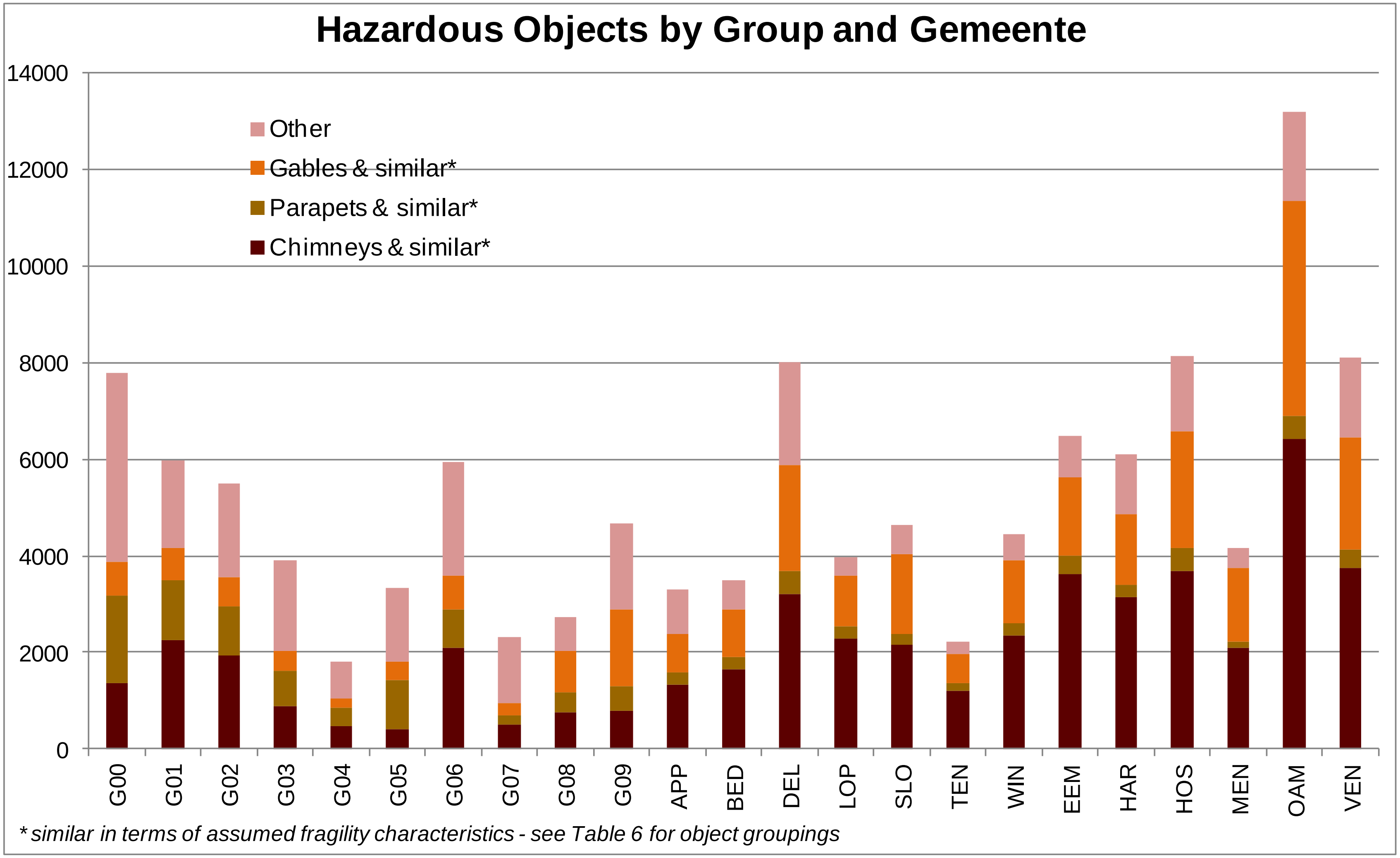


Figure 3: Hazardous Objects by Object Group and Municipality



Key: Groningen Wijken*: G00 - Binnenstadt; G01 - Schilders en Zeeheldenw; G02 - Oranjewijk; G03 - Korrewegwijk; G04 - Oosterparkwijk ; G05 - Oosterpoortwijk; G06 - Herewegwijk en Helpman; G07 - Stadsparkwijk; G08 - Hoogkerk; G09 – Noorddijk*

Key: Other Municipalities*: APP – Appingedam; BED – Bedum; DEL – Delfzijl; EEM – Eemsmond; HAR – Haren; HOS – Hoogezand-Sappemeer; LOP – Loppersum; MEN – Menterwolde; OAM – Oldambt; SLO – Slochteren; TEN – Ten Boer; VEN – Veendam; WIN – Winsum*

Annex 1: Falling Hazards Identification via Street View

X1.1. Introduction

This note summarises the results of pilot studies to collect falling hazards information using Street View in Bedum and in Groningen City.

The first part of the note provides a comparison of falling hazards identified in the central area of Bedum by Google Street View and via Rapid Visual Screening (RVS). The Street View data was collated by Florence and Harry Pickup of TTAC Ltd during December 2014 and January 2015. The RVS were carried out by Arup during the first half of 2015.

A second Street View survey was carried out by Florence Pickup in May 2015 on a sample of buildings in the central area of the city of Groningen to test the degree to which a Street View based approach would be able to identify and characterise falling hazards in a city environment with taller buildings and narrower streets.

The note presents

- The approach adopted for the Street View survey (Section 2)
- A comparison of falling hazards identified in Bedum (Section 3),
- A discussion of the pilot Street View survey in Groningen city (Section 4), and
- Conclusions as to the pros and cons of using Street View as opposed to capture falling hazard data (Section 4).

X1.2. Google Street View Survey Approach

The objective of this survey was to identify and characterise masonry falling hazards for a significant sample of buildings, so that the effort required and accuracy of identifying falling hazards could be compared via Street View and via RVS.

X1.2.1 Information collected

The survey was based on no resources other than Google Maps, Google Earth and Street View, so assignment of addresses to individual buildings was occasionally difficult. The information collected was designed to provide the necessary inputs for the falling hazard risk model currently under development, and thus includes various aspects of falling hazards not covered in the RVS. For example

- All chimneys (not just slender or poor condition ones classified as HRBEs) are covered in the Street View survey
- Falling hazard dimensions are recorded in the Street View survey

- Falling hazard location and roof information are collected in the Street View survey to enable the proportion of debris that would fall towards each building facade to be estimated.

The following categories of data were collected. A more complete description of the data fields and conventions used for data entry is provided in Appendix 1.

Building:	**Hazard:**
Location	Type
Address	Height
Type of street	Width
Identifying features	Depth
Facade	Height above ground
Door	Horizontal distance from nearest point of door
Facade width	Hazard location
Distance of wall from street	Direction of slope/Nearest facade
Number of storeys	Condition
Wall type	
Roof material	
Roof slope	
Roof type	
Neighbouring hazard	

The survey data was collected in a single pass through in Street View; no checks were carried out afterward, so that the survey would represent a “raw” sample of data.

X1.2.2 Street view survey experience

A team of two covered the town of Bedum, a total of 2592 buildings, in 3-4 weeks. Overall 1426 buildings with hazards were identified. We estimate that a fully trained and experienced person carrying out this type of analysis could cover about 100 buildings per day.

Positive and negative aspects of the experience of trying to identify and characterise falling hazards in this way were noted at the time as follows:

Positives:

- Clear view of most buildings and falling hazards (only 28 houses obscured, just over 1%)
- Ability to see most buildings and hazards from multiple angles/perspectives
- Ability to quickly explore the area
- Ability to estimate dimensions and capture other data not collected in RVS but of relevance for falling hazard risk
- Unaffected by weather/time of day
- Ability to work from any location

Negatives:

- Difficult to see condition of falling hazards – some (e.g. angled or bowed walls identified as HRBE) cannot be identified.
- Some new housing developments were not built at the time Street View was done.
- Wall type can be difficult to identify when buildings are set back from the road.
- Addresses could not always be determined with confidence.

Of the 2,592 buildings covered in the Street View survey, 556 were the subject of RVS during early 2015. A comparison between the falling hazards identified via the two approaches is presented in the following section.

X1.3. Comparison of Identified Falling Hazards

X1.3.1 Identified falling hazards - data

In order to compare the data the 556 addresses were matched up and falling hazard/HRBE categories were displayed in yes/no columns with the RVS and Street View results side by side. The Street View process identified 315 addresses with falling masonry hazards, while the RVS process identified 422 addresses with HRBE falling hazards.

Before considering which falling hazards were more or less completely identified in the Street View process it should be noted that the RVS's included 32 houses with falling hazards in a single new street, which was still being built when the current Street View photographs were taken and thus could not be covered in the Street View survey.

A summary of the numbers of identified hazards is provided in Table X1.1.

Table X1.1: Identified Falling Hazards - Bedum

Hazard Type	Street View	RVS	RVS (excl newly-built street)
Chimney	282	330	330
Parapet	12	79	71
Dormer	36	78	54
Canopy	1	101	95
Balcony	0	24	24
Decorative brick columns	10	0	0

At first sight it appears that the Street View survey has missed a lot of falling hazards identified in RVS. This is not in fact the case, as is discussed below; a major reason for difference is that the Street View survey scope was to identify masonry falling hazards whereas the RVS includes numerous lighter weight material hazards.

X1.3.2 Discussion of Street View vs RVS Identified Falling Hazards

The houses in the newly-built street noet covered by Street View account for 24 dormers, 8 parapets and 6 canopies identified in the RVS but not in the Street View survey.

There were cases where the Street View results and RVS results involved the same building, but recorded under different addresses. This type of error could be prevented if both teams used the same list of addresses, but might still require a rapid cross-check in the field to ensure 100% accuracy of address allocation to buildings in a StreetView survey. (Note - this does not affect total numbers of identified falling hazards.)

By far the largest difference in the number of addresses with hazards was attributable to the different criteria used to specify and record them. The Street View survey set out only to identify masonry hazards, whereas many of the parapets, canopies and balconies identified via RVS were not of masonry construction. This discrepancy could readily be resolved by appropriate definition of the scope of coverage in each type of survey – in some cases we felt that the RVS had included potentially significant non-masonry falling hazards, in others that identified HRBEs in the RVS corresponded to little or no risk. Additional differences were noted in relation to specific hazard types as follows.

Chimneys

The factors that contribute to the difference in the number of chimneys recorded are as follows.

Firstly, the RVS data counts a chimney that is shared by a semi-detached or terraced house as 1 chimney per address. As such chimneys are shared by 2 addresses they are counted twice in the RVS dataset. Similarly in a row of terraced houses each address has been identified as having a chimney. In the Street View data such chimneys were recorder once, and a column ‘Neighbouring hazard’ was used where a chimney was shared between two addresses (typically in a row of terraced houses) and was close to the door of the neighbouring address. This ensured that the chimney was not counted twice but any potential hazard to other properties was identified.

Secondly, there are houses where RVS has recorded a chimney but it cannot be seen on Street View. This could be because the chimneys are on the rear of the property and there is a way of seeing it that is not accessible on Street View, or because metal chimney pipes have been classed as chimneys. In either case, there is no hazard or risk in relation to the public space outside the front of the building.

Chimneys: the 50 net additional chimneys identified via RVS to those identified via Street View are made up as follows:

- 18 shared chimneys counted twice in RVS
- 28 chimneys were not visible from Street View (obscured – largely presenting little or no hazard to people in streets)
- 9 were missed in the Street View survey
- 11 had no visible falling hazard in Street View
- 16 chimneys identified in Street View but not classified as HRBE in RVS.

Of the chimneys missed, most related to confusion over building addresses, and only 1 presented a potential hazard to people in the street. Two were genuinely missed but we are confident would have been found via a simple checking process, either using Street View or (for maximum reliability) on the ground.

Parapets

There is a large difference in the number of parapets identified, arising primarily from the restriction of the Street View survey scope to masonry parapets. The RVS includes considerably numbers of parapets that are clearly not of masonry construction, or in some cases parapets that we would not have been identified as such. Such discrepancies could be resolved by agreeing a definition of potentially hazardous parapets.

There are also a number of dormers that have some decorative stonework and/or masonry around and/or above the window. In the Street View data this was included in the dormer measurement and not separated into dormer and parapet. Parapets: the 66 (net) additional parapets identified via RVS compared with Street View are made up as follows:

- 3 were obscured in Street View
- 3 were missed in Street View survey (one presented no hazard to the street, another was very small, and the third could have been identified through training of the Street View surveyor to recognise a change in brickwork corresponding to a parapet)
- 36 were not of masonry construction or would not have been classified as parapets in our Street View survey
- 12 were Dutch Gables which we would not have classified separately as parapets
- 4 parapets were identified in the Street View survey but classified as decorative brick columns, and
- 8 were not constructed in time to feature in the current Street View version.

Dormers

The largest difference between the surveys in their identification of dormers is that the RVS included examples not identified in the Street View survey where the wall is a continuation from the lower storeys, rather than a separate structure on the roof. We would expect dormers whose fronts are extensions of structural walls to behave more similarly to gables than to masonry dormers (where the masonry structure is built onto the roof beams or is providing a brick “skin” over a wooden structure).

The 47 additional dormers identified via RVS compared with Street View are made up as follows.

- 3 were obscured in Street View
- 2 were missed in the Street View survey
- 3 were counted twice (for 2 addresses) in RVS but once (as single structure) in the Street View survey
- 3 were not of masonry construction
- 11 were considered more similar to gables so were not recorded as dormers in the Street View survey, and
- 25 were not constructed in time to feature in the current Street View version.

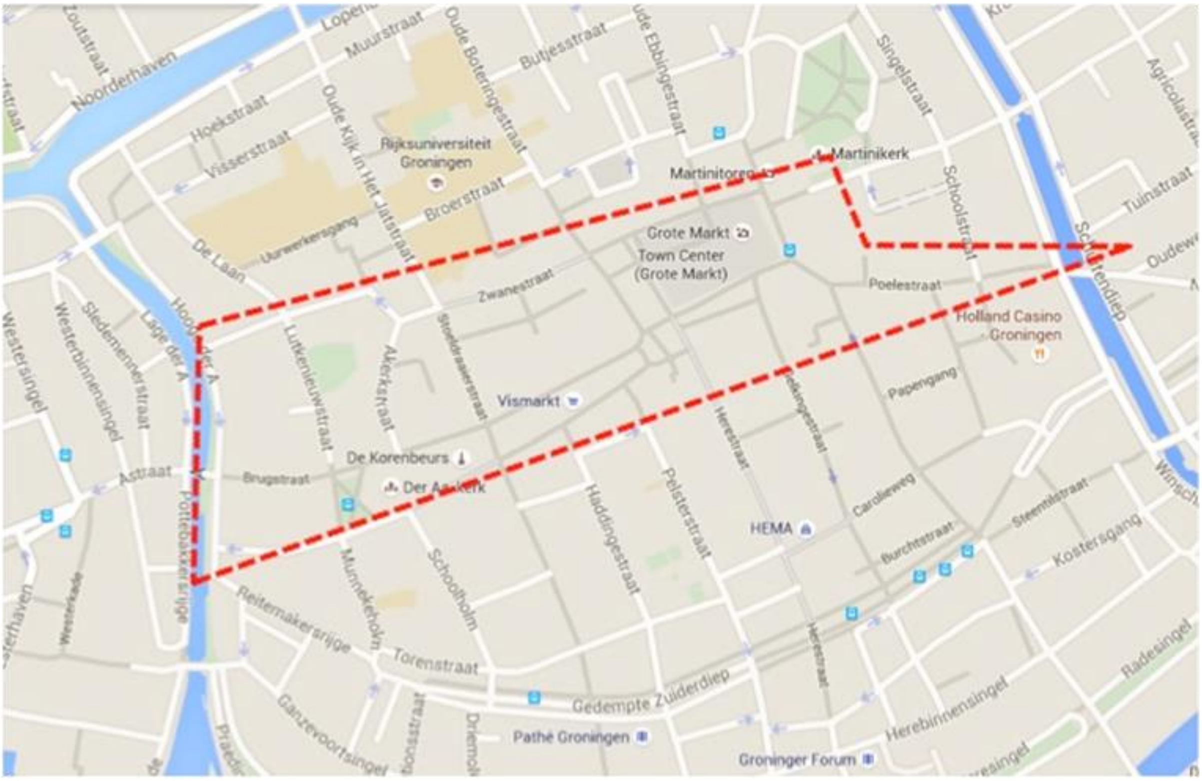
Canopies and balconies

This is the biggest apparent difference between the two datasets and accounts for most of the difference in number of addresses with hazards. The RVS sample included numerous non-masonry canopies and balconies identified as HRBEs, some of which were small and clearly of lightweight construction and were omitted from the survey as they were not considered to constitute significant falling risk. The scope of the survey was limited to canopies and balconies considered to represent a significant fatality risk were they to collapse.

X1.4. Pilot Street View Survey of Groningen City

The pilot Street View survey of Groningen was effectively an experiment to test whether the types of falling hazard that were visible on Street View in Bedum would still be visible in a city environment with taller buildings and narrower streets. An area of 22 streets in the centre of Groningen was surveyed, covering 523 buildings spanning a wide range of building uses and ages. The survey area is shown in Figure X1.7.

Figure X1.7: Area of Groningen Surveyed



The following masonry falling hazards, based on the set seen in Bedum and other small towns, were recorded

- Chimneys
- Parapets
- Dormers
- Decorative stonework
- Spires

A walk-through was carried out in Groningen to check the results of a sample of 239 buildings, already surveyed via the Internet, and compare the number of hazards visible on Street View to the number seen from the ground. The height of the buildings and the narrowness of the streets were the main differences in the two surveys. The buildings in the survey area varied from 1 to 5 storeys. However, this did not cause any difficulty in analysing HRBEs as the quality of the Street View images meant that the top of all buildings was clear to see.

A summary of the numbers of identified hazards is provided in Table X1.2. Those missed were a combination of hazards not being clearly visible, visible hazards not being identified and hazards that were a different style of construction that were not common in Bedum.

Table X1.2: Identified Falling Hazards - Groningen

Type	Total	No. missed via Street View	Reasons not identified via Street View
Chimney	52	1	Not clearly visible – between 2 buildings
Parapet	27	2	1 not identified due to style and 1 missed
Dormer	25	1	Not identified due to style
Decorative stonework	9	0	
Spire	1	0	

Overall, there were only 4 hazards missed in Street View survey out of 120 identified in total (Street View plus walk-around). This is a better proportion than was achieved in the Bedum pilot survey – the difficulties associated with tall buildings and narrow streets were considerably less than those associated with trees obscuring buildings in the small village environment of Bedum. In addition there was one significant street (Zwanestraat) which could not be accessed on Street View, presumably because it is pedestrianized (though we had to walk around several delivery and maintenance vehicles while walking along it).

An interesting observation during our checking walk through Groningen was the number of buildings that had large visible wall ties. We believe that these were largely installed at the time when buildings were originally built, generally as a precaution against subsidence. Out of the sample number of buildings surveyed so far, 18% had visible wall ties. This could be of particular significance in evaluating the potential hazard from gables and parapets failing under earthquake shaking, and we would include consideration of such ties and other restraints or mitigating features in our review of falling hazards and their features to be identified in any future studies of this sort.

The visit to Groningen also highlighted a number of potential masonry falling hazards that had not been noted in the Bedum pilot survey, including:

- Bay windows
- Dutch Gables
- Gable end walls on facades above streets
- Brick infill panels in concrete framed buildings
- Pinnacles
- Balconies

Several non-masonry hazards were also noted that could be potentially hazardous to people in the streets, including:

- Glass atria
- Flag poles, statues, large signs and other objects protruding from the sides of, or above the facades of, buildings
- Large glass windows
- Balconies and canopies

We propose that a thorough review of the set of “potential falling hazards” is carried out, including these masonry and non-masonry items but also considering where the boundary should be set between (for example) a small, lightweight canopy of the type seen on the right in Figure 6 above (which we do not believe represents a hazard to life) and heavier canopies that do present a genuine risk in their own right (as opposed to when collapsing under masonry detached from above them).

As in Bedum, we carried out our survey in Groningen relying on Street View and Google Maps to find building addresses. We included an ‘Identifying features’ field in our database to reduce potential confusion, but considerable time in address matching could be saved by starting any such survey with an accurate list of buildings and addresses from which to work.

X1.5. Conclusions

Our conclusions are as follows.

1. Street View can enable someone who is not a buildings expert quickly and reliably (90% or considerably better) to identify significant falling hazards in either a village or a city environment, and to collect information on them necessary for risk assessment which is not currently collected in the RVS process.

2. A trained and experienced Street View surveyor should be able to survey of order 100 buildings per day, including collection of information on falling hazard dimensions and locations and other building/roof/facade features of relevance for falling hazard risk assessment.

3. The main limitations in using Street View to collect falling hazards information relative to “on the ground” inspection/survey are
    a. Inability to survey recently built buildings
    b. Obscuring of buildings by trees and, occasionally, other buildings, and
    c. Limited ability to assess the condition of potentially hazardous building elements.

4. In our Street View vs. RVS comparison for Bedum, out of a total of 556 buildings covered by RVS, the Street View survey

   a. Could not cover 32 buildings (with falling hazards identified via RVS) which were not built when the most recent Street View photographs were taken
   b. Was unable to survey 15 buildings of which the view was obscured by trees or other buildings
   c. Missed 14 other masonry falling hazards that were identified in RVS (largely for reasons readily addressable via simple checking processes, and in all but one case presenting minimal or no risk to people in the street), and
   d. Identified 16 masonry chimneys not classified as HRBEs in RVS.

5. Our pilot survey in Groningen City found that
   a. the difficulty of identifying falling hazards associated with tall buildings and narrow streets in an urban environment was less than that associated with trees and limitations of Street View access in a village environment, but
   b. several types of building elements presenting potential falling hazards needed to be added to the list developed to date (based on RVS and other surveys in village environments) for application in an urban environment.

6. A thorough review of the set of building features constituting “falling hazards”, the criteria for identifying them as potential hazards to life, and of their features to be recorded, should be carried out prior to wider surveys based on Street View, or to any other data collection programme for use in assessing falling hazard risk (note that RVS does not currently provide the information on falling hazards that is used to calculate their risk in our falling hazards risk model).

7. Street View could NOT be used to provide a definitive analysis with 100% accuracy of every falling hazard. It is, however, eminently suited in our view for collection of data to support risk assessment and prioritisation of buildings for upgrade of building elements (as opposed to structural upgrading) at regional, community or more local levels.

