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TNO report

TNO 2016 R11323/A

Monitoring Network Building Vibrations - Analysis Earthquakes in 2014 and 2015

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Copy no	0100300465
No. of copies	
Number of pages	48 (incl. appendices)
Number of appendices	4
Sponsor	NAM PO Box 28000 9400 HH Assen
Project name	Earthquakes 2014-2015
Project number	060.16792

Contents

1 Introduction

1.1 Background

In Groningen, so-called induced earthquakes occur, as a result of the extraction of natural gas. These earthquakes cause ground-borne vibrations that transfer to the building foundation, causing the building itself to vibrate. These vibrations may result in damage to the building.

To determine the effects of the induced earthquakes, NAM has set up a research program. Part of this research program is a monitoring network for building vibrations. In about 300 buildings, a vibration sensor is installed, measuring continuously the building vibrations at foundation level. To gain insight in the vulnerability of the buildings in Groningen for particular vibration levels, this monitoring network also includes a damage survey. By surveying the damage in these buildings before and after an earthquake, a relation can be found between the building vibrations due to an earthquake and the building damage caused by that earthquake.

TNO has designed and built this monitoring network for building vibrations, including an IT infrastructure to handle, process and analyse the data (the vibration data centre). The set-up of this monitoring network is described in TNO-report 2015 R10501 “Monitoring Network Building Vibrations” [ref 01].

1.2 Purpose

NAM has commissioned TNO to analyse the effects of induced earthquakes. These analyses comprise the transfer of ground-borne vibrations to building vibrations and the damage inflicted on the buildings due to the induced earthquake vibration.

The analysis of the effects of the induced earthquakes is executed for earthquakes with a magnitude of 2.5 or higher (according to KNMI). For each of these earthquakes, all buildings for which the measured vibration velocity has exceeded the trigger level of 1 mm/s are analysed.

For the period September 2014 – December 2015 a total of five induced earthquakes with a magnitude of 2.5 or higher took place (Table 1.1).
After these five earthquakes, this report will consider all data obtained so far and will combine and analyze this data together.

Table 1.1: Characteristics of analysed earthquakes (see KNMI website)

Name	Garmerwolde	Zandeweer	Woudbloem	Wirdum	Hellum
Date	30-9-2014	5-11-2014	30-12-2014	6-1-2015	30-9-2015
Time (UTC)	11:42	1:12	2:37	6:55	18:05
Magnitude	2.8	2.9	2.8	2.7	3.1
Location epicentre (latitude)	53258	53374	53208	53324	53234
Location epicentre (longitude)	6655	6678	6728	6768	6834
Location epicentre (X)	239605	240908	244580	247004	251603
Location epicentre (Y)	58461	599397	580985	593944	584016

1.3 Guide

This report gives the combined analysis of the five induced earthquakes mentioned in Table 1.1.
Firstly, Chapter 2 provides information about the set-up of the monitoring network, vibration analyses and the damage surveys.
Subsequently, Chapter 3 gives an overview of the buildings for which the measured vibration velocity at foundation level has exceeded a preset trigger value of 1 mm/s.
Information about vibration characteristics and their analyses is given in Chapters 4 and 5 and Chapter 6 will consider transfer functions.
In Chapters 7 and 8, results of the repetitive damage surveys and damage curves will be presented.
Finally, Chapter 9 to 11 give the conclusions, references and the signature.

2 Set-up of the analysis procedures of the monitoring network

2.1 Monitoring network

2.1.1 Background information

The analysis procedure of the monitoring network is based on the path the vibrations travel from source to building. The path the vibrations travel comprises of (Figure 2.1):

1. Ground-borne vibrations caused by an earthquake which spread towards the surroundings.
2. Ground-borne vibrations which are transferred to the buildings and result in vibration loads on the building foundations.
3. Building vibrations which can cause damage.

The effects caused in the three steps are analysed separately.

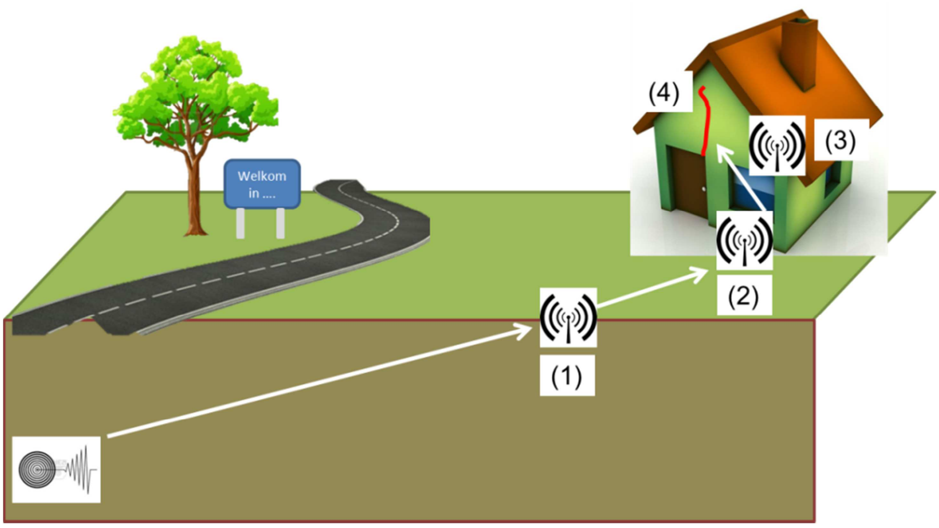

Figure 2.1: Illustration of the vibration path of an earthquake.

<u>Ad 1: Ground-borne vibrations</u>

The ground-borne vibrations of step 1 are measured and analysed by KNMI via their own (