Florence Pickup & Tony Taig

TTAC Ltd

9 June 2015

(a) WIN Falling Hazard Objects by OCR and OIR Bands

Community Risk (OCR), fatalities/year	Individual Risk (OIR), probability of fatality per year						OCR Band TOTALS
	OIR<=1E-8	1E-8<OIR <=1E-7	1E-7<OIR <=1E-6	1E-6<OIR <=1E-5	1E-5< OIR<=E-4	OIR>1E-4	
OCR>1E-4	0	0	0	0	0	0	**0**
1E-5<OCR<=1E-4	0	0	1	0	0	0	**1**
1E-6<OCR<=1E-5	1	5	32	28	0	0	**66**
1E-7<OCR<=1E-6	12	170	487	0	0	0	**669**
1E-8<OCR<=1E-7	187	1899	17	0	0	0	**2103**
OCR<=1E-8	1321	296	0	0	0	0	**1617**
OIR Band TOTALS	**1521**	**2370**	**537**	**28**	**0**	**0**	**4456**

(b) Significant WIN Falling Hazard Objects by Object Type and Community Risk (OCR) Band

		Community Risk (OCR) Band					
Object Type	**Total**	**OCR>1E-4**	**1E-5<OCR <=1E-4**	**1E-6<OCR <=1E-5**	**1E-7<OCR <=1E-6**	**1E-8<OCR <=1E-7**	**OCR<=1E-8**
Chimney	2322	0	0	12	233	1311	766
Decorative feature	19	0	0	1	2	2	14
Pinnacle	11	0	0	0	2	5	4
Parapet	120	0	0	4	40	44	32
Balustrade	31	0	0	1	4	4	22
Free standing wall	79	0	0	1	46	27	5
Gable	1287	0	0	38	287	608	354
DG-parapet	15	0	1	2	6	6	0
DG-gable	15	0	0	1	6	6	2
Dormer	53	0	0	4	33	15	1
Canopy-supported	44	0	0	0	1	19	24
Canopy-unsupported	319	0	0	0	6	42	271
Balcony	34	0	0	0	0	5	29
Bay window	3	0	0	0	0	0	3
Large glass area	11	0	0	2	1	1	7
Sign - vert	24	0	0	0	0	0	24
Sign - horiz	50	0	0	0	0	8	42
Industrial object	1	0	0	0	1	0	0
TOTAL	**3303**	**0**	**46**	**1035**	**1373**	**699**	**150**
% of objects in OCR band ====>			*1.4%*	*31.3%*	*41.6%*	*21.2%*	*4.5%*

(c) WIN Falling Hazard Objects by Object Type and Individual Risk (OIR) Band

		Individual Risk (OIR) Band					
Object Type	**Total**	**>10-4**	**10-5 to 10-4**	**10-6 to 10-5**	**10-7 to 10-6**	**10-8 to 10-7**	**<=10-8**
Chimney	2322	0	0	4	161	1355	802
Decorative feature	19	0	0	1	1	2	15
Pinnacle	11	0	0	0	2	7	2
Parapet	120	0	0	0	33	56	31
Balustrade	31	0	0	0	5	4	22
Free standing wall	79	0	0	0	22	54	3
Gable	1287	0	0	22	260	843	162
DG-parapet	15	0	0	0	10	5	0
DG-gable	15	0	0	0	5	9	1
Dormer	53	0	0	0	37	16	0
Canopy-supported	44	0	0	0	0	4	40
Canopy-unsupported	319	0	0	0	0	8	311
Balcony	34	0	0	0	0	1	33
Bay window	3	0	0	0	0	0	3
Large glass area	11	0	0	1	1	5	4
Sign - vert	24	0	0	0	0	0	24
Sign - horiz	50	0	0	0	0	0	50
Industrial object	1	0	0	0	0	1	0
TOTAL	**4456**	**0**	**0**	**28**	**537**	**2370**	**1521**
% of objects in OIR band ====>			*0.0%*	*0.8%*	*16.3%*	*71.8%*	*46.0%*

Client: Nederlandse Aardolie Maatschappij

Arup Project Title: Groningen Earthquakes Structural Upgrading

Risk Assessment of Falling Hazards in Earthquakes in the Groningen region: Appendix 8 Evaluation of Uncertainties and Inaccuracies

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Arup bv
PO Box 57145
1040 BA
Amsterdam
The Netherlands

ARUP

Contents

Appendix 8: Falling Hazards Survey and Risk Assessment - Evaluation of Uncertainties and Inaccuracies

Summary

The Falling Hazards Risk Assessment carried out for non-structural building elements in respect of seismicity in the Groningen region is based on

a) a quick-look internet-based survey of objects present and their characteristics, which has inherent limitations and contains inevitable inaccuracies, and

b) a simple risk model combining empirical fragility information with simplified models for people's exposure to risk.

Obvious questions thus arise as to what the survey might have missed, and what reliance can be placed on the results. In particular, to what degree does the approach generate "false positives" (objects assessed as high risk but which are not in fact so), or "false negatives" (objects assessed as lower risk but which might in fact be high risk)?

This appendix explains the approach adopted and the results of work carried out to address these important questions, in particular

- Checks of the survey data carried out by TTAC Ltd and Arup
- "Sense checks" carried out after risk assessment, and re-work to address the findings of the survey data and sense checks, and
- Sensitivity studies carried out to explore the impact of modelling uncertainties on risk.

Our conclusions are:

1. It has been possible to characterise the impact on the assessed risk of survey omissions and inaccuracies and of the risk model assumptions and uncertainties used.
2. As expected the combination of survey and simple risk assessment assumptions provide both false positives (cases identified as higher risk where the true risk is lower) and false negatives (cases of high risk that fail to be so identified by the assessment).
3. For building facades that could be surveyed, the proportion of higher risk cases missed is expected to be no greater than about 10%, while the proportion of cases in which risk is significantly overstated may be around 15-20%.
4. The combination of survey and risk assessment results is fit for purpose for prioritising areas for on-the-ground inspection for falling hazard risk.
5. The sense checks carried out have provided substantial insight into the local issues that can make a big difference to risk, and which should be reflected in both
   a) Specifying what information is to be collected during on-the-ground inspection, and
   b) Tools to assist local inspectors and others in making upgrade decisions for specific objects and buildings.
6. The combination of survey and risk assessment results does not provide a reliable assessment of overall risk from falling hazards for the region. In particular

a) About 10% of buildings could not be surveyed
b) There will be additional objects and risk associated with facades not visible (particularly the rear) on the buildings that could be surveyed
c) About 10% of relatively high risk objects may have been missed by the survey
d) 15-20% of objects may have their risk overstated significantly as a result of the combination of survey data and simple model assumptions, and finally
e) Uncertainties in modelling seismicity, object fragility and people's exposure to risk make the model results uncertain within about a factor of 10 in either direction from the estimates presented in this report and companion reports.

Our recommendations are

1. After appropriate review, the falling hazards risk assessment should be adopted as the basis for prioritising areas for on-the-ground inspection with a view to falling hazard upgrades.

2. The insights gained from the sense checking described in this report should be used to assist in developing specifications for
   a) Information to be collected in on-the-ground inspections and
   b) Tools to guide decision making on upgrades for specific falling hazard objects

3. Considerable work will be required to adapt and develop the results of this assessment to provide reliable absolute estimates of falling hazard risk for the region. This should address
   a) Fragility of masonry objects
   b) Fragility of other objects such as balconies, canopies and large areas of glazing, for which we have little direct evidence to support the suppositions of relatively low fragility in comparison with masonry objects, and
   c) Exposure pathways to risk, for which the simple assumptions adopted in the model appear to overstate risk in a considerable number of cases (largely for building occupants exposed to risk running outside during earthquakes or via objects falling through roofs), but also to be capable of understatement in others (largely for people outside buildings where occupancy depends strongly on local factors related to building use which cannot be seen in photographs), and
   d) Migration of the spreadsheet model into a more robust framework for holding and updating data and calculating results, along with work to harmonise the provenance of falling hazards risk and collapse risk quantitative models.

Tony Taig
Florence Pickup
TTAC Ltd

1. Introduction

The Falling Hazards Risk Assessment carried out for non-structural building elements in respect of seismicity in the Groningen region is based on

c) a quick-look internet-based survey of objects present and their characteristics, which has inherent limitations and contains inevitable inaccuracies, and

d) a simple risk model combining empirical fragility information with simplified models for people's exposure to risk.

Obvious questions thus arise as to what the survey might have missed, and what reliance can be placed on the results. To what degree does the approach generate "false positives" (objects assessed as high risk but which are not in fact so), or "false negatives" (objects assessed as lower risk but which might in fact be high risk)?

This appendix explains the approach adopted and the results of work carried out to address these important questions. It covers

- The approach adopted (Section 2)
- Survey data quality checks (Section 3)
- Post-risk assessment checks and re-work (Section 4), and
- Sensitivity studies into the effects of uncertainties (Section 5) before presenting
- Our conclusions and recommendations (Section 6).

The reader is assumed to be familiar with the terminology in widespread use in discussion and management of seismic hazards in the Groningen region; this appendix does not repeat explanations already covered in the main report and other appendices.

2. Evaluation approach

The Falling Hazards Survey on which this assessment is based was by design a rapid, once-through, internet-based (Google Street View) scan of buildings. The risk model used to assess risk for the objects identified in the Survey is a simple, empirical tool. It has been recognised from the outset of this project that there would inevitably be inaccuracies and omissions from the Survey, and that the simple assumptions made in the risk model would be more or less appropriate for different objects and buildings.

The overall approach to quality control is based on the principles that

1. It was impossible with the time and resources available to remove all errors, inconsistencies and sub-optimal model assumptions for individual buildings and objects from the survey data and risk assessment

   BUT

2. It was possible through appropriate checks on samples of data and assessment results to evaluate the impact of errors, inconsistencies and sub-optimal model assumptions on the risk outputs calculated through this process.

The measures taken to control Survey data quality and evaluate the appropriateness of the model assumptions (via what we refer to as “Sense checking”) are explained in terms of what was done during the survey process, and what was then done with the data once an area had been surveyed.

The High and Medium (H & M) priority Gemeenten referred to throughout this report are as follows.

High Priority (H)	Medium Priority (M)
Appingedam	Eemsmond
Bedum	Haren
Delfzijl	Hoogezand-Sappemeer
Groningen (city)	Menterwolde
Loppersum	Oldambt
Slochteren	Veendam
Ten Boer	
Winsum	

2.1 During the Survey Process

The measures taken to control survey data quality included the following.

1. Buildings were split into convenient size groups (small enough to collect data and carry out risk assessments in an Excel spreadsheet) corresponding to individual Gemeenten or (for Groningen city) individual Wijken.
2. A standardised survey spreadsheet template was devised, using standardised data fields and drop-down menus to prevent inadvertent mis-keying of entries. Conditional formatting was used to guide surveyors as to which fields required completion, dependent on initial inputs for a whole building
3. Surveyors were recruited by invitation only from among people well known to the Project Director and/or Manager, based on intelligence, speed and reliability. Most were recent graduates or current undergraduates.
4. All surveyors were trained not only in the mechanics of carrying out the survey process, but also in the purpose of the survey to ensure that they knew why they were collecting information, as well as what it was they were being asked to collect. This proved particularly valuable – for example early in the process the surveyors identified important issues associated with objects with the potential to fall from height onto roofs which led to significant changes in the survey process and spreadsheet.
5. A Survey Handbook was produced at the start of the project to guide surveyors through the process, and was frequently updated (daily at the start of the project) to incorporate adjustments and clarifications revealed during surveying.
6. Prior to surveying individual potential falling objects, each building was categorised making it easy to identify and trace buildings that could not be surveyed via Street View.
7. Surveyors were asked to provide their own assessment of their survey of each building and hazardous object, enabling the Team Leader to appraise the judgment and reliability of individual surveyors.
8. The Project Manager carried out a daily review of a large sample of surveyors' work and, after consultation with the Project Director, made regular updates to the Survey Handbook
9. Weekly meetings of the survey team were held to discuss difficulties and share good practice. These included both discussion of issues requiring clarification and sessions to "accelerate" individuals by coaching from the quickest team members with fastest keyboard and short-cut skills.
10. Survey files were shared with Arup Groningen office staff, who carried out sample spot checks of buildings surveyed via the internet with "HRBEs" identified via RVS reports where available.

The Arup Groningen office staff provided invaluable advice throughout the survey process, based on their extensive experience in carrying out RVS and EVS inspections and in evaluating and dealing with High Risk Building Elements (HRBEs)[1].

2.2 On Completion of Surveying

Measures taken, first to check the survey spreadsheet files and then to assess the impact on risk of survey inaccuracies and appropriateness of model assumptions were as follows.

1. ***For H priority Gemeenten only:*** 20% of the buildings surveyed were selected at random for peer review by fellow-surveyors. Any modifications made were in addition applied to similar buildings in the same street – providing coverage to 40%+ buildings for most Gemeenten/Wijken).
2. ***For M as well as H priority Gemeenten (this and subsequent steps):*** The risk assessment process was applied to the survey spreadsheets. This revealed various anomalies that had been missed during checking, in particular via risk fields which failed to compute because other (survey data) fields had been entered incorrectly.
3. 2% of buildings were randomly selected for final TTAC review by trusted surveyors, with the aim of quantifying the error still embedded in the checked files.
4. The risk assessment was repeated for the 2% checked buildings and the risk results compared before and after the 2% checks.
5. Arup Groningen office staff randomly selected a 10% sample of all TTAC's 2% checked buildings and carried out more thorough checks (using RVS reports to provide higher resolution photographs and more detailed building information where available) to provide independent verification of the quality of the final TTAC checks. As for the TTAC 2% checks the risk was then re-assessed for the checked objects and a before/after checking comparison was made.
6. Details of buildings that could not be surveyed via Street View (either because they were obscured, or because they did not exist when the most recent Street View photographs were taken, or for any other reason) were collated. A surveyor then visited the Arup Groningen office, identified such buildings for which RVS reports were available, and carried out a "Survey via RVS reports" of a substantial sample of buildings. This enabled the risk associated with "Not surveyable" buildings to be compared with that from otherwise similar buildings for which Street View survey had been possible.
7. Beside the specific Falling Hazards survey data, there were relatively small numbers of objects for which risk was assessed as zero because of missing or zero internal population Where data was missing this triggered an error messages in the risk assessment and estimates of internal population were made by reference to average values for buildings of the same primary use; buildings. Where internal population in the exposure database had a zero value this did not trigger an error; such cases (of "zero risk only because of zero stated internal population") were flagged in the risk assessment spreadsheets.

[1] HRBE is a term defined specifically in relation to RVS. HRBEs include most of the types of non-structural building elements that could present falling hazards, plus some types of defective walls, but do not include all of the falling hazards included in this study (for example not all gable walls are classified as HRBEs, nor are chimneys with an aspect ratio less than 2:1).

8. Workshops were held with Arup Groningen staff both before and after risk assessment of the survey files, to discuss and qualify differences revealed in the checking process and to “sense check” the risk assessment results (and thus the survey data which underpinned them). In particular
    a) The discussion of findings from the Arup checking process focused on objects missed and potentially underestimated in risk terms (addressing the “What might have been missed/underestimated in risk?” question), while
    b) The sense-checks focussed on objects assessed as high Community Risk (>10^{-5} deaths per year), addressing the “To what degree is this process providing false positives, overstating cases of high risk?”
9. This process identified a number of key issues which warranted further work prior to completion and issue of the Version 1 Risk Model and assessment results. In particular
    a) Significant numbers of objects had been missed in the survey and TTAC checking process. The most significant in risk terms related to objects located where they could potentially fall from height onto/through roofs of occupied buildings.
    b) One other scenario was identified where the combination of (survey data) + (risk model) appeared potentially to be systematically underestimating risk in such a way that high risk objects might be overlooked. This related to public use buildings, where footfall around the buildings (as opposed to footfall of people walking past in the street) appeared to have been underestimated in some cases.
    c) Several areas were identified in which the simple risk model appeared likely to err on the high side in estimating risk. The most common related to
        i. Overestimation of the fragility of modern gables, and
        ii. Overestimation of exposure to risk via people running outside buildings during earthquakes, for larger buildings in particular.
    d) Further, more systematic checks were requested to ensure that objects were not being unduly assessed as “Not high risk” (focusing on objects within a factor of 10 risk of the 10-5/year definition of “High risk” used during checking).
10. Further work was undertaken to address the issues as follows.
    a) A rapid re-survey of all H priority Gemeenten was carried out focusing in particular on objects with potential to fall from height onto the roofs of occupied buildings.
    b) A check of 100 randomly selected objects was carried out on buildings where passers-by in the street would not be at risk but where there was public access to the exterior and the footfall around the building facade had been rated as low. This confirmed the finding from the initial checks that there had been a degree of systematic underestimation of footfall for “Low” rated such buildings. The 2,600 or so such buildings were resurveyed using improved guidance on conversion of different types of activity into footfall ratings.

c) A final review of fragility assumptions[2] was carried out leading to a modest downward revision of the assumed fragility of modern gables (but also to an upward revision of the assumed fragility of parapets and similar structures generally). The issue of over-estimation of risk associated with people running out of large buildings was considered too complex to be addressed via “quick fixes” prior to issue of the Version 1 risk model and assessments.

d) An evaluation of the risk assessments for 100 randomly selected objects with Community Risk in the range 10^{-6} to 10^{-5} deaths/year was carried out to provide a more systematic check on whether objects that should be assessed as “High risk” (taken for checking purposes as $>10^{-5}$ deaths/year) were incorrectly being assessed as lower risk based on either survey or model assumptions.

It should be noted that all these checks were being carried out whilst the risk assessment was still in progress, during which time both the model itself and the process of its application to surveyed objects was subject to review and refinement. The numbers of objects in particular risk bands in the final assessment is likely to differ from the numbers that are reported in the following sections of the report as a result.

By the nature of the survey and risk assessment process it is inevitable that there will be inaccuracies and inconsistencies within the final survey and risk assessment spreadsheet files. The purpose of the work reported here is to characterise inaccuracies and uncertainties, NOT to try and remove every error or inaccuracy.

The results of the post-survey checks and studies are presented in Section 3 (for activities focused primarily on the quality of the survey data) and Section 4 (for activities focused primarily on the appropriateness of the risk model).

[2] The fragility assumptions used in the model are based heavily on engineering judgment, informed (but not determined) by empirical evidence on performance of chimneys, parapets and gables in other earthquakes.

3. Survey Data Quality Checks

We present in turn the findings of our studies into the implications for risk of buildings where data could not be obtained (3.1), the findings of the systematic checking process and their implications for risk (3.2), and our conclusions from these checks (3.3).

3.1 Absence of Data

Neither the Survey nor the Exposure Database from which internal building populations were obtained was able to cover all buildings. The buildings covered in the Survey were categorised as shown in Table A8.1(a).

Table A8.1(a): Building Classification of Buildings within Survey Scope

Survey Category	H Priority Gemeenten	M Priority Gemeenten	Category Acronym
1 or more facade within 5m of public space	51,946	37,696	P
1 or more object within 1m of a doorway	15,204	9,285	D
Facades clearly visible, no objects recorded[3]	16,074	8,614	N
Out of scope, minor sheds, huts etc	3,620	1,878	X
Buildings obscured or otherwise not visible	9,261	5,168	O
Buildings not built when Street View photos taken	886	572	T
Buildings not in the building dataset provided by Arup	12	0	
TOTAL buildings within scope	**97,003**	**63,214**	

There were thus over 15,000 buildings in categories O and T above for which no survey was possible. In order to evaluate whether these buildings were typical of the others surveyed, or whether on the whole they represented higher or lower risk, a separate study was carried out in which one of the Surveyors visited the Arup Groningen office and surveyed a sample of 245 “O&T” buildings using the RVS reports, rather than Google Street View, as the source of information (note that this restricted the scope that could be covered to the Gemeenten around Loppersum where RVS had been carried out). The 245 buildings were selected at random from the RVS database for Appingedam, Loppersum and Slochteren Gemeenten. The mix (with “before” and “after” the RVS-based survey) is shown in Table A8.1(b).

[3] It should be noted that, by intent, the Survey recorded potentially hazardous objects only if they were situated above a doorway, public space, or 2m or more above the roof of an occupied building. This was because trial calculations with the risk model showed that the risk otherwise was very small in comparison. The set of objects identified thus does not include many objects that are situated elsewhere, in locations presenting relatively low risk. “Above a doorway” is defined as “Any part of the object is within 1m to left or right of the edge of the doorway, viewed from directly in front of the facade in which the door is located”. “Above public space” means that at least one facade to which the object might in principle fall were it to collapse is within 5 metres of land to which there is a public right of access. This thus includes the facades of many buildings such as schools, churches and hospitals as well as building facades within 5m of a public footpath, street or pavement.

Table A8.1(b): Building Classification of O&T Sample Buildings

Gemeente	*Buildings Analysed*			Category Determined via RVS						
	O	*T*	*Total*	P	D	N	O	T	X	Total
Appingedam	*54*	*10*	***64***	45	8	4	6	1	0	**64**
Loppersum	*125*	*9*	***134***	58	48	27	1	0	0	**134**
Slochteren	*42*	*5*	***47***	25	15	2	0	0	5	**47**
TOTAL	***221***	***24***	***245***	**128**	**71**	**33**	**7**	**1**	**5**	**245**

Note that the mix of buildings is dominated by "O" rather than "T", so the results tell us more about obscured than newly-built buildings. Note also that not all of the selected buildings could be classified as one of the main categories in relation to falling hazards (P, D, N), as files were not available for all buildings (e.g. because not yet in the central database or the RVS had not been able to be carried out), a handful of buildings were out of scope small utilitarian buildings (X) and one had been demolished before the RVS was carried out (T).

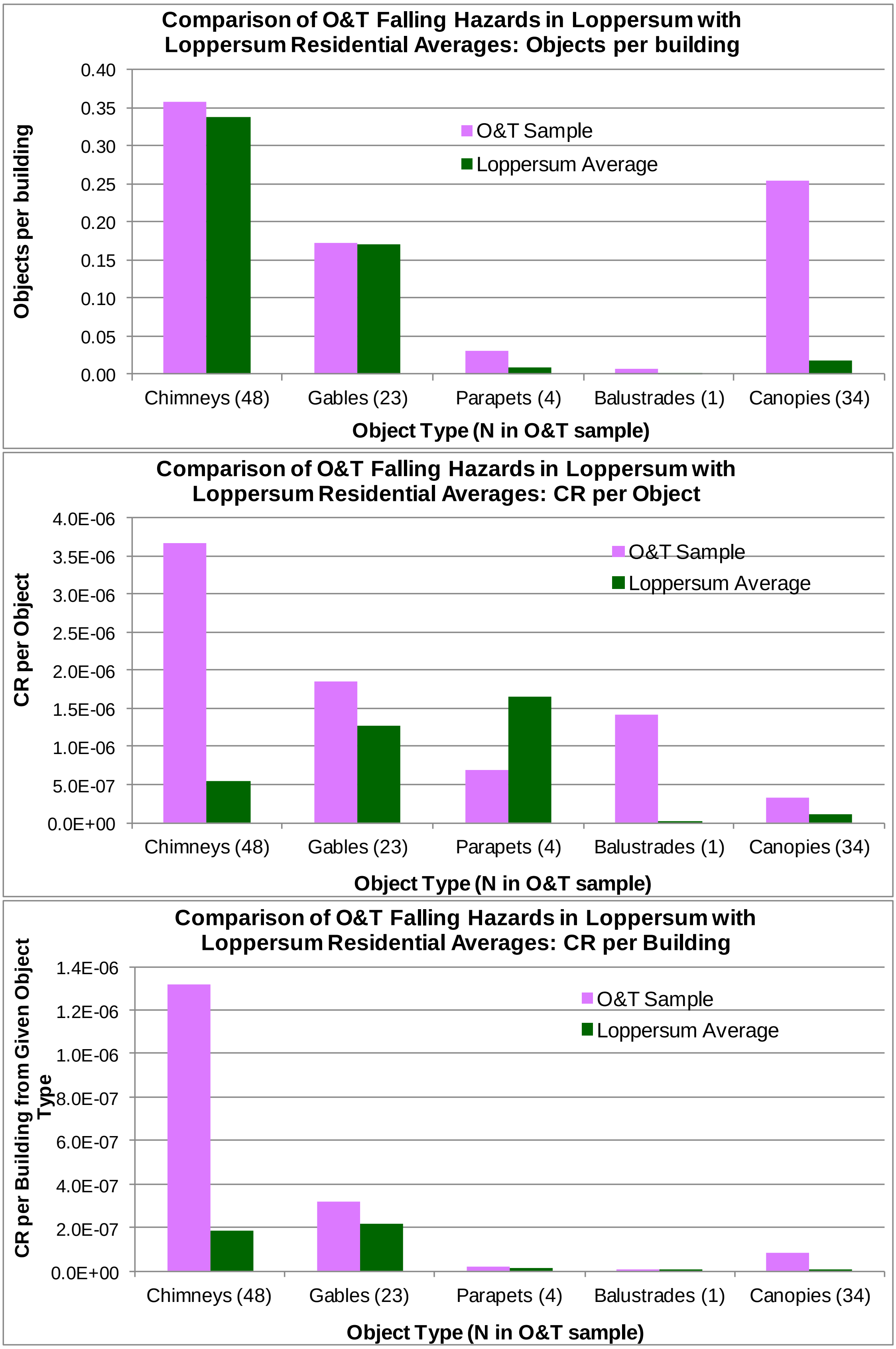
The results for the largest comparable sample of buildings (residential buildings) in the area with most buildings sampled (Loppersum Gemeente) are shown in Figure A8.1.

The charts in Figure A8.1 show that there are similar numbers of objects per building for the O&T sample in comparison with the average for all (4,304) residential buildings, with the exception of parapets and canopies. In the case of parapets this is because the O&T survey, based on the high resolution photographs available in the RVS reports, identified 3 tiny parapets above doors which would probably have been missed from Street View. In the case of canopies, those identified via the RVS reports were with one exception lightweight wooden structures (largely cornices at the top of building walls) which may not have been recorded in the Street View survey. We do not consider the results in terms of "Objects per Building" to differ significantly from the averages for other residential buildings in the Gemeente.

Of greater apparent significance is the substantially greater Community Risk (CR) per chimney assessed in the O&T sample in comparison with the average for the Gemeente. On closer examination, this turns out to be attributable entirely to the top 7 (in CR terms) of the 49 chimneys in the O&T sample. All seven were identified as "Capable of falling from elevated height onto a roof", which is identified in our risk assessment results generally as a particular risk factor associated with higher risk chimneys and gables.

With so small a sample we cannot be sure whether the set of "buildings not surveyable via Street View" does or does not on average have a higher percentage of chimneys situated where, if they fell, they might fall from height onto a roof. Without these top 7 chimneys, the risk per chimney in the O&T sample is similar to that from chimneys generally; with them the risk for chimneys is significantly higher among the O&T sample.

Figure A8.1: Comparison of Falling Hazards & Risk, Loppersum O&T vs Other Houses



The inability to survey buildings obscured (O) or not yet built when Street View photographs were taken (T) means that about 10% of buildings could not be surveyed. The O&T comparison study suggests that these buildings are likely to have similar numbers of hazardous objects per building, but may have higher average CR per object than their counterparts that were able to be surveyed.

The second area in which data for risk assessment was less than 100% reliable involved internal populations of buildings, which were looked up into our risk assessment spreadsheets from a table provided for all buildings in the region by NAM based on the V2 exposure database[4]. For over 90% of buildings this provided a sensible figure. Three types of issues were identified, though, with a minority of buildings:

a) Failure to find an internal population for the building (3,461 cases)
b) Finding a zero internal population for the building (5,229 cases), and
c) Inappropriate populations for buildings (unknown total number of cases).

For the first of these, a "fix" was adopted by filling in blank values with the averages for other buildings of the same Primary Use type for that Municipality (or Wijk in the case of Groningen city). It is recognised that this may mean the absolute values of risk when aggregated over all buildings are somewhat overstated, as the V2 exposure database was set up to exactly mirror the whole population of the region – by adding in further population for more buildings we may thus have effectively increased the total population at risk. The effects of any such overstatement are, though, small and are not considered material to the primary use of this study, which is to help prioritise areas for ground-based inspection as a prelude to upgrading decisions.

The second issue, of zero internal populations, is also a minor one. Most of the buildings concerned are of primary use "Other utilitarian", which are likely for the most part to be sheds, garages, outbuildings and others which are not normally occupied. A reasonable minority, though, were of other primary uses which did appear as though they should have reasonable average internal populations.

In the course of our checking of spreadsheet risk assessment files we identified several buildings that we would have expected to have significantly high Community Risk but did not because the building had zero population. These are highlighted in the risk assessment spreadsheets. We consider it possible that there may be a few percent underestimation of the numbers of buildings in high CR bands (via exposure outside doorways, or indoors via objects falling through roofs) for this reason (exposure of people outside buildings is not affected by this issue).

The third issue arose particularly in our "sense checking" of assessed high CR objects (see examples in Section 4.3 below). The key issue identified here was of ordinary residential buildings with anomalously large time-averaged populations, leading to anomalously large estimated CR.

[4] The Exposure Database developed by Arup and NAM is a database of buildings potentially at risk from seismicity caused by gas extraction. It includes estimates of the day, night and time-averaged populations inside buildings based on data brought together from a variety of population and demographic databases, along with information on people's patterns of building use as revealed through studies such as the National Time Use survey.

Our sense checking suggests that this may mean that around 5% of buildings identified in the risk assessment as "Higher CR" might not be so assessed if the population data were corrected. We have not identified significant numbers of buildings with anomalously low internal populations (other than those with zero internal population discussed above).

3.2 QA of Survey Data and Implications for Risk

Two tiers of checks on randomised samples of buildings were undertaken to characterise the risk impacts of errors and inaccuracies in the survey data. The first involved 2% of all buildings and was undertaken by TTAC surveyors. The second, more thorough check involved 10% of those "2% checked" buildings and was undertaken by Arup staff based in the Groningen office, using RVS reports where available.

The purpose of these checks was not primarily to correct errors and inaccuracies, but to identify them and characterise their impact on risk. Because the buildings were sampled randomly, they included a substantial proportion of buildings with no identified significant risk falling hazard objects, so the checks provided a good test of missed objects on "No hazards present" buildings as well as a test of whether objects identified in the survey were inaccurately characterised.

3.2.1 TTAC "2% Checks"

A total of over 4,200 checks were carried out (2701 for the H priority and 1544 for the M priority Municipalities). A high level overview of the results is shown in Table A8.2.

Table A8.2: Overview of Final TTAC "2% Checking" Results

	Number of Checks		% of Checks		
Checking Result	**H Priority Gemeenten**	**M Priority Gemeenten**	**H Priority Gemeenten**	**M Priority Gemeenten**	**Overall**
No hazard present	997	569	37%	37%	**37%**
Risk decreased or changed to "No hazard"	371	139	14%	9%	**12%**
No change	870	582	32%	38%	**34%**
Hazardous object missed	196	128	7%	8%	**8%**
Risk increased after checking	266	134	10%	9%	**9%**
TOTAL	**2700**	**1552**	***100%***	***100%***	

Figure A8.2 provides a quantified breakdown of the degree to which risk had been over or under-estimated based on the raw Survey data in comparison with the modified data after checking. Figure A8.2(a) is for the H and Figure A8.2(b) for the M priority Gemeenten.

Figures A8.3(a) and (b) then show, for the Top 20 missed objects, what sort of objects were involved and which risk exposure pathways were principally responsible for the increase in risk. Figures A8.4(a) and (b) provide a similar picture for the Top 20 other objects whose risk was increased as a result of changes made during checking.

Significant observations from this exercise include

a) There is a mix of cases where the Survey data led to over as opposed to under-estimation of risk, with more cases overall of underestimation (including objects missed) than of overestimation (Table A8.2 and Figure A8.2).

b) About 8% of the total of objects identified after checking had been missed in the original Survey, while a further 9% or so were found in which changes made as a result of checking led to an increase in the assessed risk (Figure A8.2)

c) About 5% of the objects recorded in the Survey were determined in checking not to be hazardous at all (Figure A8.2). The impact on risk is modest as most of these would have been assessed as low risk in any case.

d) The most significant of the missed and 'risk underestimated' objects involved risk exposure to building occupants (rather than people outside buildings) via either
a) exposure to falling debris outside doorways, or
b) objects falling through roofs (Figure A8.3 & 4).

e) The proportion of objects checked where survey inaccuracy had led to particularly high Community Risk estimates (taken throughout this report and the companion risk assessment report as "greater than 10^{-5} deaths per year") is small:

- 9 objects in the H priority Municipalities had their CR value increased from below to above 10^{-5} per year as a result of changes made following the 2,700 checks made
- No objects in the M priority Municipalities had their CR value increased from below to above 10^{-5} per year as a result of the 1,552 checks made.
- 12 objects in the M priority Municipalities had their CR value increased from below to above 10^{-6} per year as a result of those 1,552 checks.

Figure A8.2(a): Quantification of Impacts of ‘2% Checks’ on Risk – H Priority Gemeenten

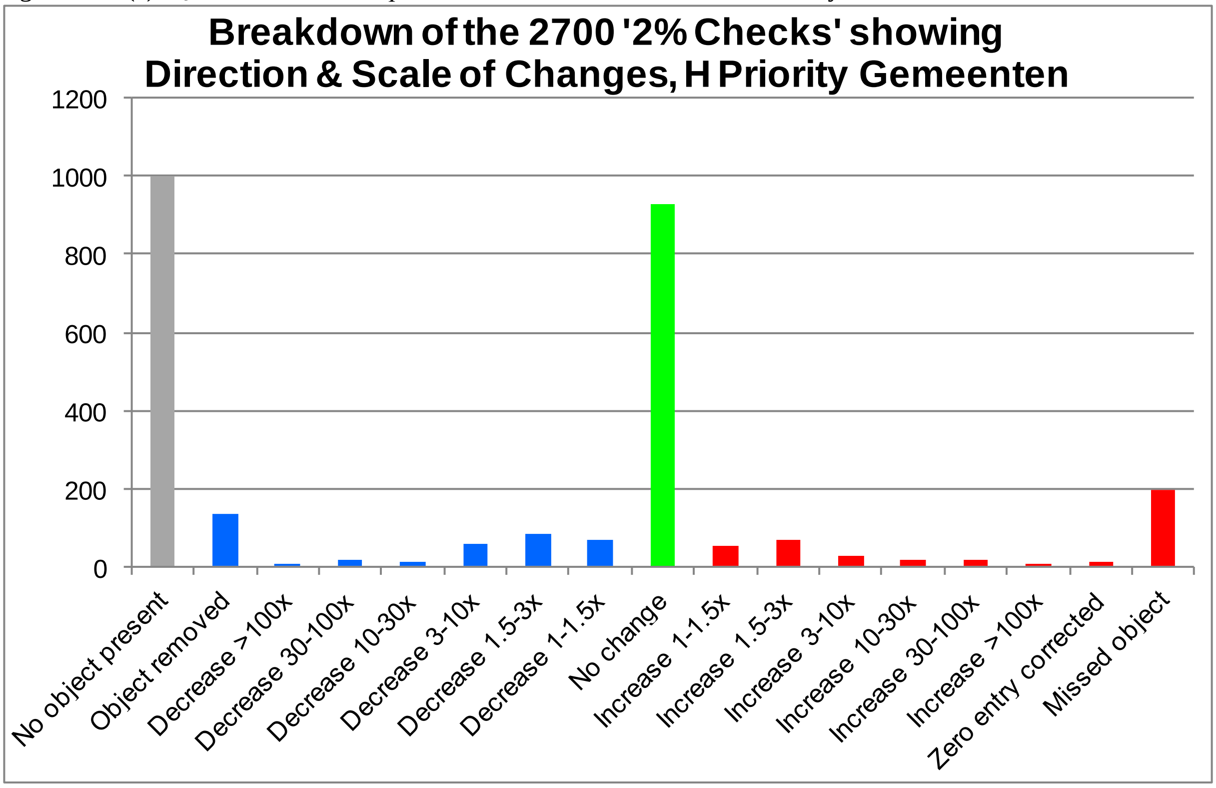


Figure A8.2(b): Quantification of Impacts of ‘2% Checks’ on Risk – M Priority Gemeenten

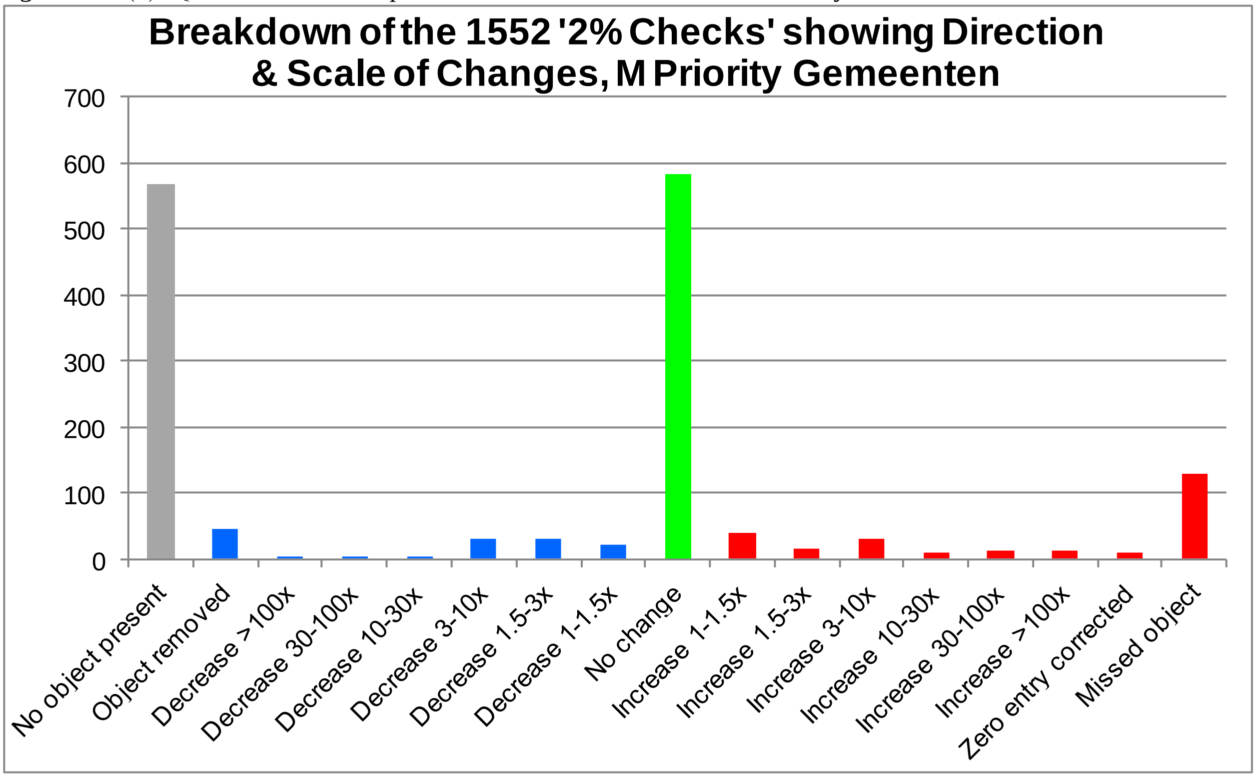


Figure A8.3(a): TTAC '2% Checks' – Top 20 Missed Objects, H Priority Municipalities

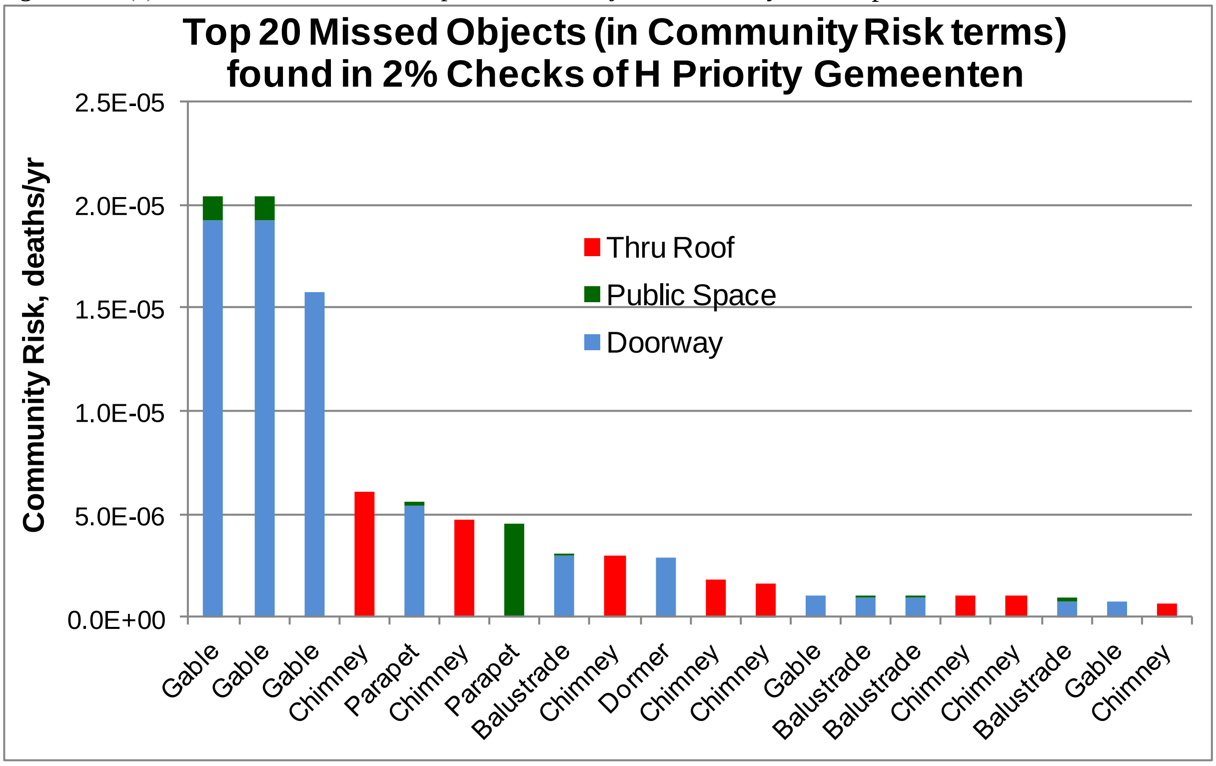


Figure A8.3(b): TTAC '2% Checks' – Top 20 Missed Objects, M Priority Gemeenten

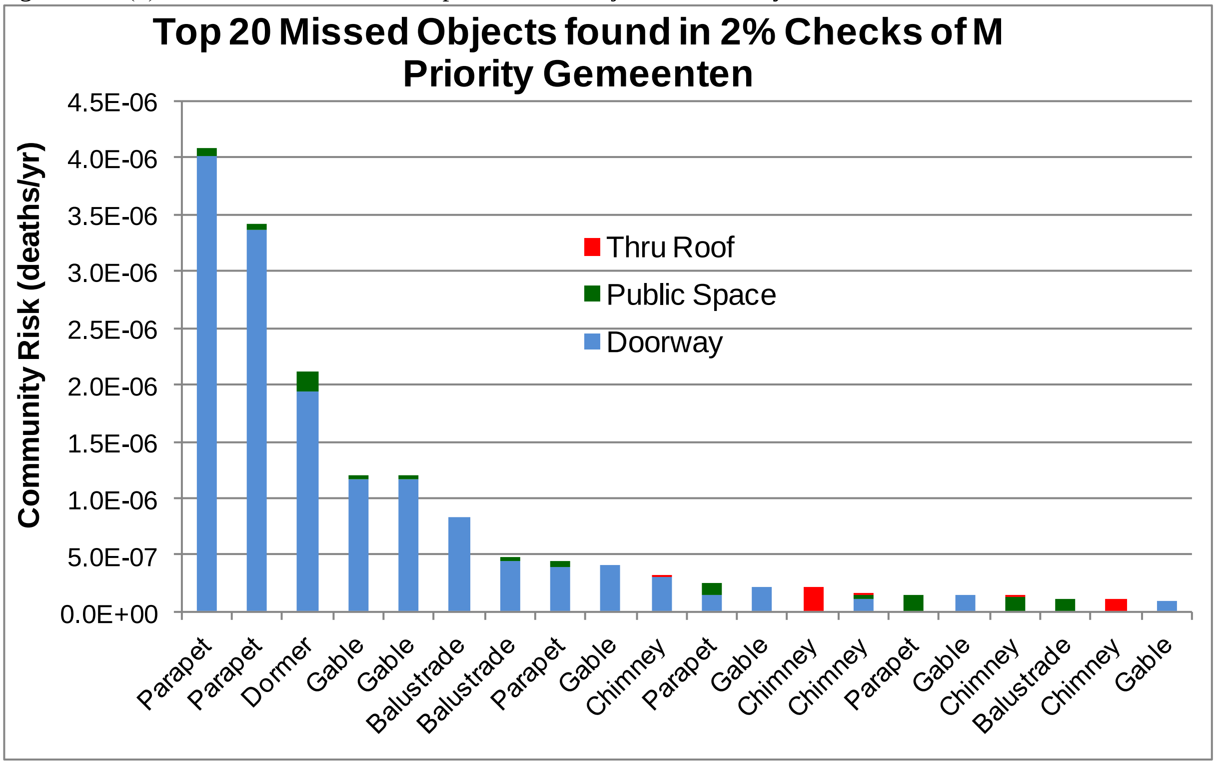


Figure A8.4(a): TTAC '2% Checks' – Top 20 Other Increased Risk Objects, H Municipalities

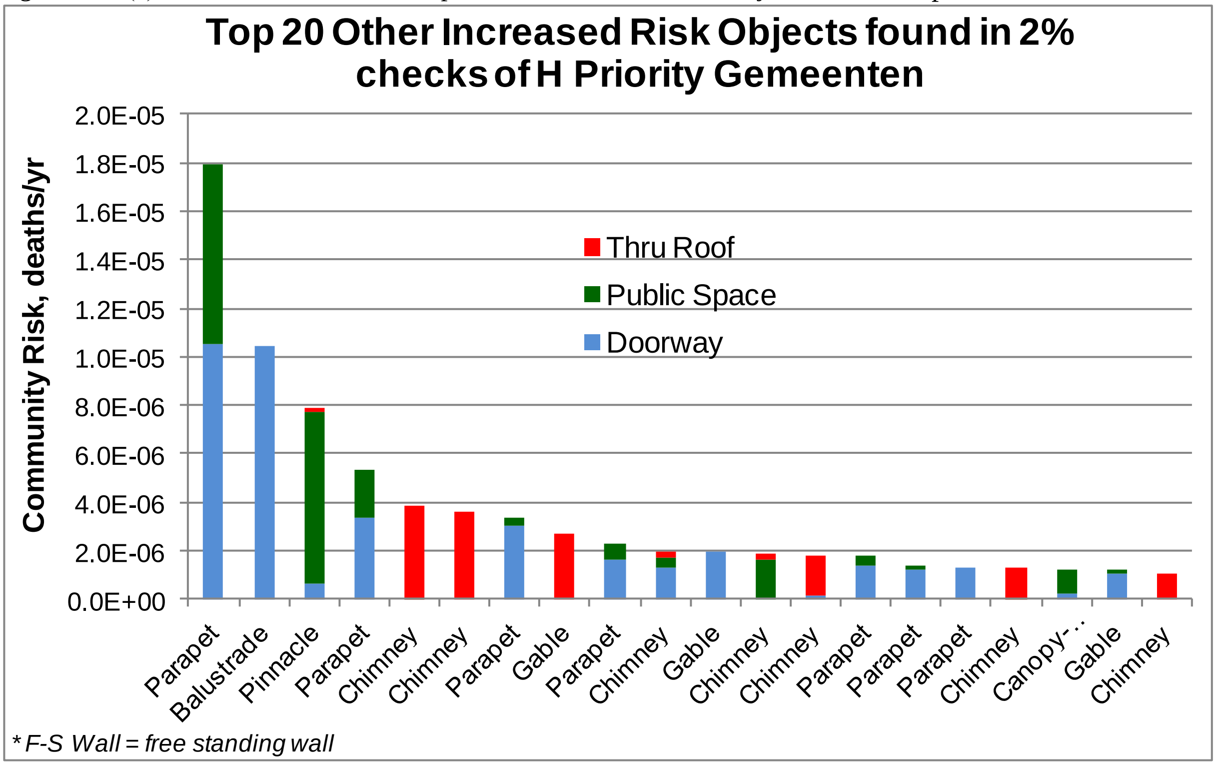
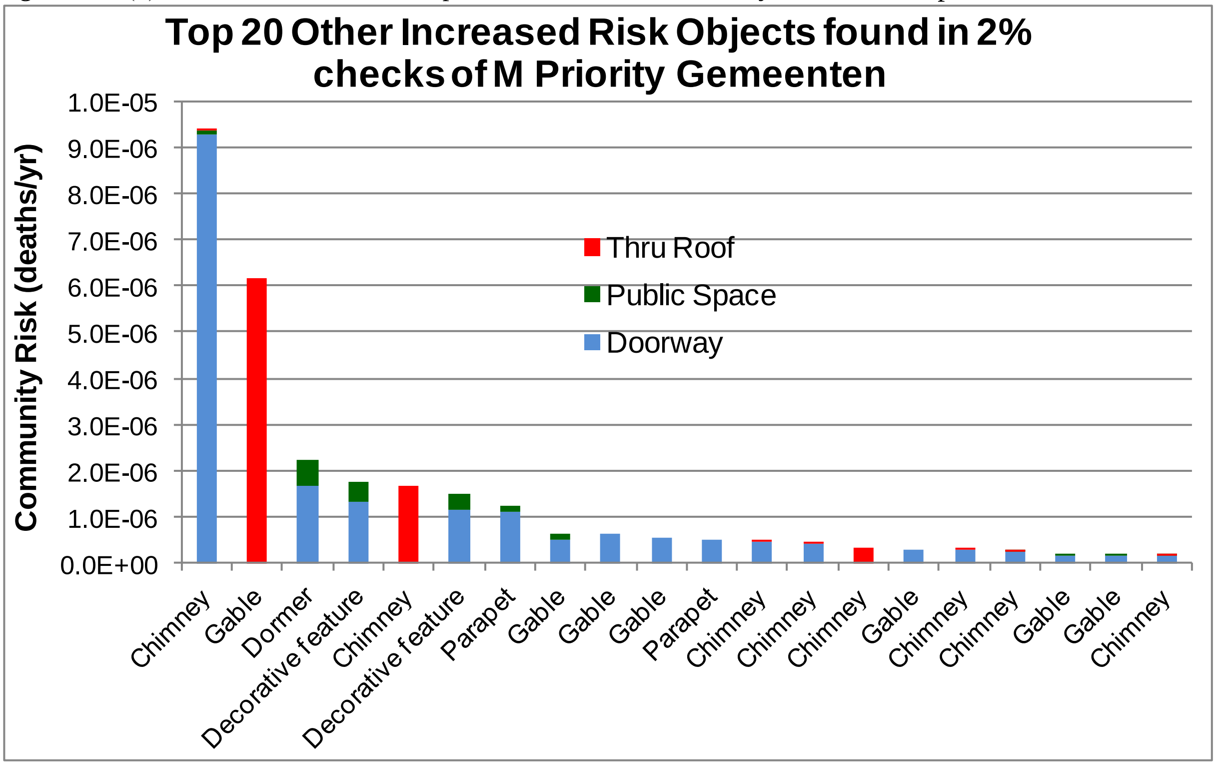


Figure A8.4(b): TTAC '2% Checks' – Top 20 Other Increased Risk Objects, M Municipalities



To assist in understanding the sorts of issues that may have been involved in objects being missed, or having risk underestimated, by the original survey assumptions, it may be helpful to discuss some specific examples. The objects are numbered according to their position in Figures A8.3 and 4 (i.e. 01 corresponds to the highest risk object on the left of Figure A8.3 or 4 as appropriate).

The following notes explain some of the issues involved and may help give some impression of the elements of judgment and subjectivity that are inherent in trying to classify large populations of diverse objects and situations using a relatively simple model and structure. (Note – photographs were used extensively in earlier versions of this report to facilitate checking but have been removed from the published version to protect privacy.)

Figures A8.3(a) and A9.4(a) – H Priority Gemeenten Example Objects

Missed Objects 01/02: Despite being in an area of relatively low seismicity (around the 0.12g PGA contour on the 2015 KNMI 1 in 475 year map), two gables on a large school were assessed as relatively high risk because the checker amended the survey record to include the doorways between them as being "within 1m of any part of the potential falling hazard object" (the guideline given to decide whether an object above a doorway should or should not be treated as hazardous). The strict application of this rule led to almost certain overstatement of the risk in this case, as

a) The doors are at the very edge of the gables, and the space into which people would most likely run out away from the building in an earthquake is well away from them,

b) The gables are in any case particularly shallow and of modern construction. The model treats all post-1920 gables or other masonry structures as equal and may well have overstated the fragility of a gable such as this, and

c) The time-averaged population attributed to the buildings by the exposure model seemed high and may have referred to a larger proportion of the school.

Missed Object 03: A relatively small chimney was assessed as relatively high risk because of its potential to fall several metres onto/through the roof of the adjoining building. The issue here was whether the neighbouring building onto which the chimney might fall should or should not be treated as "occupied", which could not be determined from the Street View photograph. The original surveyor and the checker took different views.

Missed Object 04: A gable was assessed as relatively high risk because of its location above the doorway of a house which was linked with a business and was been allocated a correspondingly high internal population in the exposure database (5.8, in comparison with typically 1 to 1.5 for houses, leading to some overstatement of risk). The gable had clearly been missed by the original surveyor rather than judged inappropriate to record.

Underestimated Risk Object 01: A chimney on the side of this building, above a busy pedestrianized street, had been recorded but a parapet had not. The combination of a substantial mass of masonry, busy public space and a doorway beneath led to a relatively high risk assessment . Small parapets can be easily overlooked – in this case the view used to identify other hazardous objects on the building had made the parapet difficult to see.

Underestimated Risk Object 02: A continuous balustrade (balcony wall) spanning two properties was originally recorded as 2 objects, one for each house. On checking, the reviewer chose to classify it as a single object. This doubled the risk at one address while reducing it for the other.

Underestimated Risk Object 03: A church tower was recorded in the survey as a "pinnacle" and was assessed as relatively high risk because of the presumption that substantial numbers of people were likely to mill around the outside of churches on a regular basis. A minor correction to the footfall estimate was made during checking, which made less than 10% difference to the estimated risk.

Figures A8.3(b) and A9.4(b) – M Priority Gemeenten Example Objects

Missed Object 01: A dormer was obscured by trees until moving some distance down the road past the address of the house. Its situation above a doorway and assumed fragility similar to that of a parapet combined to give it a relatively high assessed risk.

Missed Objects 02/03: Gables above a school playground were obscured from the front view of the school and had been missed in the original survey. The assessed risk was relatively high as the extreme edges of both gables were within 1m of a doorway. The assessment almost certainly overstated risk in this instance, as the gables were not directly above the dorrway at all; anyone running away from the building would hardly, if at all, pass through the area at risk from falling debris

Underestimated Risk Object 01: This chimney was obscured from most angles and had been missed by the original surveyor. The chimney, though not particularly large, was assessed as relatively high risk because of its situation above a main doorway of a busy school, in an area of relatively high seismicity from among the M priority Municipalities areas (0.20g contour on the 2015 KNMI map).

Underestimated Risk Object 02: The original surveyor had missed a small extension on the ground floor below a gable (the extension was obscured by trees from most angles). This substantially increased the estimated risk because of the possibility of the gable falling from height through the roof of a relatively highly occupied space.

Underestimated Risk Object 03: A dormer had already been estimated as relatively high risk because of its position above a busy town street and a doorway. The checker made a modest amendment to the object dimensions which increased CR by about 50%.

3.2.2 Arup checks

Staff in the Arup Groningen office carried out checks on a randomly selected 10% of the objects and buildings that had been subjected to the TTAC Ltd '2% checks' described in the previous section. All of the Arup staff involved had considerable experience of inspection (RVS and EVS) of buildings in the region. Wherever possible, they used the available RVS reports to provide more detailed and accurate information about buildings and "High Risk Building Elements" than could be obtained from Street View.

The total number of checks carried out was 374 (247 for the H priority and 127 for the L priority Municipalities). Figure A8.5 provides a breakdown of the types of object checked and the bands of CR into which those objects fell. Because both the number of checks and the proportion of objects with high assessed risk were both small, Arup checked relatively few particularly higher risk objects. On the other hand, a relatively large sample of buildings and objects rated as "not hazardous" by the survey team was checked. The deficiency of higher risk objects reviewed by Arup was remedied during the sense checking (see Section 4).

The balance of objects checked means that the Arup checks provide a better check against the issue of "Do the Survey records tend to understate risk?" than against the issue of "Can objects assessed as high risk based on the Survey results be relied on to be high risk?"

Figure A8.5: Objects Checked, by Risk Level (prior to checking)

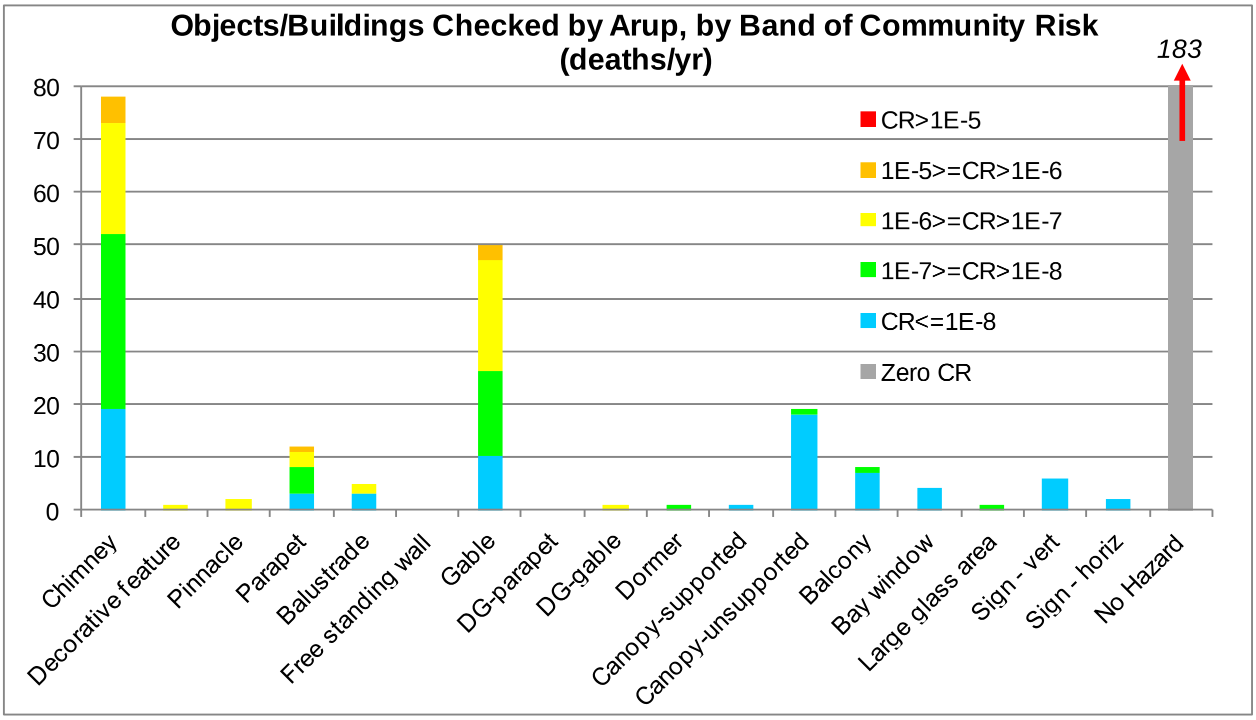


Figure A8.6 provides a quantified breakdown of the degree to which risk had been over or under-estimated based on the raw Survey data in comparison with the modified data after checking, for all of the checks made by Arup. Figure A8.6(a) is for the H and Figure A8.6(b) for the M priority Municipalities.

Figure A8.6(a): Quantification of Impacts of '2% Checks' on Risk – H Priority Municipalities

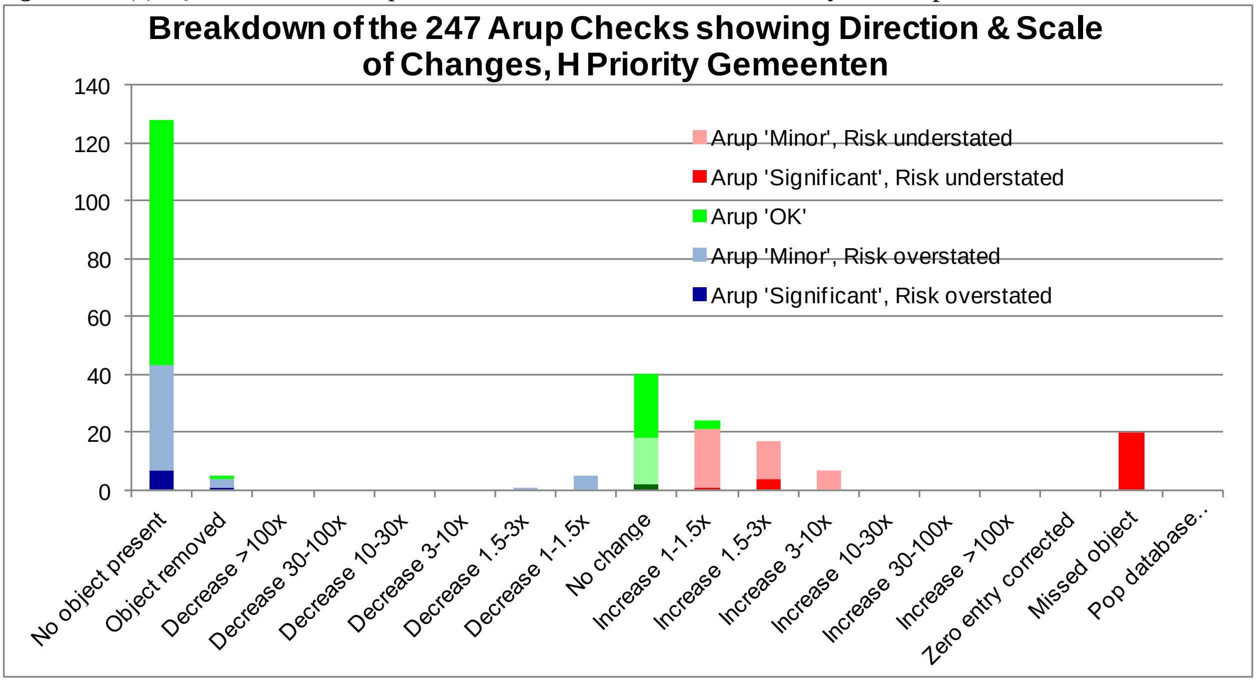
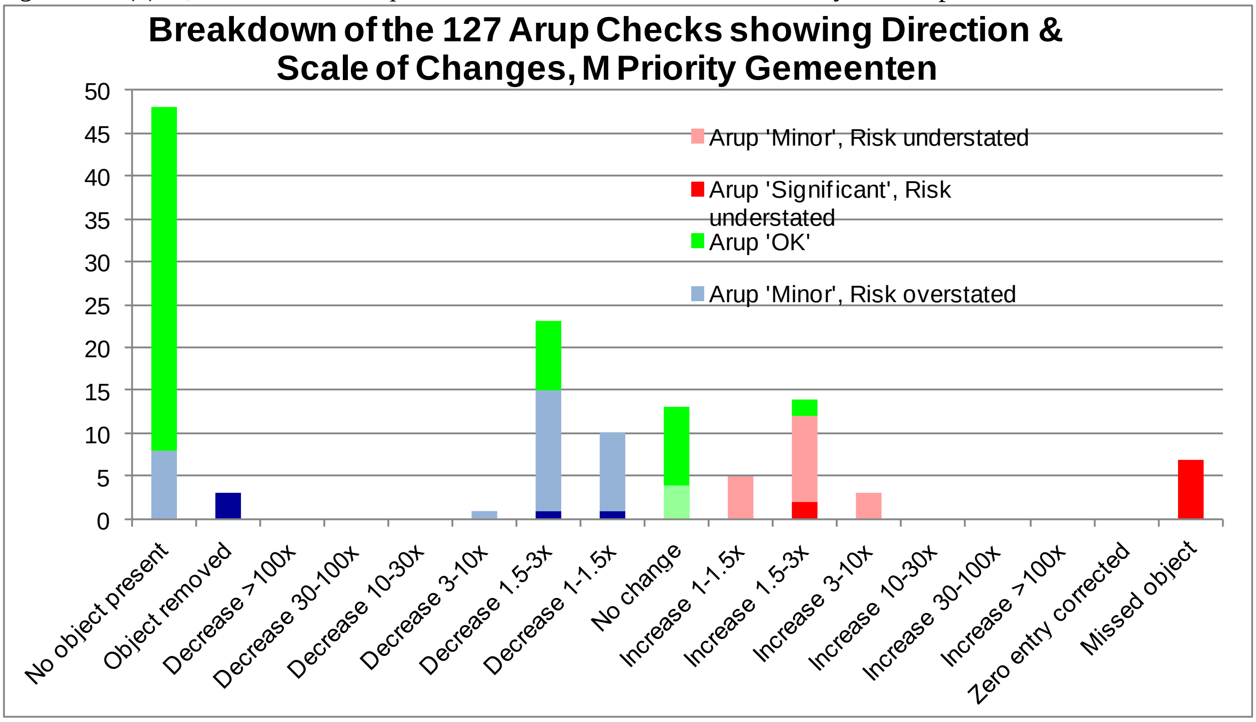


Figure A8.6(b): Quantification of Impacts of '2% Checks' on Risk – M Priority Municipalities



Arup classified their opinions on the buildings/objects surveyed into "OK" (111) "Minor" (91) and "Significant (36). "Significance" was judged based on departures from what was stated in the Survey Handbook, rather than on a quantitative risk assessment basis. There were thus issues (for example, mis-classification of walls as solid or cavity) that Arup classified as "Significant" but which (in the risk model as ultimately adopted for this assessment) made no difference to risk.

Risks before and after checking are illustrated in Figure A8.7. The results for Arup "Significant" issues (those with non-zero differences) are shown in Figure A8.7(a) and those for the top 30 "Minor" issues in Figure A8.7(b). The results for H and M priority Municipalities are combined in both figures.

Figure A8.7(a): "Significant" Arup Issues and Risk Impact

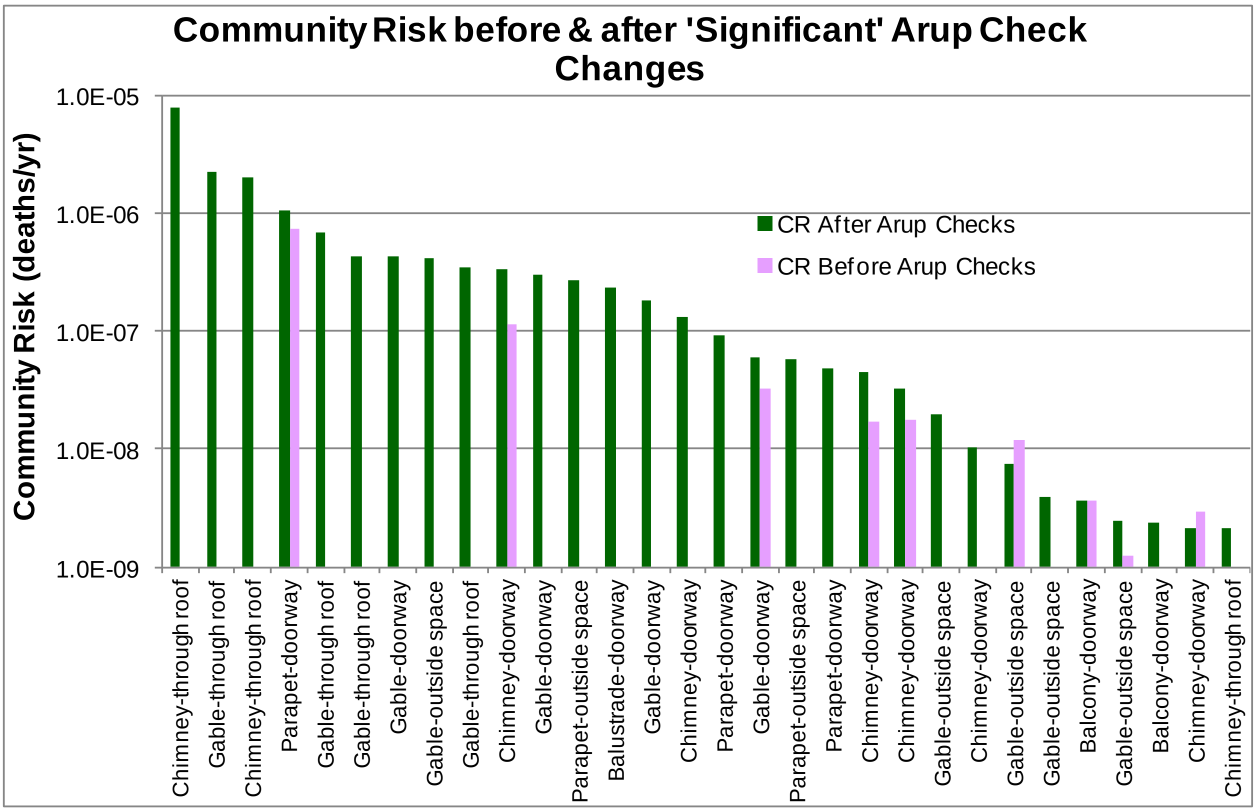
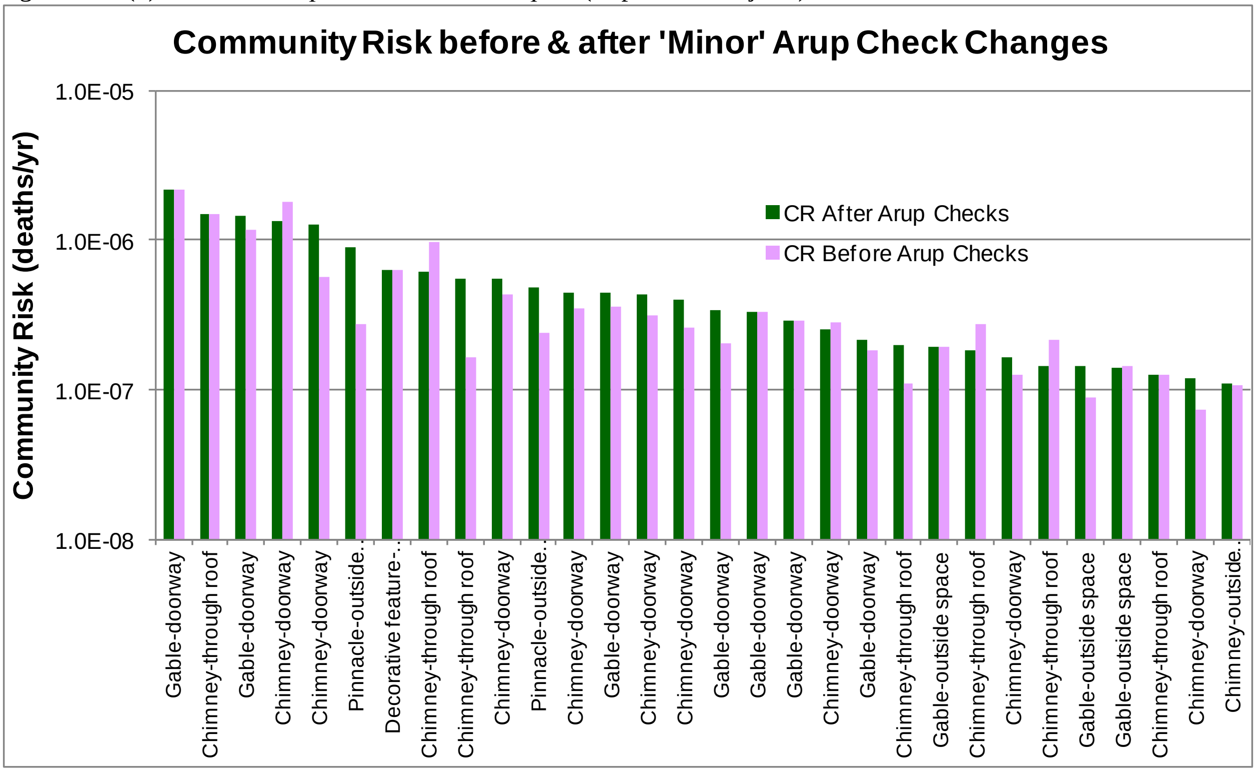


Figure A8.7(b): "Minor" Arup Issues and Risk Impact (Top 30 CR Objects)



As can be seen from Figures A8.6 and A8.7,

a) Arup identified (Figure A8.6) significant numbers of objects that had been missed by both surveyor and checker within TTAC Ltd.

b) Arup also identified (Figure A8.6) significant numbers of objects classified as hazardous in the survey that were not considered hazardous (surveyors and checkers had been advised to err on the side of caution in deciding what to include and what not to record, and were not building experts, so this was not surprising).

c) The modifications suggested by Arup where a hazardous object had already been identified have relatively modest effects on risk (see Figure A8.7 - typically factors of 2-3 for the more significant issues, and smaller factors of difference for the minor issues).

d) The missed objects are substantially more significant in terms of the chance of overlooking a high risk object than are the inaccurately characterised objects, and

e) Much the most significant class of missed objects involve objects with the potential to fall from height onto/through the roofs of occupied buildings. The 5 highest risk objects on the left of Figure A8.6a were all of this type.

The check results rated "Significant" by Arup suggested a general tendency by TTAC Surveyors to understate risk by understating object dimensions, as indicated by the difference between the lilac and green bars in Figure A8.6(a), though the numbers of objects involved is small. The corresponding results for the "Minor" significance objects (Figure A8.6b) suggested that inaccuracies were more evenly distributed between those tending to understate and those to overstate risk.

A possible reason that some objects were missed is that policy on recording of objects elevated above roofs evolved significantly during the course of the survey. The initial focus of the survey was placed on objects above doorways and public space, but the surveyors had been trained in examples of ways people had been harmed by falling objects in other earthquakes and themselves raised numerous issues associated with the potential for objects to fall through roofs. It is possible that these objects were simply missed, but it may also indicate systemic confusion about when and how to record objects elevated above roofs among the survey team.

3.3 Summary and Conclusions from Survey Checking

The primary issue capable of giving “false negatives” (cases of high risk objects failing to be identified via the combination of survey and risk assessment) was hazardous objects missed in the survey. The TTAC 2% checks suggested that these could amount to about 7-8% of the total of objects recorded for the buildings surveyed (Figure A8.2).

The Arup checks suggested that there might be a further 8% or so of objects that had been missed by both the survey and the TTAC 2% checking process. Objects elevated above roofs were conspicuous among this set of objects by both their number and by their dominance of the risk impacts of missed objects.

In discussion of the results of the risk analysis of the Arup checks with the Arup Groningen staff, it was agreed that the TTAC 2% checks appeared to have done a generally good job of identifying missed object above doorways and public space, but had failed in particular to pick up a substantial number of objects with potential to fall from height onto roofs.

“Missed objects elevated above roofs” was therefore made the subject of a special study to re-survey streets throughout the H priority Municipalities (see Section 4.2.1).

There is likely to be a further contribution to “false negatives” from objects identified in the survey but with inaccuracies in the survey data recorded for them. This is considered, though, a much smaller issue than the missed objects discussed above.

The survey is also likely to provide significant numbers of “false positives” associated with objects inappropriately classified as hazardous, or situations where the simple assumptions used in the model overstate either the fragility of the object involved or people’s exposure to risk. These are discussed further in the “Sense checks” covered in Section 4.1.

4. Post-Risk Assessment Checking

This section describes the additional checks carried out after the risk assessment process had been applied to the survey results. It covers

- "Sense checks" carried out to test the risk model results against engineering judgment for specific objects/buildings (4.1)
- Re-visiting survey data and risk model assumptions following discussion of the Sense Checks and Arup Survey Checks results with Arup Groningen staff (4.2), and
- Correction of survey errors revealed during risk assessment (4.3).

4.1 "Sense Checks"

The checks described in Section 3 focused on inaccuracies in the Survey identification and recording of data on potentially hazardous objects. In parallel, a series of "Sense Checks" were carried out to examine results from the risk assessment for specific buildings/objects and discuss whether the risk assessment process, as applied to real objects and their situations, was delivering plausible results.

The focus of this process was on our risk model assumptions, and their potential impact on risk in real situations, rather than on revealing further issues to do with survey data quality. Where practicable the observations from this process have been fed back into the risk model. Where this is not practicable, the process helps us understand the limitations of the current assessment, and the factors we would ideally like to be able to build into a future model, or any tools to help inspectors "on the ground" make improved judgments of risk based on locally observable factors.

Three sets of sense checks were carried out:

- (Section 4.1.1) A sample of high Community Risk ($CR>10^{-5}$/yr) objects was reviewed with Arup Groningen staff. This provided a good complement to the Arup survey checks (Section 3.2) which covered a large sample of low/zero risk buildings/objects but very few high CR objects.
- (Section 4.1.2) A sample of 100 objects in the risk bracket from CR 10^{-5} to 10^{-6}/yr was checked after agreement with Arup that a more systematic check should be made on issues with potential to escalate objects up into the high risk $CR>10^{-5}$/yr category.
- (Section 4.1.3) A further sample of 100 objects on public use buildings where people other than those passing by in the street could be exposed to risk in the course of movement into, out of or around buildings.

4.1.1 Workshop with Arup Groningen staff

A sample of 75 objects which had generated high assessed risk (generally greater than 10^{-5}/yr community risk[5]) was reviewed with Arup Groningen staff who had been involved in checking of Survey files and had extensive experience of RVS and EVS on buildings in the region. The notes of the workshop are attached as Annex 1.

The workshop process involved working through the high Community Risk objects identified for the Municipalities of Appingedam and Loppersum, and the central area of Groningen city (the Binnenstadt Wijk). In each case a photograph of the object was presented along with an explanation of how the risk had been assessed and why it emerged as a "high risk" object.

The combination of survey and assessment was considered to have done what was intended in all but four cases for which modifications to Survey data were agreed. In three of these cases the risk was overstated and in one understated. The evaluation revealed a generally conservative bias (towards overstating risk) resulting from a combination of surveyors following the guidance they were given to err on the side of caution if in doubt, and simple risk exposure models and assumptions leading to overstatement of risk exposure in real situations.

Discussion among the building/structural engineers from Arup was not generally able to resolve the debates between TTAC surveyors and checkers as to what precisely should be recorded for objects when in doubt – they were inherent in what could be seen from Street View rather than attributable to a lack of confidence or expertise among the surveyors. The evaluation identified numbers of cases as follows, where:

- the assessment & high risk rating made sense: 47
- assumption around running from doors tended to overstate risk 1
- assumptions about object fragility tended to overstate risk 8
- the location/definition of hazard/target objects tended to overstate risk 8
- the internal building population tended to overstate risk 4
- assumptions about occupancy/usage of doorways tended to overstate risk 4
- the assumed vulnerability of target object tended to overstates risk 2
- the assumed occupancy of space outside tended to understate risk 1

The workshop concluded that there could be reasonable confidence that "If the risk assessment says something is high risk, then by and large it IS high risk", and that inaccuracies in either Survey data or in applying the simple risk assessment assumptions to real buildings generally had a tendency to overstate rather than to understate risk.

[5] With risk assessment inputs and assumptions as at 18 November 2015 – these were still under review and subject to change as the risk assessment progressed. Such changes are considered unlikely to affect the observations made here.

In discussion of the workshop findings alongside those of the Arup checks on Survey results, it was concluded that further work was needed

a) To answer the key question "If the risk assessment says something is NOT high risk, can that conclusion be relied on?" (see Section 4.1.2)

b) To address the objects missed by the survey, in particular those with the potential to fall from height onto adjacent roofs, which had by some margin the greatest implications for risk (see Section 4.2.1), and

c) To address the other issue identified where the Survey and risk assessment in combination may have systematically understated risk, which was the under-estimation of footfall around public use buildings rated in the Survey as "low footfall" (see Section 4.2).

4.1.2 Checks on objects in the 10^{-5} to 10^{-6}/yr CR bracket

These checks were carried out to identify whether there were issues associated with either the survey data or the risk assessment model and assumptions that might lead to objects which should be categorised as "High Community Risk" failing to be so. With "High CR" defined as meaning "10^{-5}/yr or greater", objects within the 10^{-5} to 10^{-6}/yr bracket might have been wrongly classified as "Not high CR" because of a relatively small under-assessment of the risk.

A sample of 100 objects in this CR band was selected from the Municipalities of Appingedam, Delfzijl, Loppersum, Slochteren and various parts of the city of Groningen (including both the Centrum and suburban areas). For each an evaluation was carried out in which the risk assessment assumptions were checked against what could be seen of the object and its surroundings in the best available photograph from Street View. The evaluation result was expressed as one of the following:

- OK
- Optimistic (risk understated by the assessment)
- Pessimistic (risk overstated by the assessment)

Wherever an evaluation other than "OK" was made, comments were added.
The results were

- 83 cases evaluated as "OK"
- 2 evaluated as "Optimistic", and
- 15 evaluated as "Pessimistic".

The two "optimistic" cases (where risk was judged likely to have been underestimated) both involved underestimation of people present around or entering/leaving public use buildings (one a school, one a leisure centre).

The fifteen "pessimistic" cases were split between those where the object itself was considered more robust/less fragile than was typical for its object type (9 cases) and those were the simple exposure pathway assumptions were considered likely to have overstated the real degree to which people would be exposed to risk (6 cases).

This study confirmed the conclusion of the first round of Sense Checks (4.2.1) that

a) the assessment results were for the most part plausible and realistic

b) the assessment tended to err on the cautious side when inaccurate, and

c) the only identified area of potential systematic risk underestimation involved the underestimation of footfall/exposure around public use buildings.

4.1.3 Checks on footfall in public space

These checks were carried out to explore whether there might be systematic underestimation of footfall in public spaces (around public use buildings such as schools and churches in particular) that could be leading to systematic underestimation of risk.

100 buildings categorised as 'P' (i.e. as having publicly accessible space within 5m of one or more building facades) and with identified falling hazard objects were reviewed in terms of the appropriateness or otherwise of the footfall rating applied. The results are summarised in tabular form in Annex 3.

The conclusions were that footfall had been appropriately estimated in over 80% of cases, but that in the remainder the general tendency had been for underestimation, particularly around "public use" buildings where it would be building users, rather than passers-by in the street, who were exposed to risk.

From this study and the "Sense checks" carried out with Arup (Section 4.1.1) it was concluded that objects on public use buildings that had been allocated a P*L footfall category represented the most significant possibility that risk could have been substantially underestimated. Objects rated as P*M could also have had footfall, and thus risk, underestimated but there was lower potential for very large effects here as the gap in footfall from P*M to P*H is less than that from P*L to P*H.

4.2 Re-visiting Survey Data and Risk Model Assumptions

The key issues emerging from all of the Survey and Post-Risk Assessment checks described above were

1. Objects missed in the survey, with objects elevated above roofs of occupied buildings having substantially the greatest potential for the survey to have missed "high risk" objects.
2. Objects on public use buildings that were given inappropriately low footfall classifications, leading to the potential for high risk objects to have been to some degree systematically under-identified.
3. Risk model assumptions about object fragility, leading generally to conservatism in the risk assessment (tending to overstate risk), and

4. Risk model assumptions about people's exposure, via running out of doorways and objects falling through roofs in particular, which also led generally to conservatism in the risk assessment (tending to overstate risk).

In discussion with Arup it was considered that the first three of these were capable of being addressed before Version 1 of the model and risk assessment was finalised. In the first two cases this involved re-surveying, which was limited to H priority Municipalities where the effects would be greatest. In the third case, the work involved was a final review of object fragilities focusing in particular on whether modern gables were being assumed to be inappropriately fragile.

In the fourth case, it was decided that, though the sense checks had led to identification of many of the local factors that were important in modifying risk from the simple assumptions built into the model, it would not be feasible to address those factors in the Version 1 model and risk assessment because

a) It would require extensive additional information on objects and their situation, some of which might be acquired via re-surveying but much of which would require local inspection and knowledge of the building use, and
b) Refinement of the simple exposure models would require substantial research (for example into people's egress from buildings in emergencies) for which there was insufficient time available.

The re-work carried out in respect of the first three cases above is briefly described below.

4.2.1 Re-Surveying for potential to fall from height onto roofs

It would be impossible to resurvey every building on an individual basis, but was considered feasible to carry out a rapid re-survey, "driving" each way down each street in Google Street View, identifying whether there were any objects present with the potential to fall from height onto roofs, and then going back to the Survey files to check whether and how those objects had been recorded.

In order to enable this process to be carried out in time for the Version 1 risk assessment, the scope was limited to H priority Municipalities and to streets with 5 or more buildings. This led to well in excess of 95% of all buildings in the H priority Municipalities being covered. The H priority Municipalities were selected for resurvey not only because, on average, each object would be significantly higher risk than in the M priority Municipalities but also because the Arup checks (see 3.2 above) identified "missed objects above roofs" as a particular issue in the H priority checks made, but as a lesser issue in the M priority checks.

(Note - this was not unexpected as the M priority survey was carried out after the H priority one. Policy for recording objects elevated above roofs evolved during the H priority survey but was stable during the M priority survey. Moreover, the M priority survey was largely conducted by a smaller team of more mature graduate surveyors – the undergraduate surveyors had returned to university before the bulk of the M survey work was carried out).

As was expected, the number of missed objects above roofs was significant. The overall total of such objects before this re-survey was 2,803 (note this is ALL objects elevated above roofs of occupied buildings, NOT in any sense “high risk” objects). The total after this re-survey was 4,335, an increase of 55%.

We are confident that this resurvey process has identified a large majority of the objects elevated above roofs that were missed in the original survey.

4.2.2 Re-Surveying for “low footfall” public use buildings

The first set of sense checks carried out with Arup and the separate check of 100 buildings with objects above public space both suggested that there may have been a degree of systematic understatement of footfall around public use buildings. In particular, objects rated as P*L (the lowest category of footfall for building users, as opposed to passers-by in the street, for public use buildings such as schools and churches) were considered likely to have had footfall and thus risk underestimated in potentially a few 10’s of % of cases.

A re-survey was thus carried out of all falling hazard objects in the H priority Municipalities that had originally been assigned a P*L footfall rating. A total of 2,388 such objects were re-surveyed, with changes being made to 671 of the ratings.

4.2.3 Fragility assumptions review

The sense checks with Arup (4.1.1) identified significant numbers of cases in which the general assumptions of fragility used in the risk model appeared to be overstating the likelihood of failure of specific objects. The objects involved were largely modern, of masonry construction, with gables in particular featuring frequently.

The fragility values used in the model are judgments, informed by but by no means dictated by the performance of masonry chimneys, parapets and gables in other earthquakes. A review was carried out in light of the Arup comments on gable fragility in particular, to explore whether there were alternative judgments on fragility that might be made, consistent with the limited empirical evidence available.

The result of this review was that the relative fragilities of parapets and of gables assumed in the Version 1 risk model was changed, with gable fragilities being reduced while parapet fragilities were increased. Chimney fragilities were little changed.

4.3 Sense Checking and Review/Re-Surveying Conclusions

Our conclusion on completing the sense checking, survey checks and subsequent re-work on the survey and risk model is that the combination of survey and risk model are providing reasonable results for a substantial majority of objects and building situations.

In terms of providing “false negatives” (inappropriate reassurance that objects are low risk) the sense checking reinforced the views developed from the TTAC and Arup post-survey checks, that

a) by far the most important issue was missed objects, with objects elevated above roofs being a particularly important group of such objects because those missed had included a substantial proportion of relatively high risk objects, while

b) the only other issue identified with the potential to lead to systematic understatement of risk was underestimation of footfall around public use buildings.

The proportion of missed objects prior to undertaking the re-surveying described in Section 4.2 is estimated at about 15% (based on 7-8% missed in the TTAC '2% checks' and a further 7-8% missed by those checks, as revealed by the Arup checks).

Given the efforts made to address survey deficiencies in the areas identified as having greatest potential to underestimate risk, we are confident that the proportion of serious (high risk) missed objects has been reduced to around 10% or below. In particular, missed objects with potential to fall from height onto roofs accounted for a large proportion of the high risk missed cases identified by the TTAC and Arup checks. The re-surveying has covered over 95% of buildings in the H priority Municipalities, scanning specifically for objects at height above roofs, and we are confident has identified and recorded a large majority of objects of this type that are identifiable via a Street View survey.

In terms of providing "false positives" (inappropriate identification of objects as high risk when they are not truly so), the combination of

a) Surveyors "erring on the safe side" when deciding what to record and not to record, and how to do so,

b) Simple general model assumptions about object fragility, and in particular

c) Simple model assumptions about exposure,

may provide significant over-estimates of risk in around 15-20% of cases, based on the sense checks described in Section 4.1 above.

5 Sensitivity Studies

Sensitivity studies were carried out to explore the impact on Community Risk, and on numbers of objects assessed as "High Community Risk" (taken as CR>=10^{-5}/year in this study), of the major uncertainties in the risk model. These sensitivity studies took the form of simple recalculation of the risk spreadsheets for each Municipality under each of a number of scenarios corresponding to different parameters being varied around the base case. The results have no statistical significance; the parameter ranges explored are not extremes, or 10-90% confidence limits but what we regard as plausible ranges within which we would hope (but by no means be certain) to find that the true values for the Groningen region would lie.

The scenarios modelled are:

- Scenario 1: Lower fragility, masonry objects (chimneys, parapets, gables)
- Scenario 2: Higher fragility, masonry objects (chimneys, parapets, gables)
- Scenario 3: Lower exposure assumptions
- Scenario 4: Higher exposure assumptions
- Scenario 5: Lower fragility AND seismicity assumptions
- Scenario 6: Higher fragility AND seismicity assumptions
- Scenario 7: Lower fragility, other objects (balconies, canopies, glazing etc.)
- Scenario 8: Higher fragility, non-conventional objects
- Scenario 9: Lower risk – All Assumptions simultaneously
- Scenario 10: Higher risk – All Assumptions simultaneously

The parameters varied, and the values used for higher, lower and base case assumptions are shown in Table A8.3. It was not possible on the timescale of this study to carry out systematic exploration of the impact of key uncertainties on the KNMI seismicity model, which are critically important. To provide an indication of the combined effect of uncertainties in seismicity and object fragility we made a simple assumption that the KNMI estimates of frequency of earthquakes in our lowest shaking band (0.05-0.1g) should be quite accurate, as the associated frequency is high enough to be directly testable against experience. The frequency was assumed to be uncertain within +/- 10% for this band. At the other extreme, there is clearly much greater uncertainty as to the frequencies estimated for the rare events in our top shaking band (>0.9g). We assumed that frequencies for this band were uncertain by x/÷ 5, and interpolated smoothly between these assumed uncertainties for top and bottom bands to estimate uncertainty for the intermediate PGA bands.

The results are shown in Figure A8.8 in terms of the total, aggregate Community Risk for the region[6] and in Figure A8.9 in terms of the numbers of objects assessed as relatively high CR (>=10-5 per year). Note that in Figure A8.9 the lower end of the bar for "All uncertainties" is actually zero objects, which could not be displayed on the logarithmic scale shown.

[6] Note that Figure A8.8 is based on the H and M priority Municipalities surveyed and does not include corrections for buildings not surveyable, missed objects, facades not surveyable on buildings that could be surveyed, and objects in L priority Municipalities, which together would increase the total CR by several 10's of %.

Table A8.3: Parameters Varied for Sensitivity Studies

GROUP	Parameter	Low case	Base case	High case
Object Fragility	*Failure probabilities for masonry chimneys, parapets & gables*	Lower end of range proposed for Groningen region	Centre of range (geometric mean)	Higher end of range proposed for Groningen region
	Failure probabilities for canopies, balconies	0.03 x those for comparator masonry objects	0.1 x those for comparator masonry objects	0.3 x those for comparator masonry objects
Seismicity	*Frequency of shaking in 0.05-0.1g PGA band*	KNMI(2015) / 1.1	KNMI 2015 (as simulated by Arup)	KNMI(2015) x 1.1
		varying smoothly up to		*varying smoothly up to*
	Frequency of shaking in >0.9g PGA band	KNMI(2015) / 5		KNMI(2015) x 5
Exposure - people passing outside building	*Width of at-risk zone used in risk calculation*	3m	5m	5m
	Footfall	All footfall categories moved down 1	Standard footfall table for categories 1-10	All footfall categories moved up one
Exposure - building occupants running outside	*Area at risk outside doorway*	15m2	10m2	10m2
	% occupants who try to run out in earthquake	30%	70%	80%
	% people running out whose timing coincides with debris falling	1%	5%	10%
Exposure - objects falling through roofs	*Probability an object falling from height penetrates right through to ground level*	0.3	1	1

Figure A8.8: Impact of Uncertainties on Aggregate Community Risk

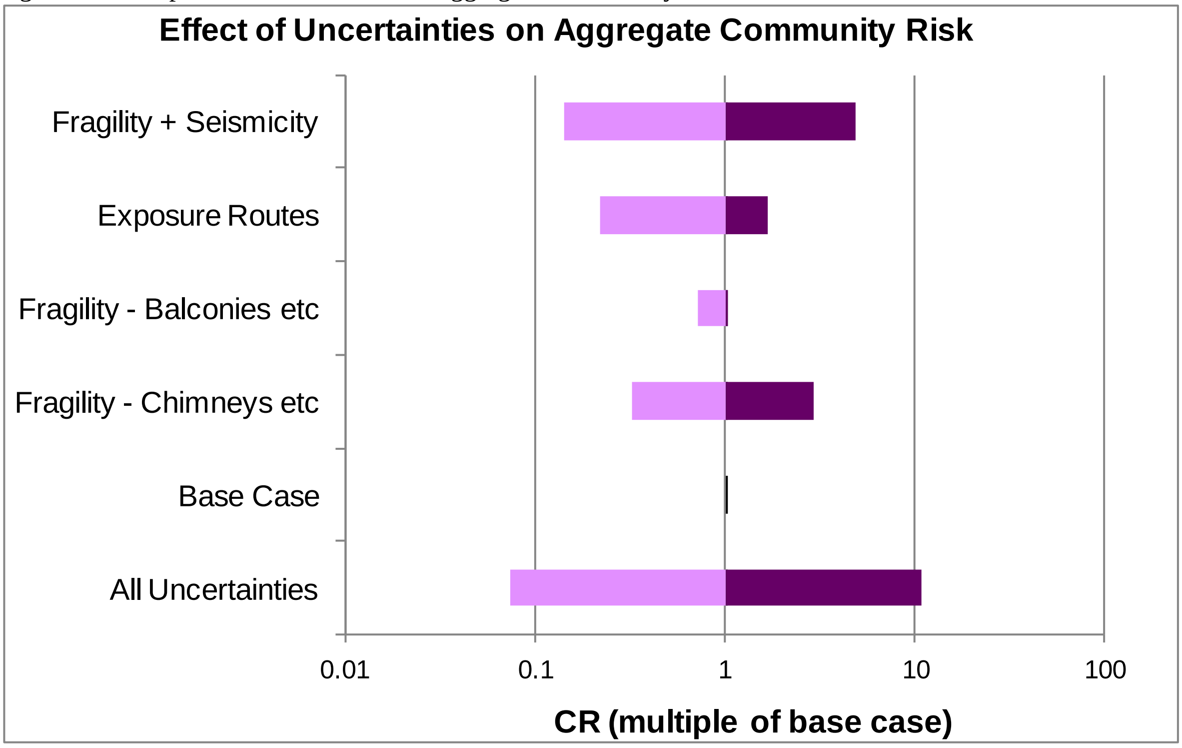
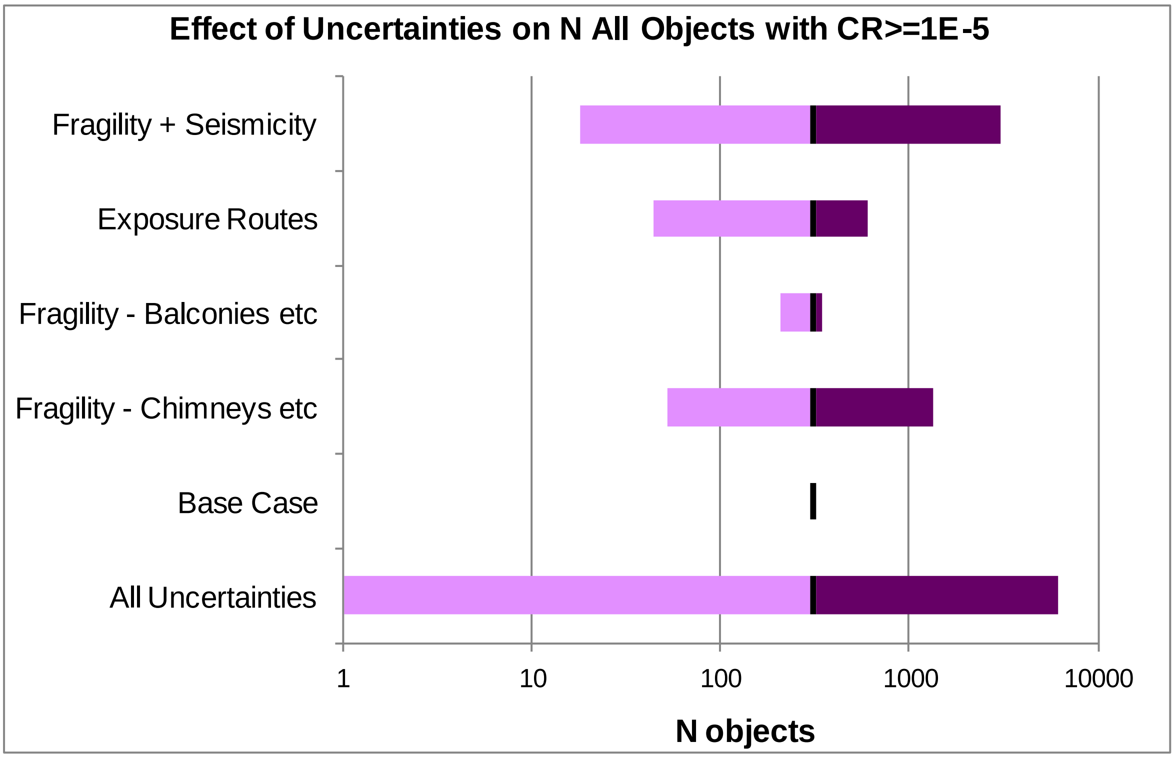


Figure A8.9: Impact of Uncertainties on Numbers of High Risk (CR>=10-5/yr) Objects



Annex 4 provides tables summarising the impact of each scenario investigated on the numbers of different object types in different risk bands.

Our conclusions from the sensitivity studies are as follows:

1. The overall uncertainty in the results is about an order of magnitude (factor of 10) in either direction in Community Risk, with the uncertainties to the lower side somewhat greater than those to the upper side.
2. The uncertainty in numbers of objects exceeding a "High CR" criterion is somewhat greater, varying from zero with all uncertainties taken into account up to several thousand at the higher end.
3. The inclusion of uncertainty in seismicity as well as object fragility does not make as big a difference as might be expected. This is because to some extent these uncertainties cancel each other out – at low shaking there is high uncertainty in object fragility but low uncertainty in shaking frequencies, while for rare, severe shaking events there is high uncertainty in shaking frequency but little uncertainty in fragility (most masonry objects can be relied on to fail).
4. Exposure assumptions are of similar impact to fragility assumptions to the lower side of the base case, but of lesser potential impact to the higher side. This is consistent with the observation made in the sense checks above that in many cases the simple exposure assumptions in the model produce results that appear to overstate risk – effectively the model assumptions have been pitched nearer to the higher than to the lower end of the range of reasonable assumptions.

5. The generally low assumed fragilities of balconies, canopies and large areas of glass relative to masonry objects mean that the results are relatively insensitive to variation of assumed fragilities around their base case values. Given the lack of direct evidence behind these assumed low fragilities (they are judgments based on a workshop held with Arup Groningen staff, as described in the companion Risk Model report) we are less confident in the robustness of this conclusion than in our other conclusions.

As a final observation on the sensitivity studies, we note that the current configuration of the risk model (as a series of spreadsheets built on the survey outputs) is extremely unwieldy for routine risk assessment. For each of the ten scenarios modelled here, it was necessary to paste a new set of input values into each of 23 spreadsheets, recalculate (taking several minutes per spreadsheet for the larger Municipalities on a fast computer), then paste the results into separate spreadsheets to enable simple comparisons to be presented such as those shown in Figure A8.8 and Figure A8.9.

It is physically impossible, with the model as currently configured, to carry out the kind of "simultaneous variation of multiple inputs" exploration of uncertainty and sensitivity that we would prefer. The spreadsheet approach worked well for collecting survey information but does not provide a sustainable basis for maintaining and using the model – there is too much manual processing required both to set up and to maintain and vary assumptions within the spreadsheets. They could be more highly automated, but the price would be even slower and more unwieldy calculation.

6. Conclusions & Recommendations

Our conclusions from the studies covered in this report are:

1. It has been possible to characterise the impact on the assessed risk of survey omissions and inaccuracies and of the risk model assumptions and uncertainties used.

2. As expected the combination of survey and simple risk assessment assumptions provide both false positives (cases identified as high risk where the true risk is lower) and false negatives (cases of high risk that fail to be so identified by the assessment).

3. For building facades that could be surveyed, the proportion of high risk cases missed is expected to be no greater than about 10%, while the proportion of cases in which risk is significantly overstated may be around 15-20%.

4. The combination of survey and risk assessment results is fit for purpose for prioritising areas for on-the-ground inspection for falling hazard risk.

5. The sense checks carried out have provided substantial insight into the local issues that can make a big difference to risk, and which should be reflected in both
6. Specifying what information is to be collected during on-the-ground inspection, and
7. Tools to assist local inspectors and others in making upgrade decisions for specific objects and buildings.

8. The combination of survey and risk assessment results does not provide a reliable assessment of overall risk from falling hazards for the region. In particular
   a) About 10% of buildings could not be surveyed
   b) There will be additional objects and risk associated with facades not visible (particularly the rear) of the buildings that could be surveyed
   c) About 10% of high risk objects may have been missed by the survey
   d) 15-20% of objects may have their risk overstated significantly as a result of the combination of survey data and simple model assumptions, and finally
   e) Uncertainties in seismicity, object fragility and people's exposure to risk make the model results uncertain within about a factor of 10 in either direction from the estimates presented in this report and companion reports. Fragility and exposure assumptions are of broadly similar importance.

Our recommendations are

1. After appropriate review, the falling hazards risk assessment should be adopted as the basis for prioritising areas for on-the-ground inspection with a view to falling hazard upgrades.

2. The insights gained from the sense checking described in this report should be used to assist in developing specifications for
   a) Information to be collected in on-the-ground inspections and
   b) Tools to guide decision making on upgrades for specific falling hazard objects

3. Considerable work will be required to adapt and develop the results of this assessment to provide reliable absolute estimates of falling hazard risk for the region. This should address
   a) Fragility of masonry objects
   b) Fragility of other objects such as balconies, canopies and large areas of glazing, for which we have little direct evidence to support the suppositions of relatively low fragility in comparison with masonry objects, and
   c) Exposure pathways to risk, for which the simple assumptions adopted in the model appear to overstate risk in a considerable number of cases (largely for building occupants exposed to risk running outside during earthquakes or via objects falling through roofs), but also to be capable of understatement in others (largely for people outside buildings where estimation of "occupancy" can be strongly dependent on local factors related to building use as well as to what can be seen in building photographs), and
   d) Migration of the spreadsheet model into a more robust framework for holding and updating data and calculating results, along with work to harmonise the provenance of falling hazards risk and collapse risk quantitative models.

Tony Taig
Florence Pickup
TTAC Ltd

Annex 1: Sense Check of Falling Hazard Risk Results

Notes of a workshop at Arup Groningen, 18 November 2015

Present: Mark Beukema, Sjoerd Cats Ed Zwart (Arup)
Florence Pickup, Tony Taig (TTAC)

Purpose

The aim was to "sense check" the results emerging from the Falling Hazards risk assessment being carried out by TTAC, so that any significant changes could be incorporated into the V1 report and spreadsheet risk assessments now in preparation. To this end

a) We discussed progress on the Falling Hazards Survey

b) Tony explained the calculational approach of the risk model

c) Florence walked us through the higher risk (>1E-5 Community Risk) objects identified for Appingedam, Groningen Centrum and Loppersum, and

d) Mark talked us through the findings of the Arup checks carried out on the Falling Hazards surveys of a sample of 238 objects (10% of those on which TTAC had carried out in-house checks made on 2% of all buildings surveyed).

Conclusion and Actions

Much of our discussion focused on the first key question for the sense checks:

> ***"Are the buildings identified as High Risk (CR>1E-5) genuinely so, or are their high risk ratings just artefacts of the model/data?"***

This note provides a summary of our discussion on the 67 identified High Risk objects which are the basis for our conclusion that the answer to this question is broadly "Yes".

We agreed actions to answer the second key question

> ***"Are the buildings identified as Lower Risk (CR<1E-5) genuinely so, or might a significant proportion of them in reality be Higher Risk buildings?"***

as follows:

1. Tony to circulate risk assessment of objects checked by Arup, with and without Arup observations incorporated (provides a sample of 238 objects across the whole risk range).

2. Florence to complete a quick survey of lower footfall ratings outside public use buildings (educational, healthcare, elderly homes etc.) to identify whether there are others (like that flagged as OO in the Loppersum table below) which have been rated too lowly in the survey.

3. Florence to carry out a check of a sample of objects in the 10^{-6} to 10^{-5} CR band and provide a folio for review containing a photo of each with assessment of "Appears OK" or "Assessment may err in {H/L} direction because ...."

Summary of Observations/Evaluation of Reviewed Objects/Assessments

The Tables below provide a summary of the group opinions on the sense or otherwise of the assessments of the sample of 74 objects with high risk (generally greater than 10^{-5}/yr community risk[7]) reviewed. The key for the two columns on the right is as follows:

Status of risk assessment:

- a ✓ means the survey appears to have been applied and the assessment to have been carried out as intended.
- MOD means that a modification was recommended to the survey record on which the risk assessment was based.

Flag to be attached, implying a consensus over whether the resulting risk rating might significantly overstate (be too conservative) or understate risk (be too optimistic):

- First letter C implies assessment conservative (overstates risk)
- First letter O implies assessment over-optimistic (understates risk)
- Second letter gives reasons as follows:
  D – relates to assumptions about people running out of doorways
  F – relates to assessed fragility
  L – relates to relative location of falling object and target
  O – relates to occupancy or usage of space outside buildings or doorways
  P – relates to population value inside building
  V – relates to vulnerability of target beneath falling object.

The combination of survey and assessment was considered to have done what was intended in all but four cases, in three of which risk was overstated and in one understated. The evaluation revealed a generally conservative bias (towards overstating risk) resulting from a combination of surveyors following the guidance they were given to err on the side of caution if in doubt, and simple risk exposure models and assumptions leading to overstatement of risk exposure in real situations. Discussion among the building/structural engineers from Arup was not generally able to resolve such uncertainties – they were inherent in what could be seen from Street View rather than attributable to a lack of confidence or expertise among the surveyors. The final totals of ratings given by the evaluation were as follows:

- Assessment & high risk rating made sense: 47
- CD (running from door assumptions overstate risk) 1
- CF (fragility assumptions overstate risk) 8
- CL (location/definition of hazard/target objects overstate risk) 8
- CP (internal building population overstates risk) 4
- CO (likely occupancy/usage of doorways means risk overstated) 4

[7] With risk assessment inputs and assumptions as at 18 November 2015 – these are still under review and may change as the risk assessment progresses, but are considered unlikely to affect the observations made here.

- CV (assumed vulnerability of target object overstates risk) 2
- OO (occupancy of space outside understates risk) 1

NOTE: In an earlier version of this document the BAGID of each building was provided to facilitate review and checking. Building identifiers have been removed to protect the privacy in the published version of this report.

Dealing with these issues (note added by Tony Taig following the meeting)

After consideration of the recurring issues identified above, the proposed approach to dealing with these issues for Version 1 of the model (for release December 2015) is as follows.

1. CF (fragility assumptions overstate risk, 8 cases):

Gables were significantly the most frequent object type leading to observations that risk had been incorrectly estimated (consistently overstated) for this reason. The evidence base for gables is significantly smaller than that for chimneys. But the combination of current assumptions in the model does appear to be leading to overall results for gables that are anomalous relative to those for parapets. **Action: TT to review interpretation of gable evidence in light of sense check observations and incorporate revisions if appropriate.**

2. CL (location/definition of hazard/target objects overstate risk, 8 cases)

The commonest issues here are chimneys and gables above doorways or parts of buildings where either

a) the falling object is offset significantly to the side of the doorway (objects are classified as “above doorway” if any part of them is within 1m of any part of the doorway; this affects gables in particular), or

b) the building has multiple doorways, and the one in question would not be used by a substantial proportion of the building occupants (for example, doorways in houses attached to shops or large farm buildings, where most of the assumed internal population would be in the non-residential part of the building).

This is a much more difficult issue to deal with – there is no “quick fix” solution possible via changing input assumptions for the model globally. **Action: None for V1. Defer to wider review of issues associated with egress from doorways for a later version of the model.**

3. CP (internal building population overstates risk, 4 cases)

This is an artefact of internal populations generated by the algorithms used in the V2 exposure model. Action: Advise NAM of cases so that the algorithms can be improved for future exposure model versions. No action for V1 risk model, but flag up results where this is suspected to have caused anomalously high risk estimates.

4. CO (likely occupancy/usage of doorways means risk overstated, 4 cases)

This is similar to item (2) above in that there is no general “quick fix” that can be applied without examining buildings on an individual basis. As for item (2), no action is proposed for V1 of the risk model; it is proposed that this be reviewed as part of the development of future versions of the model.

Municipality Appingedam Review

BAG ID (building)	Summary of Discussion	Status of risk ass’t	Flag attached
(A) Objects Above Doorways assessed as Higher Risk			
	Many main doors on ‘gathering buildings’ are seldom used, but this one probably is the main access	✓	
	Porch/balustrade may be wood (tend to reduce risk) and is well supported (likewise)	✓	CF
	Gable fragility assessed OK, population seems high, probably relating to shop on other side	✓	CP
	Gable above warehouse/retail premise – material unclear, adjacent buildings metal (lower risk)	✓	CF
	Long balcony – well supported at frequent intervals; debatable whether significantly risky	✓	CF
	Canopy above school entrance appears assessed OK; issue whether egress assumptions overstate risk (internal population 124)	✓	CD
	Dutch Gable – appears correctly measured (including whole triangular area) and assessed as higher risk	✓	
	Large glass area – can’t see reinforcements for wind loading. Significantly uncertain risk but correctly assessed as higher risk in absence of ability to determine (easily resolved by inspection)	✓	
	Gable appears correctly measured & assessed (general point – after explanation of the risk model process it makes sense that gables figure strongly in the list of higher risk objects, though the model generally seems to be making significantly conservative assumptions about risk from modern gables)	✓	
	Glass area – comments v similar to previous example (can’t tell how mounted; correctly assessed under uncertainty)	✓	

	Dutch gable above doorway – appears correctly measured and assessed (no surprise it's higher risk given large internal population of school)	✓	
	Left chimney – assessment makes sense. Would fall directly onto lower roof		
(B) Objects Above Public Space assessed as Higher Risk			
	Balcony with red metal framing – correctly assessed (minimal/no structural benefit of red framing)	✓	
	Gable – appears correctly measured & assessed; no surprise it's higher risk	✓	
	Pinnacle – some discussion of whether the whole tower is a falling hazard or just the weather vane on top. Different views possible, but assessment considered OK, erring on the side of caution	✓	CL
	Parapet on front facade above the street appears correctly assessed.	✓	
	Could the parapet on L facade fall through roof? Only if large pieces were to fall (as risk dominated anyway by larger pieces falling, answer to the question is "Yes").	✓	
	Dutch Gable & gable over square – appear correctly assessed & measured; no surprise they're H risk	✓	
	Curved shop parapets difficult to judge, but closer inspection shows the bricks are laid vertically which would significantly increase fragility. Risk correctly assessed in higher bracket	✓	
	Glass area – Significantly uncertain risk but correctly assessed as higher risk in absence of ability to determine how glass mounted & supported (easily resolved by inspection)	✓	
	Glazing correctly assessed in absence of info on how it's mounted in the frames.	✓	
	Free standing wall – appears correctly assessed (tall slender object like this v fragile, & by entrance)	✓	
(C) Objects Above Roofs assessed as Higher Risk			

	Would probably fall into valley between adjoining roof and own building, but if a large proportion fell could go through neighbouring roof. Assessment OK but somewhat conservative	✓	CV
	Questionable whether would go through roof but assessment considered OK (some discussion whether conservative but was not conclusive)	✓	
	Correctly assessed as high vulnerability to gable falling through the roof from several metres height	✓	
	Also certainly vulnerable to falling thru roof based on height of fall(note that chimney definitely does NOT support gable as there is a window directly beneath – probably this is or was an example of an angled chimney duct through the roof space)	✓	
	Assessment quite conservative for such a modern, shallow gable [Note – our assessments generally look conservative for modern gables with current fragility assumptions]	✓	CF
	Assessment is conservative for several reasons: a) half the gable is timbered, b) fall path not aligned with the lower roof, c) low occupancy part of the house is at risk (entrance between garage & house)	✓	CL
	Difficult to see from Street View photos but assessment appears correct as the chimney could topple onto neighbouring building from considerable height	✓	
	Assessment conservative as a) fall path not aligned with lower roof and b) low occupancy part of house at risk.	✓	CL
	Long depth of fall from gable onto flat roofed annex (& high occupancy space beneath) mean high risk assessed makes good sense	✓	
	Examination of these chimney from a wider variety of angles shows that it would have a long height of fall onto the neighbouring roof – high risk assessed makes good sense	✓	

BAG ID (building)	Summary of Discussion	Status of risk ass’t	Flag attached
(A) Objects Above Doorways assessed as Higher Risk			
	University building – high assessed risk makes sense given the massive building population (note – the conservatism in the ‘running out’ is balanced by not taking into account those already there)	✓	
	The projection of these turrets (& weathervanes) out from the building makes them v vulnerable – correct to treat as non-structural; higher risk assessed makes sense	✓	
	Object characterised as pinnacle included masonry tower beneath. Should be changed to include only the metal portion above the masonry. Risk over-assessed at present	MOD	C
	The gable itself and its situation make sense of the high CR rating (Note – masonry porch appears on this photo to have “dangling” pieces either side. Examination from other Street View angles shows these are actually properly supported from underneath.	✓	
	High assessed risk from this pinnacle/tower makes sense	✓	
	This steel canopy would be very low fragility; fragility assumptions in the risk assessment are delivering a clearly conservative result.	✓	CF
	The triangular “parapet” from which the flag is suspended is part of the structure and should not be classified as a hazardous non-structural object	No Hazard	
	Classic slender Dutch gable above doorway of high occupancy building plus quite busy street. Assessment as high risk makes sense	✓	
	Decorative feature above door is (a) too small and thin to be very fragile and (b) above a door that looks unlikely to be used as the regular entrance for hundreds of students/staff. Assessment likely to be conservative on basis of both fragility and usage.	✓	CF, CU

(B) Objects Above Public Space assessed as Higher Risk			
	Will large church spires like this be included in a separate workstream for churches and monuments? (Discussed with NAM 19/11/15 – **please include** until clear that specific objects will be covered in other workstreams)	✓	
	Large parapet is likely to be relatively stable (both shallow and deep), the fragility assumptions in the model are probably conservative.	✓	CF
(C) Objects Above Roofs assessed as Higher Risk			
	High assessed risk for gable above roof makes sense – large gable and long height of fall to neighbouring roof.	✓	
	Tall chimney plus long drop height onto the flat roof of a high occupancy building – high risk rating makes sense.	✓	

Municipality Loppersum Review

BAG ID (building)	Summary of Discussion	Status of risk ass’t	Flag attached
(A) Objects Above Doorways assessed as Higher Risk			
	Large gable on church – high risk assessed makes sense	✓	
	Gable above workshop – population at risk would be only a small subset of the population of the whole building. No way to avoid this kind of issue in large scale application of the model but makes result here considerably conservative	✓	CU
	Gable is to side of door; minor failures wouldn’t affect the space around the doorway. Assessment correctly followed the identified survey features, but conservative in this case. Also high population may include the working farm building as well as the farmhouse, so true at-risk population in house may be well below the 5.24 from the exposure database.	✓	CL
	Risk assessment performed correctly but clearly erroneous population (average indoor population of 19 for an ordinary detached house of 148m^2) gives excessive CR result	✓	CP
	Risk assessment performed correctly but clearly erroneous population (17 for a large detached house of perhaps 250m^2) gives excessive CR result – population may include working population in large contiguous farm buildings behind house.	✓	CP
	Gable above cafe area – high assessed risk makes sense	✓	
	Survey categorisation of gable as “above public space” (P*) is theoretically correct as there is no barrier to public access, but the gable is above a grassed area with no footpath where it is unimaginable that people would regularly be walking. Better classified as No Hazard.	MOD	C
	Balcony material not certain, but even if wooden is very heavy, and the hotel doorway underneath is heavily used and the main egress. High risk rating makes sense.	✓	

	Petrol station gable appears to be risk rated sensibly (typical gable + high occupancy space)	✓	
	Gable is on opposite side from shop which accounts for most of internal population, and is not directly above the doorway. Assessment done correctly, but conservative in this case.	✓	CL
	Gable above school entrance makes sense to have high risk rating	✓	
	This door would not be expected to be used regularly and to be kept locked, but no way to tell this from survey information. Risk correctly assessed but resulting risk rating likely to be conservative in this case	✓	CU
	Gable above shop appears correctly assessed as high risk rating	✓	
	Gable to one side of door, and on side away from shop. Assessment correct but conservative	✓	CL
	Large glass area appears correctly assessed in absence of visible information on support/mounting	✓	
	Dormer assessed OK but population greatly overstated (12 for an ordinary house)	✓	CP
	Assessment makes sense – gable above school entrance	✓	
	Gables above agricultural machinery store entrance – gable assessment OK, some discussion of footfall led to agreement that P*M was appropriate – related to people walking in and out, rather than along the facade.	✓	
	Gable above main entrance of school – measurement by surveyor was appropriate and assessment as high risk makes good sense	✓	
(B) Objects Above Public Space assessed as Higher Risk			
	Long parapet above relatively busy shopping street; high risk rating makes sense	✓	
	Vulnerably parapet in high footfall location; assessment & rating make sense	✓	
	Area outside school gables rated P*L and P*M; should clearly have been P*H given the 100's of children walking past each gable every day. [**ACTION** - Review P*L/P*M ratings outside public buildings]	MOD	OO

	School – difficult to characterise from Street View. Can't argue with assessment/rating	✓	
	Wooden pinnacle may be covered in other workstreams on churches/monuments, but retained in falling hazards assessment after discussion with NAM. Assessment sensible in view of large area covered in heavy tiles/metal.	✓	
(C) Objects Above Roofs assessed as Higher Risk			
	Gable directly above conservatory – though modern (so possibly lower fragility) the path of fall is directly onto an extremely vulnerable, potentially high occupancy part of the house. Assessment as higher risk entirely sensible		
	Large drop from chimney & gable to much lower outhouse (which should not be assumed to be low occupancy – could for example be heavily used utility room. Chimney built into gable should not be assumed to provide substantial strengthening. Assessment/rating OK	✓	
	Though relatively short and squat, if this chimney DID fall it would have a good chance of falling towards the significantly lower flat roof on the adjoining part of the building. Assessment/rating OK.	✓	
	Modern gable & heavy chimney at considerably height above flat shop roof - genuinely vulnerable if either object falls. Assessment/rating OK	✓	
	Extra large chimney on sports hall; assessment looks sensible & rating appropriate.	✓	
	Low drop onto steep roof makes it seem unlikely this would penetrate the (lower) neighbouring roof. Assessment clearly conservative in this case	✓	CV
	Only occupied area at risk is the entrance way between house and garage – would be expected to be very low occupancy, so risk assessment here likely to be quite conservative	✓	CL

[End of Annex 1]

Annex 2: Evaluation of Objects in the 10^{-5} to 10^{-6}/yr CR Bracket

The results are tabulated below. An assessment of "Conservative" means that the combination of survey data and model assumptions is likely to have led to the risk being overstated. An assessment of "Optimistic" means the opposite – that the risk assessment is likely to have understated the risk. NOTE: BAG identifiers have been removed from the published version of this report to protect privacy.

BAG ID	Hazard Object Type	Total CR assessed	Review Assessment	Comment
	Canopy-unsupported	1.0E-06	Conservative	The overhang of the roof appears relatively light weight and well supported. Fragility and lethality likely to be lower than that assumed for unsupported canopies generally in the risk model.
	Gable	1.3E-06	Conservative	The gable is fully clad in part concrete and part wood. The fragility and lethality is likely to be lower than masonry gables due to the restraint of the cladding.
	Gable	1.3E-06	Ok	
	Gable	3.0E-06	Ok	
	Gable	3.5E-06	Ok	
	Chimney	2.7E-06	Ok	
	Gable	1.3E-06	Conservative	Main door can be seen on front of building, so although the gable could fall over people running out of the door of the left, it may overestimate the risk as people could exit via the front door and not be affected by this hazardous object.
	Dormer	1.1E-06	Conservative	The dormer is attached to the roof and so has additional support from the wooden frame. The fragility is therefore lower than that of traditional masonry dormers built directly onto the roof's surface.
	Gable	1.1E-06	Ok	
	Gable	1.0E-06	Ok	
	Chimney	1.5E-06	Ok	

	Gable	1.4E-06	Conservative	The gable is only marginally higher than the flat roof. If it were to fail the debris would not gather enough force to break through the roof.
	Chimney	1.3E-06	Ok	
	Chimney	1.7E-06	Ok	
	Balustrade	5.2E-06	Conservative	The concrete balustrades are restrained by the metal poles and support one another. Hence fragility of this object would be lower than for traditional balustrades of this type.
	Gable	1.7E-06	Ok	
	Chimney	1.1E-06	Ok	
	Chimney	1.0E-06	Ok	
	Gable	1.3E-06	Conservative	Unable to see a clear image of the door, if the door is on a different side to the gable then it is not a falling hazard object.
	Chimney	1.0E-06	Ok	
	Gable	2.6E-06	Ok	
	Chimney	1.1E-06	Ok	
	Gable	1.9E-06	Ok	
	Gable	1.9E-06	Ok	
	Chimney	3.7E-06	Ok	
	Parapet	2.0E-06	Ok	
	Chimney	4.5E-06	Ok	
	Gable	1.7E-06	Conservative	The gable is made of concrete. The fragility and lethality will therefore be lower than that of masonry gables assumed in the risk model.
	Parapet	3.9E-06	Ok	
	DG-parapet	1.4E-06	Ok	
	Parapet	1.4E-06	Ok	
	Parapet	2.5E-06	Ok	
	Dormer	1.1E-06	Conservative	The dormer is attached to the wall below and so will have additional support through the roof and walls of the house. The fragility of this object will be lower than that assumed for typical masonry dormers within the risk model.

	Canopy-unsupported	1.3E-06	Conservative	The Canopy is supported by large stone pillars and so is unlikely to fail. The fragility of this object is lower than that assumed for canopies within the risk model.
	Decorative feature	1.9E-06	Conservative	The feature is predominantly made of metal. There are stone sections on each side. Metal has a lower fragility and so this object would have a lower fragility and lethality than assumed by other decorative features within the risk model.
	Pinnacle	3.2E-06	Ok	
	Chimney	1.9E-06	Conservative	Due to the size of the chimney, it would not have enough force to break through the roof if it were to fail. The lethality of this object is therefore lower than that assumed for other chimneys which pose a risk from falling through roofs within the risk model.
	Parapet	1.8E-06	Ok	
	Gable	2.0E-06	Ok	
	Large Glass Area	2.3E-06	Ok	
	DG-Gable	2.4E-06	Ok	
	DG-Gable	4.3E-06	Ok	
	Decorative feature	4.3E-06	Ok	
	Chimney	4.2E-06	Ok	
	Parapet	3.5E-06	Ok	
	Gable	3.9E-06	Ok	
	Gable	2.6E-06	Ok	
	Chimney	4.8E-06	Optimistic	The chimney is over the main entrance to the gym. Due to the chimney's height and weight and the amount of people that would walk past it during the day in order to enter/leave the building, the lethality of the object would likely be greater than is assumed in the risk model.
	Parapet	1.6E-06	Ok	
	Chimney	4.3E-06	Ok	
	Chimney	4.3E-06	Ok	

	Chimney	1.9E-06	Ok	
	Parapet	1.4E-06	Ok	
	Gable	8.9E-06	Optimistic	The gable is over a main exit to the school. The lethality of this object is high due to the number of people passing through the doors below.
	Gable	1.4E-06	Ok	
	Chimney	2.1E-06	Ok	
	Gable	1.4E-06	Ok	
	Chimney	3.0E-06	Ok	
	Gable	3.6E-06	Ok	
	Gable	2.3E-06	Ok	
	Chimney	2.2E-06	Ok	
	Chimney	2.8E-06	Ok	
	Chimney	2.0E-06	Ok	
	Sign - horizontal	1.3E-06	Ok	
	Chimney	1.9E-06	Ok	
	Chimney	1.3E-06	Ok	
	Chimney	1.0E-06	Conservative	The chimney is made from concrete. The fragility and lethality of this object would be lower than that assumed for masonry chimneys within the risk model.
	Parapet	4.2E-06	Ok	
	Gable	1.6E-06	Ok	
	Gable	1.0E-06	Conservative	The gable is of similar height to the building on its right and so if it were to collapse it would not gain enough momentum to break through the roof.
	Chimney	1.7E-06	Ok	
	Chimney	6.3E-06	Ok	
	Parapet	1.2E-06	Ok	
	Gable	2.6E-06	Ok	
	Gable	1.1E-06	Ok	
	Gable	1.1E-06	Ok	
	Chimney	3.1E-06	Ok	
	Chimney	1.8E-06	Ok	

	Chimney	1.8E-06	Ok	
	Chimney	1.0E-06	Ok	
	Gable	1.1E-06	Ok	
	Gable	3.5E-06	Ok	
	Gable	2.9E-06	Ok	
	Chimney	1.0E-06	Ok	
	Parapet	5.1E-06	Ok	
	Gable	1.1E-06	Ok	
	Chimney	1.3E-06	Ok	
	Gable	1.2E-06	Ok	This gable is clearly above part of the school playground and is correctly rated P*H
	Gable	4.4E-06	Ok	
	Gable	2.4E-06	Ok	
	Gable	1.4E-06	Ok	
	Gable	1.0E-06	Ok	
	Chimney	2.2E-06	Conservative	Chimney would fall to the right façade of the building, which is out of public access. The risk from this object is lower as the only exposure pathway is people running out of the door and being impacted by it.
	Chimney	5.0E-06	Ok	
	Chimney	1.3E-06	Ok	
	Gable	1.3E-06	Ok	
	Chimney	2.6E-06	Ok	
	Gable	1.9E-06	Ok	
	Gable	3.4E-06	Ok	
	Gable	1.5E-06	Ok	

Annex 3: Evaluation of Objects above Public Space

The results are tabulated below. An assessment of "Conservative" means that the combination of survey data and model assumptions is likely to have led to the risk being overstated. An assessment of "Optimistic" means the opposite – that the risk assessment is likely to have understated the risk. NOTE: BAG identifiers have been removed from the published version of this report to protect privacy.

BAG ID	Primary Use	CR building (overall)	Review evaluation
	Gathering Place	1.8E-05	Ok
	Health Care	1.4E-06	Ok
	Gathering Place	1.5E-05	Optimistic
	Educational	1.4E-05	Ok
	Health Care	1.4E-05	Ok
	Gathering Place	4.6E-07	Optimistic
	Gathering Place	5.6E-07	Ok
	Gathering Place	4.9E-05	Ok
	Gathering Place	1.1E-05	Ok
	Gathering Place	4.4E-06	Ok
	Gathering Place	1.4E-07	Optimistic
	Health Care	6.1E-07	Ok
	Residential	1.7E-08	Ok
	Gathering Place	9.2E-07	Ok
	Educational	1.6E-05	Ok
	Educational	3.9E-06	Ok
	Gathering Place	5.1E-06	Optimistic
	Gathering Place	2.0E-05	Conservative
	Gathering Place	1.1E-07	Optimistic
	Gathering Place	1.3E-05	Optimistic
	Gathering Place	8.6E-06	Ok
	Educational	7.4E-05	Optimistic
	Gathering Place	1.7E-07	Ok
	Educational	2.5E-05	Ok
	Educational	5.8E-05	Ok
	Residential	1.2E-06	Optimistic
	Gathering Place	5.4E-08	Ok
	Gathering Place	1.1E-08	Optimistic
	Educational	4.3E-06	Optimistic
	Educational	5.5E-06	Ok
	Educational	2.2E-06	Ok
	Health Care	1.5E-05	Ok
	Health Care	4.5E-07	Ok

	Health Care	3.3E-09	Ok
	Gathering Place	5.8E-07	Ok
	Residential	5.5E-06	Optimistic
	Residential	2.3E-07	Ok
	Retail	9.8E-08	Ok
	Educational	1.5E-07	Ok
	Educational	2.8E-05	Optimistic
	Gathering Place	4.2E-05	Conservative
	Gathering Place	1.2E-06	Ok
	Gathering Place	6.9E-08	Ok
	Health Care	5.4E-07	Ok
	Educational	4.1E-04	Ok
	Gathering Place	3.7E-07	Optimistic
	Educational	6.2E-08	Ok
	Gathering Place	1.4E-06	Ok
	Residential	2.2E-06	Ok
	Industrial	9.7E-07	Optimistic
	Residential	3.4E-09	Conservative
	Residential	7.0E-08	Ok
	Office	8.2E-08	Ok
	Residential	5.8E-06	Ok
	Industrial	1.9E-08	Ok
	Educational	5.4E-07	Ok
	Retail	1.8E-06	Ok
	Industrial	1.3E-06	Ok
	Industrial	1.9E-08	Optimistic
	Industrial	6.6E-09	Ok
	Industrial	4.4E-08	Ok
	Industrial	7.1E-07	Ok
	Gathering Place	1.6E-08	Ok
	Educational	6.4E-10	Ok
	Gathering Place	5.2E-07	Ok
	Office	7.6E-09	Ok
	Retail	6.7E-08	Ok
	Industrial	1.4E-07	Ok
	Gathering Place	1.1E-08	Ok
	Office	4.9E-06	Ok
	Office	1.6E-07	Ok
	Gathering Place	4.7E-08	Ok
	Office	5.9E-08	Ok
	Industrial	8.0E-07	Ok
	Gathering Place	2.7E-09	Ok
	Industrial	7.9E-08	Conservative
	Industrial	3.3E-09	Ok

	Office	2.7E-08	Ok
	Educational	5.3E-07	Optimistic
	Retail	5.8E-06	Ok
	Gathering Place	4.1E-06	Ok
	Educational	4.6E-06	Ok
	Gathering Place	4.5E-06	Ok
	Office	4.9E-07	Ok
	Educational	4.0E-07	Ok
	Industrial	2.0E-06	Ok
	Gathering Place	7.1E-07	Ok
	Educational	1.4E-06	Ok
	Office	4.3E-06	Ok
	Industrial	3.1E-08	Ok
	Industrial	5.5E-07	Optimistic
	Gathering Place	2.4E-08	Ok
	Industrial	2.8E-06	Ok
	Gathering Place	1.9E-06	Ok
	Educational	4.8E-07	Ok
	Gathering Place	6.6E-07	Ok
	Gathering Place	1.8E-08	Ok
	Gathering Place	3.4E-09	Ok
	Gathering Place	8.1E-07	Ok
	Gathering Place	1.4E-06	Optimistic

[end of Annex 3]

Annex 4: Sensitivity Study Results

Tables of results are presented for each scenario, showing the overall community risk contributed by different exposure routes and the numbers of different object types assessed as “High risk” (CR>=10^{-5}/yr) under each of the following scenarios:

- Base Case
- Scenario 1: Lower fragility, masonry objects (chimneys, parapets, gables)
- Scenario 2: Higher fragility, masonry objects (chimneys, parapets, gables)
- Scenario 3: Lower exposure assumptions
- Scenario 4: Higher exposure assumptions
- Scenario 5: Lower fragility AND seismicity assumptions
- Scenario 6: Higher fragility AND seismicity assumptions
- Scenario 7: Lower fragility, other objects (balconies, canopies, glazing etc)
- Scenario 8: Higher fragility, non-conventional objects
- Scenario 9: Lower risk – All Assumptions simultaneously
- Scenario 10: Higher risk – All Assumptions simultaneously

The parameters varied in each scenario and the ranges of values used are explained in Table 3 in the main report.

NOTE: The sensitivity studies were carried out while checks on the survey and assessment were still in progress, rather than on the finalised spreadsheets. The results for the Base Case thus differ slightly from those of the final risk assessment. The differences are minor and we are confident that they do not make any material difference to the results of the sensitivity studies or the conclusions drawn from them.

Base Case

Total Falling Hazards CR	3.4E-02	fatalities/year					
of which	2.2E-02	are associated with running out of doors					
	5.3E-03	are associated with people in public space near the building					
	6.6E-03	are associated with objects falling through building roofs					

Count of Falling Hazard Objects

		Community Risk Band				
Object Type	**Total**	**$>10^{-4}$**	**10^{-5} to 10^{-4}**	**10^{-6} to 10^{-5}**	**10^{-7} to 10^{-6}**	**10^{-8} to 10^{-7}**
Chimney	47370	0	36	1459	9804	20399
Decorative feature	706	3	8	60	218	263
Pinnacle	362	1	9	38	73	100
Parapet	7542	9	70	720	3086	2625
Balustrade	4311	0	49	235	1311	1178
Free standing wall	1507	0	6	266	742	416
Gable	28121	0	54	1970	7342	10561
DG-parapet	729	0	16	79	335	233
DG-gable	722	0	4	50	243	336
Dormer	2245	0	23	284	1361	485
Canopy-supported	1683	1	2	11	114	529
Canopy-unsupported	14004	0	2	66	440	2594
Balcony	3472	0	0	27	133	732
Bay window	2034	0	0	3	30	295
Large glass area	537	1	12	50	167	215
Sign - vert	1182	0	0	3	41	253
Sign - horiz	2380	1	2	22	203	500
Industrial object	80	0	0	3	12	27
Flagpole	1086	0	0	0	0	68
TOTAL	**120073**	**16**	**278**	**4689**	**19901**	**24227**

Falling Hazards by Main Exposure Pathway, for CR >= 1.0E-05

Object Type	**Above doorways**		**Above public**		**Elevated risk above**		**TOTAL objects**
	Total objects	**No. with CR>=10^{-5}**	**Total objects**	**No. with CR>=10^{-5}**	**Total objects**	**No. with CR>=10^{-5}**	
Chimney	23494	6	27367	0	4766	30	**36**
Decorative feature	457	11	613	0	11	0	**11**
Pinnacle	160	6	334	2	26	2	**10**
Parapet	6273	50	6375	21	217	8	**79**
Balustrade	3664	19	3332	30	50	0	**49**
Free standing wall	1094	5	685	1	72	0	**6**
Gable	7859	17	17948	0	1180	37	**54**
DG-parapet	629	12	671	3	15	1	**16**
DG-gable	634	3	663	1	8	0	**4**
Dormer	1967	16	1996	7	4	0	**23**
Canopy-supported	1303	3	1025	0	1	0	**3**
Canopy-unsupported	13383	2	7345	0	6	0	**2**
Balcony	3100	0	2567	0	1	0	**0**
Bay window	1543	0	1893	0	0	0	**0**
Large glass area	393	12	436	1	4	0	**13**
Sign - vert	526	0	1139	0	1	0	**0**
Sign - horiz	1252	3	2218	0	17	0	**3**
Industrial object	20	0	56	0	18	0	**0**
Flagpole	479	0	1049	0	4	0	**0**
TOTAL	**68230**	**165**	**77712**	**66**	**6401**	**78**	**309**
% of objects that are high CR	***0.24%***		***0.08%***		***1.2%***		***0.20%***

Scenario 1: Low Fragility, Masonry Objects

Total Falling Hazards CR	1.1E-02	fatalities/year					
of which	6.8E-03	are associated with running out of doors					
	1.9E-03	are associated with people in public space near the building					
	2.3E-03	are associated with objects falling through building roofs					

Count of Falling Hazard Objects		*1.00E-04*	*1.00E-05*	*1.00E-06*	*1.00E-07*	*1.00E-08*
		Community Risk Band				
Object Type	**Total**	**$>10^{-4}$**	**10^{-5} to 10^{-4}**	**10^{-6} to 10^{-5}**	**10^{-7} to 10^{-6}**	**10^{-8} to 10^{-7}**
Chimney	47370	0	2	373	4903	15689
Decorative feature	706	0	4	38	127	260
Pinnacle	362	0	5	20	56	77
Parapet	7542	0	20	300	1984	3353
Balustrade	4311	0	1	98	757	1437
Free standing wall	1507	0	1	99	543	679
Gable	28121	0	6	549	5112	8880
DG-parapet	729	0	2	43	198	354
DG-gable	722	0	2	24	111	370
Dormer	2245	0	3	128	804	1117
Canopy-supported	1683	1	0	5	40	314
Canopy-unsupported	14004	0	0	30	207	1123
Balcony	3472	0	0	5	38	466
Bay window	2034	0	0	3	5	107
Large glass area	537	0	4	21	110	235
Sign - vert	1182	0	0	1	10	149
Sign - horiz	2380	1	0	10	77	364
Industrial object	80	0	0	0	12	12
Flagpole	1086	0	0	0	0	6
TOTAL	**120073**	**2**	**43**	**1582**	**12545**	**23434**

Falling Hazard Objects by Main Exposure Pathway, for CR >= 1.0E-05

Object Type	**Above doorway**		**Above public**		**Elevated risk above**		**TOTAL objects**
	Total objects	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	
Chimney	23494	1	27367	0	4763	1	**2**
Decorative feature	457	4	613	0	11	0	**4**
Pinnacle	160	4	334	1	26	0	**5**
Parapet	6273	14	6375	4	217	2	**20**
Balustrade	3664	1	3332	0	50	0	**1**
Free standing wall	1094	1	685	0	72	0	**1**
Gable	7859	2	17948	0	1177	4	**6**
DG-parapet	629	1	671	1	15	0	**2**
DG-gable	634	2	663	0	8	0	**2**
Dormer	1967	3	1996	0	4	0	**3**
Canopy-supported	1303	1	1025	0	1	0	**1**
Canopy-unsupported	13383	0	7345	0	6	0	**0**
Balcony	3100	0	2567	0	1	0	**0**
Bay window	1543	0	1893	0	0	0	**0**
Large glass area	393	4	436	0	4	0	**4**
Sign - vert	526	0	1139	0	1	0	**0**
Sign - horiz	1252	1	2218	0	17	0	**1**
Industrial object	20	0	56	0	18	0	**0**
Flagpole	479	0	1049	0	4	0	**0**
TOTAL	**68230**	**39**	**77712**	**6**	**6395**	**7**	**52**
% of objects that are high CR	***0.06%***		***0.01%***		***0.1%***		***0.00%***

Scenario 2: High Fragility, Masonry Objects

Total Falling Hazards CR	1.0E-01	fatalities/year					
of which	5.2E-02	are associated with running out of doors					
	3.0E-02	are associated with people in public space near the building					
	1.8E-02	are associated with objects falling through building roofs					

Count of Falling Hazard Objects		*1.00E-04*	*1.00E-05*	*1.00E-06*	*1.00E-07*	*1.00E-08*
		Community Risk Band				
Object Type	**Total**	**$>10^{-4}$**	**10^{-5} to 10^{-4}**	**10^{-6} to 10^{-5}**	**10^{-7} to 10^{-6}**	**10^{-8} to 10^{-7}**
Chimney	47370	3	300	4514	18496	19271
Decorative feature	706	4	41	121	293	189
Pinnacle	362	5	18	61	85	152
Parapet	7542	14	292	2072	3499	1423
Balustrade	4311	26	63	803	1554	894
Free standing wall	1507	0	61	603	714	119
Gable	28121	3	266	5208	11565	8529
DG-parapet	729	4	43	205	359	112
DG-gable	722	1	25	147	382	149
Dormer	2245	1	93	786	1233	123
Canopy-supported	1683	1	4	40	276	807
Canopy-unsupported	14004	0	28	200	1170	5498
Balcony	3472	0	3	33	458	1157
Bay window	2034	0	3	5	126	932
Large glass area	537	2	22	116	245	116
Sign - vert	1182	0	1	10	164	419
Sign - horiz	2380	1	6	80	394	741
Industrial object	80	0	1	11	15	26
Flagpole	1086	0	0	0	11	267
TOTAL	**120073**	**61**	**1154**	**12461**	**26616**	**21991**

Falling Hazard Objects by Main Exposure Pathway, for CR >= 1.0E-05

Object Type	**Above doorway**		**Above public**		**Elevated risk above**		**TOTAL objects**
	Total objects	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	
Chimney	23494	52	27367	39	4763	212	**303**
Decorative feature	457	28	613	15	11	2	**45**
Pinnacle	160	8	334	13	26	2	**23**
Parapet	6273	133	6375	161	217	12	**306**
Balustrade	3664	29	3332	59	50	1	**89**
Free standing wall	1094	41	685	18	72	2	**61**
Gable	7859	101	17948	41	1177	127	**269**
DG-parapet	629	17	671	29	15	1	**47**
DG-gable	634	11	663	15	8	0	**26**
Dormer	1967	57	1996	37	4	0	**94**
Canopy-supported	1303	5	1025	0	1	0	**5**
Canopy-unsupported	13383	22	7345	6	6	0	**28**
Balcony	3100	3	2567	0	1	0	**3**
Bay window	1543	3	1893	0	0	0	**3**
Large glass area	393	16	436	6	4	2	**24**
Sign - vert	526	1	1139	0	1	0	**1**
Sign - horiz	1252	7	2218	0	17	0	**7**
Industrial object	20	0	56	0	18	1	**1**
Flagpole	479	0	1049	0	4	0	**0**
TOTAL	**68230**	**534**	**77712**	**439**	**6395**	**362**	**1335**
% of objects that are high CR	***0.78%***		***0.56%***		***5.7%***		***0.00%***

Scenario 3: Low Exposure

Total Falling Hazards CR	7.4E-03	fatalities/year
of which	3.5E-03	are associated with running out of doors
	1.6E-03	are associated with people in public space near the building
	2.3E-03	are associated with objects falling through building roofs

Count of Falling Hazard Objects

		1.00E-04	*1.00E-05*	*1.00E-06*	*1.00E-07*	*1.00E-08*
		Community Risk Band				
Object Type	**Total**	**$>10^{-4}$**	**10^{-5} to 10^{-4}**	**10^{-6} to 10^{-5}**	**10^{-7} to 10^{-6}**	**10^{-8} to 10^{-7}**
Chimney	47370	0	3	316	3323	9072
Decorative feature	706	0	7	27	109	233
Pinnacle	362	0	5	19	43	106
Parapet	7542	0	15	211	1034	2975
Balustrade	4311	0	1	56	325	1203
Free standing wall	1507	0	1	24	300	615
Gable	28121	0	4	275	2770	7181
DG-parapet	729	0	4	34	183	269
DG-gable	722	0	1	19	129	245
Dormer	2245	0	0	52	553	1139
Canopy-supported	1683	0	1	2	26	166
Canopy-unsupported	14004	0	0	26	151	882
Balcony	3472	0	0	0	10	148
Bay window	2034	0	0	3	6	120
Large glass area	537	0	1	19	87	180
Sign - vert	1182	0	0	1	15	159
Sign - horiz	2380	0	1	5	72	248
Industrial object	80	0	0	1	6	19
Flagpole	1086	0	0	0	0	20
TOTAL	**120073**	**0**	**44**	**1020**	**8039**	**19236**

Falling Hazard Objects by Main Exposure Pathway, for CR >= 1.0E-05

Object Type	**Above doorway**		**Above public**		**Elevated risk above**		**TOTAL objects**
	Total objects	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	
Chimney	23494	0	27367	0	4763	3	**3**
Decorative feature	457	7	613	0	11	0	**7**
Pinnacle	160	4	334	1	26	0	**5**
Parapet	6273	10	6375	3	217	2	**15**
Balustrade	3664	1	3332	0	50	0	**1**
Free standing wall	1094	0	685	1	72	0	**1**
Gable	7859	2	17948	0	1177	2	**4**
DG-parapet	629	4	671	0	15	0	**4**
DG-gable	634	1	663	0	8	0	**1**
Dormer	1967	0	1996	0	4	0	**0**
Canopy-supported	1303	1	1025	0	1	0	**1**
Canopy-unsupported	13383	0	7345	0	6	0	**0**
Balcony	3100	0	2567	0	1	0	**0**
Bay window	1543	0	1893	0	0	0	**0**
Large glass area	393	1	436	0	4	0	**1**
Sign - vert	526	0	1139	0	1	0	**0**
Sign - horiz	1252	1	2218	0	17	0	**1**
Industrial object	20	0	56	0	18	0	**0**
Flagpole	479	0	1049	0	4	0	**0**
TOTAL	**68230**	**32**	**77712**	**5**	**6395**	**7**	**44**
% of objects that are high CR	***0.05%***		***0.01%***		***0.1%***		***0.00%***

Scenario 4: High Exposure

Total Falling Hazards CR	5.7E-02	fatalities/year					
of which	4.0E-02	are associated with running out of doors					
	1.1E-02	are associated with people in public space near the building					
	6.5E-03	are associated with objects falling through building roofs					

Count of Falling Hazard Objects

		1.00E-04	1.00E-05	1.00E-06	1.00E-07	1.00E-08
		Community Risk Band				
Object Type	**Total**	**>10^{-4}**	**10^{-5} to 10^{-4}**	**10^{-6} to 10^{-5}**	**10^{-7} to 10^{-6}**	**10^{-8} to 10^{-7}**
Chimney	47370	0	75	2423	14503	21090
Decorative feature	706	4	17	84	268	233
Pinnacle	362	2	11	45	80	129
Parapet	7542	8	157	1442	3407	1972
Balustrade	4311	0	64	515	1453	997
Free standing wall	1507	0	42	469	769	191
Gable	28121	0	94	3190	9681	10191
DG-parapet	729	0	22	130	373	172
DG-gable	722	1	7	88	310	273
Dormer	2245	1	61	485	1432	222
Canopy-supported	1683	1	3	22	196	669
Canopy-unsupported	14004	0	6	127	754	4442
Balcony	3472	0	2	19	379	840
Bay window	2034	0	0	5	69	567
Large glass area	537	2	18	85	198	180
Sign - vert	1182	0	1	4	89	315
Sign - horiz	2380	1	5	41	286	605
Industrial object	80	0	0	7	8	29
Flagpole	1086	0	0	0	2	124
TOTAL	**120073**	**17**	**535**	**7950**	**24012**	**24034**

Falling Hazard Objects by Main Exposure Pathway, for CR >= 1.0E-05

Object Type	**Above doorway**		**Above public**		**Elevated risk above**		**TOTAL objects**
	Total objects	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	
Chimney	23494	44	27367	3	4763	28	**75**
Decorative feature	457	19	613	2	11	0	**21**
Pinnacle	160	7	334	5	26	1	**13**
Parapet	6273	104	6375	53	217	8	**165**
Balustrade	3664	24	3332	40	50	0	**64**
Free standing wall	1094	37	685	5	72	0	**42**
Gable	7859	55	17948	7	1177	32	**94**
DG-parapet	629	17	671	4	15	1	**22**
DG-gable	634	6	663	2	8	0	**8**
Dormer	1967	52	1996	10	4	0	**62**
Canopy-supported	1303	4	1025	0	1	0	**4**
Canopy-unsupported	13383	5	7345	1	6	0	**6**
Balcony	3100	2	2567	0	1	0	**2**
Bay window	1543	0	1893	0	0	0	**0**
Large glass area	393	16	436	4	4	0	**20**
Sign - vert	526	1	1139	0	1	0	**1**
Sign - horiz	1252	6	2218	0	17	0	**6**
Industrial object	20	0	56	0	18	0	**0**
Flagpole	479	0	1049	0	4	0	**0**
TOTAL	**68230**	**399**	**77712**	**136**	**6395**	**70**	**605**
% of objects that are high CR	***0.58%***		***0.18%***		***1.1%***		***0.00%***

Scenario 5: Low Fragility & Seismicity

Total Falling Hazards CR	4.8E-03	fatalities/year					
of which	3.0E-03	are associated with running out of doors					
	9.1E-04	are associated with people in public space near the building					
	9.4E-04	are associated with objects falling through building roofs					
Count of Falling Hazard Objects		*1.00E-04*	*1.00E-05*	*1.00E-06*	*1.00E-07*	*1.00E-08*	
		Community Risk Band					
Object Type	**Total**	**$>10^{-4}$**	**10^{-5} to 10^{-4}**	**10^{-6} to 10^{-5}**	**10^{-7} to 10^{-6}**	**10^{-8} to 10^{-7}**	
Chimney	47370	0	1	119	2375	11770	
Decorative feature	706	0	3	22	67	253	
Pinnacle	362	0	4	9	49	72	
Parapet	7542	0	4	157	1192	3355	
Balustrade	4311	0	0	56	362	1503	
Free standing wall	1507	0	0	37	399	709	
Gable	28121	0	1	73	2378	7751	
DG-parapet	729	0	0	25	130	366	
DG-gable	722	0	1	7	66	279	
Dormer	2245	0	1	57	486	1401	
Canopy-supported	1683	0	1	2	15	134	
Canopy-unsupported	14004	0	0	5	91	539	
Balcony	3472	0	0	0	9	318	
Bay window	2034	0	0	0	5	44	
Large glass area	537	0	1	12	60	192	
Sign - vert	1182	0	0	1	4	76	
Sign - horiz	2380	0	1	4	30	248	
Industrial object	80	0	0	0	4	13	
Flagpole	1086	0	0	0	0	3	
TOTAL	**120073**	**0**	**17**	**549**	**6620**	**21591**	

Falling Hazard Objects by Main Exposure Pathway, for CR >= 1.0E-05

Object Type	**Above doorway**		**Above public**		**Elevated risk above**		**TOTAL objects**
	Total objects	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	
Chimney	23494	0	27367	0	4763	1	**1**
Decorative feature	457	3	613	0	11	0	**3**
Pinnacle	160	3	334	1	26	0	**4**
Parapet	6273	4	6375	0	217	0	**4**
Balustrade	3664	0	3332	0	50	0	**0**
Free standing wall	1094	0	685	0	72	0	**0**
Gable	7859	0	17948	0	1177	1	**1**
DG-parapet	629	0	671	0	15	0	**0**
DG-gable	634	1	663	0	8	0	**1**
Dormer	1967	1	1996	0	4	0	**1**
Canopy-supported	1303	1	1025	0	1	0	**1**
Canopy-unsupported	13383	0	7345	0	6	0	**0**
Balcony	3100	0	2567	0	1	0	**0**
Bay window	1543	0	1893	0	0	0	**0**
Large glass area	393	1	436	0	4	0	**1**
Sign - vert	526	0	1139	0	1	0	**0**
Sign - horiz	1252	1	2218	0	17	0	**1**
Industrial object	20	0	56	0	18	0	**0**
Flagpole	479	0	1049	0	4	0	**0**
TOTAL	**68230**	**15**	**77712**	**1**	**6395**	**2**	**18**
% of objects that are high CR	***0.02%***		***0.00%***		***0.0%***		***0.00%***

Scenario 6: High Fragility & Seismicity

Total Falling Hazards CR	1.7E-01	fatalities/year					
of which	1.0E-01	are associated with running out of doors					
	2.7E-02	are associated with people in public space near the building					
	3.7E-02	are associated with objects falling through building roofs					

Count of Falling Hazard Objects

		1.00E-04	1.00E-05	1.00E-06	1.00E-07	1.00E-08
		Community Risk Band				
Object Type	**Total**	**>10^{-4}**	**10^{-5} to 10^{-4}**	**10^{-6} to 10^{-5}**	**10^{-7} to 10^{-6}**	**10^{-8} to 10^{-7}**
Chimney	47370	8	599	6767	18524	16009
Decorative feature	706	9	39	169	261	172
Pinnacle	362	5	29	54	93	138
Parapet	7542	22	367	2362	3135	1328
Balustrade	4311	2	109	958	1402	912
Free standing wall	1507	1	114	629	625	122
Gable	28121	36	1390	6820	10476	7073
DG-parapet	729	4	45	221	341	101
DG-gable	722	3	36	184	364	122
Dormer	2245	3	137	915	1029	128
Canopy-supported	1683	3	8	63	477	701
Canopy-unsupported	14004	1	37	331	1883	6598
Balcony	3472	0	6	74	596	1379
Bay window	2034	0	3	14	197	1131
Large glass area	537	7	37	149	233	87
Sign - vert	1182	0	1	20	217	404
Sign - horiz	2380	3	17	115	457	769
Industrial object	80	0	2	13	18	21
Flagpole	1086	0	0	0	23	268
TOTAL	**120073**	**96**	**2708**	**15839**	**24775**	**21051**

Falling Hazard Objects by Main Exposure Pathway, for CR >= 1.0E-05

Object Type	**Above doorway**		**Above public**		**Elevated risk above**		**TOTAL objects**
	Total objects	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	
Chimney	23494	192	27367	24	4763	391	**607**
Decorative feature	457	33	613	13	11	2	**48**
Pinnacle	160	15	334	12	26	7	**34**
Parapet	6273	252	6375	116	217	21	**389**
Balustrade	3664	67	3332	43	50	1	**111**
Free standing wall	1094	77	685	11	72	27	**115**
Gable	7859	924	17948	42	1177	460	**1426**
DG-parapet	629	30	671	17	15	2	**49**
DG-gable	634	26	663	12	8	1	**39**
Dormer	1967	117	1996	22	4	1	**140**
Canopy-supported	1303	11	1025	0	1	0	**11**
Canopy-unsupported	13383	33	7345	5	6	0	**38**
Balcony	3100	6	2567	0	1	0	**6**
Bay window	1543	3	1893	0	0	0	**3**
Large glass area	393	31	436	11	4	2	**44**
Sign - vert	526	1	1139	0	1	0	**1**
Sign - horiz	1252	19	2218	0	17	1	**20**
Industrial object	20	0	56	0	18	2	**2**
Flagpole	479	0	1049	0	4	0	**0**
TOTAL	**68230**	**1837**	**77712**	**328**	**6395**	**918**	**3083**
% of objects that are high CR	***2.69%***		***0.42%***		***14.4%***		***0.00%***

Scenario 7: Low Fragility, Other Objects

Total Falling Hazards CR	2.4E-02	fatalities/year					
of which	1.7E-02	are associated with running out of doors					
	5.0E-03	are associated with people in public space near the building					
	2.3E-03	are associated with objects falling through building roofs					
Count of Falling Hazard Objects		*1.00E-04*	*1.00E-05*	*1.00E-06*	*1.00E-07*	*1.00E-08*	
		Community Risk Band					
Object Type	**Total**	**$>10^{-4}$**	**10^{-5} to 10^{-4}**	**10^{-6} to 10^{-5}**	**10^{-7} to 10^{-6}**	**10^{-8} to 10^{-7}**	
Chimney	47370	0	9	876	9133	21423	
Decorative feature	706	3	6	62	216	264	
Pinnacle	362	1	6	32	75	107	
Parapet	7542	1	63	693	3067	2655	
Balustrade	4311	0	43	192	1382	1409	
Free standing wall	1507	0	6	222	782	418	
Gable	28121	0	19	1593	7262	10783	
DG-parapet	729	0	15	79	334	235	
DG-gable	722	0	4	49	239	337	
Dormer	2245	0	23	282	1361	487	
Canopy-supported	1683	1	0	4	37	265	
Canopy-unsupported	14004	0	0	29	162	1008	
Balcony	3472	0	0	3	23	447	
Bay window	2034	0	0	3	3	100	
Large glass area	537	0	5	15	105	242	
Sign - vert	1182	0	0	2	6	137	
Sign - horiz	2380	0	1	7	64	343	
Industrial object	80	0	0	0	18	20	
Flagpole	1086	0	0	0	6	190	
TOTAL	**120073**	**6**	**190**	**3719**	**19120**	**23260**	

Falling Hazard Objects by Main Exposure Pathway, for CR >= 1.0E-05

Object Type	**Above doorway**		**Above public**		**Elevated risk above**		**TOTAL objects**
	Total objects	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	
Chimney	23494	6	27367	0	4763	3	**9**
Decorative feature	457	9	613	0	11	0	**9**
Pinnacle	160	6	334	1	26	0	**7**
Parapet	6273	41	6375	21	217	2	**64**
Balustrade	3664	13	3332	30	50	0	**43**
Free standing wall	1094	5	685	1	72	0	**6**
Gable	7859	17	17948	0	1177	2	**19**
DG-parapet	629	12	671	3	15	0	**15**
DG-gable	634	3	663	1	8	0	**4**
Dormer	1967	16	1996	7	4	0	**23**
Canopy-supported	1303	1	1025	0	1	0	**1**
Canopy-unsupported	13383	0	7345	0	6	0	**0**
Balcony	3100	0	2567	0	1	0	**0**
Bay window	1543	0	1893	0	0	0	**0**
Large glass area	393	4	436	1	4	0	**5**
Sign - vert	526	0	1139	0	1	0	**0**
Sign - horiz	1252	1	2218	0	17	0	**1**
Industrial object	20	0	56	0	18	0	**0**
Flagpole	479	0	1049	0	4	0	**0**
TOTAL	**68230**	**134**	**77712**	**65**	**6395**	**7**	**206**
% of objects that are high CR	***0.20%***		***0.08%***		***0.1%***		***0.00%***

Scenario 8: High Fragility, Other Objects

Total Falling Hazards CR	3.5E-02	fatalities/year					
of which	2.3E-02	are associated with running out of doors					
	5.9E-03	are associated with people in public space near the building					
	6.5E-03	are associated with objects falling through building roofs					

Count of Falling Hazard Objects		*1.00E-04*	*1.00E-05*	*1.00E-06*	*1.00E-07*	*1.00E-08*
		Community Risk Band				
Object Type	**Total**	**$>10^{-4}$**	**10^{-5} to 10^{-4}**	**10^{-6} to 10^{-5}**	**10^{-7} to 10^{-6}**	**10^{-8} to 10^{-7}**
Chimney	47370	0	35	1449	9800	20414
Decorative feature	706	3	8	60	218	263
Pinnacle	362	1	9	38	73	100
Parapet	7542	1	69	717	3102	2638
Balustrade	4311	0	46	237	1863	1678
Free standing wall	1507	0	6	266	742	416
Gable	28121	0	49	1942	7369	10567
DG-parapet	729	0	16	79	335	233
DG-gable	722	0	4	50	243	336
Dormer	2245	0	23	284	1361	485
Canopy-supported	1683	1	4	37	267	689
Canopy-unsupported	14004	0	28	169	1009	5201
Balcony	3472	0	3	23	447	951
Bay window	2034	0	3	3	100	781
Large glass area	537	4	18	104	239	131
Sign - vert	1182	0	1	7	137	353
Sign - horiz	2380	1	8	63	345	645
Industrial object	80	0	0	6	24	25
Flagpole	1086	0	0	6	191	369
TOTAL	**120073**	**11**	**313**	**4839**	**21754**	**27928**

Falling Hazard Objects by Main Exposure Pathway, for CR >= 1.0E-05

Object Type	**Above doorways**		**Above public**		**Elevated risk above**		**TOTAL objects**
	Total objects	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	
Chimney	23494	6	27367	0	4763	29	**35**
Decorative feature	457	11	613	0	11	0	**11**
Pinnacle	160	6	334	2	26	2	**10**
Parapet	6273	41	6375	21	217	8	**70**
Balustrade	3664	16	3332	30	50	0	**46**
Free standing wall	1094	5	685	1	72	0	**6**
Gable	7859	17	17948	0	1177	32	**49**
DG-parapet	629	12	671	3	15	1	**16**
DG-gable	634	3	663	1	8	0	**4**
Dormer	1967	16	1996	7	4	0	**23**
Canopy-supported	1303	5	1025	0	1	0	**5**
Canopy-unsupported	13383	24	7345	4	6	0	**28**
Balcony	3100	3	2567	0	1	0	**3**
Bay window	1543	3	1893	0	0	0	**3**
Large glass area	393	16	436	4	4	2	**22**
Sign - vert	526	1	1139	0	1	0	**1**
Sign - horiz	1252	8	2218	0	17	1	**9**
Industrial object	20	0	56	0	18	0	**0**
Flagpole	479	0	1049	0	4	0	**0**
TOTAL	**68230**	**193**	**77712**	**73**	**6395**	**75**	**341**
% of objects that are high CR	***0.28%***		***0.09%***		***1.2%***		***0.00%***

Scenario 9: Low Fragility & Seismicity & Exposure

Total Falling Hazards CR	2.5E-03	fatalities/year					
of which	1.9E-03	are associated with running out of doors					
	2.8E-04	are associated with people in public space near the building					
	3.7E-04	are associated with objects falling through building roofs					

Count of Falling Hazard Objects		*1.00E-04*	*1.00E-05*	*1.00E-06*	*1.00E-07*	*1.00E-08*
		Community Risk Band				
Object Type	**Total**	**$>10^{-4}$**	**10^{-5} to 10^{-4}**	**10^{-6} to 10^{-5}**	**10^{-7} to 10^{-6}**	**10^{-8} to 10^{-7}**
Chimney	47370	0	0	11	937	8446
Decorative feature	706	0	3	13	45	220
Pinnacle	362	0	2	5	34	71
Parapet	7542	0	3	64	738	2821
Balustrade	4311	0	0	14	275	1164
Free standing wall	1507	0	0	9	274	677
Gable	28122	0	0	27	1544	6138
DG-parapet	729	0	0	15	82	330
DG-gable	722	0	0	4	40	201
Dormer	2245	0	0	25	298	1304
Canopy-supported	1683	0	1	0	4	27
Canopy-unsupported	14004	0	0	0	29	123
Balcony	3472	0	0	0	3	27
Bay window	2034	0	0	0	3	4
Large glass area	537	0	0	4	16	76
Sign - vert	1182	0	0	0	3	14
Sign - horiz	2380	0	1	0	6	58
Industrial object	80	0	0	0	0	17
Flagpole	1086	0	0	0	0	6
TOTAL	**120074**	**0**	**9**	**182**	**3913**	**17392**

Falling Hazard Objects by Main Exposure Pathway, for CR >= 1.0E-05

Object Type	**Above doorway**		**Above public**		**Elevated risk above**		**TOTAL objects**
	Total objects	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	
Chimney	23494	0	27367	0	4763	0	**0**
Decorative feature	457	3	613	0	11	0	**0**
Pinnacle	160	2	334	0	26	0	**0**
Parapet	6273	3	6375	0	217	0	**0**
Balustrade	3664	0	3332	0	50	0	**0**
Free standing wall	1094	0	685	0	72	0	**0**
Gable	7859	0	17949	0	1177	0	**0**
DG-parapet	629	0	671	0	15	0	**0**
DG-gable	634	0	663	0	8	0	**0**
Dormer	1967	0	1996	0	4	0	**0**
Canopy-supported	1303	1	1025	0	1	0	**0**
Canopy-unsupported	13383	0	7345	0	6	0	**0**
Balcony	3100	0	2567	0	1	0	**0**
Bay window	1543	0	1893	0	0	0	**0**
Large glass area	393	0	436	0	4	0	**0**
Sign - vert	526	0	1139	0	1	0	**0**
Sign - horiz	1252	1	2218	0	17	0	**0**
Industrial object	20	0	56	0	18	0	**0**
Flagpole	479	0	1049	0	4	0	**0**
TOTAL	**68230**	**10**	**77713**	**0**	**6395**	**0**	**0**
% of objects that are high CR	***0.01%***		***0.00%***		***0.0%***		***0.00%***

Scenario 10: High Fragility & Seismicity & Exposure

Total Falling Hazards CR	3.7E-01	fatalities/year					
of which	2.7E-01	are associated with running out of doors					
	6.4E-02	are associated with people in public space near the building					
	3.7E-02	are associated with objects falling through building roofs					
Count of Falling Hazard Objects		*1.00E-04*	*1.00E-05*	*1.00E-06*	*1.00E-07*	*1.00E-08*	
		Community Risk Band					
Object Type	**Total**	**$>10^{-4}$**	**10^{-5} to 10^{-4}**	**10^{-6} to 10^{-5}**	**10^{-7} to 10^{-6}**	**10^{-8} to 10^{-7}**	
Chimney	47370	24	1108	10122	22236	10935	
Decorative feature	706	10	62	210	271	121	
Pinnacle	362	8	34	72	92	129	
Parapet	7542	53	674	3141	2705	819	
Balustrade	4311	45	327	1883	1706	295	
Free standing wall	1507	5	252	785	413	43	
Gable	28121	57	2440	8977	10840	4313	
DG-parapet	729	11	77	303	277	57	
DG-gable	722	7	66	259	327	59	
Dormer	2245	15	264	1336	547	74	
Canopy-supported	1683	7	44	330	756	500	
Canopy-unsupported	14004	15	227	1242	6144	4867	
Balcony	3472	5	44	497	1155	1432	
Bay window	2034	0	8	148	914	839	
Large glass area	537	28	124	265	84	19	
Sign - vert	1182	1	7	134	383	479	
Sign - horiz	2380	13	69	387	717	774	
Industrial object	80	0	5	24	24	13	
Flagpole	1086	0	6	204	416	358	
TOTAL	**120073**	**281**	**5123**	**22681**	**30098**	**13265**	

Falling Hazard Objects by Main Exposure Pathway, for CR >= 1.0E-05

Object Type	**Above doorway**		**Above public**		**Elevated risk above**		**TOTAL objects**
	Total objects	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	**Total objects**	**No. with CR>=1x10-5**	
Chimney	23494	658	27367	73	4763	401	**1132**
Decorative feature	457	47	613	23	11	2	**72**
Pinnacle	160	22	334	16	26	4	**42**
Parapet	6273	499	6375	208	217	20	**727**
Balustrade	3664	291	3332	80	50	1	**372**
Free standing wall	1094	205	685	25	72	27	**257**
Gable	7859	1914	17948	124	1177	459	**2497**
DG-parapet	629	53	671	32	15	3	**88**
DG-gable	634	44	663	28	8	1	**73**
Dormer	1967	218	1996	60	4	1	**279**
Canopy-supported	1303	43	1025	8	1	0	**51**
Canopy-unsupported	13383	164	7345	74	6	4	**242**
Balcony	3100	40	2567	9	1	0	**49**
Bay window	1543	8	1893	0	0	0	**8**
Large glass area	393	92	436	57	4	3	**152**
Sign - vert	526	6	1139	2	1	0	**8**
Sign - horiz	1252	67	2218	14	17	1	**82**
Industrial object	20	2	56	1	18	2	**5**
Flagpole	479	6	1049	0	4	0	**6**
TOTAL	**68230**	**4379**	**77712**	**834**	**6395**	**929**	**6142**
% of objects that are high CR	***6.42%***		***1.07%***		***14.5%***		***0.00%***

[end of Annex 4]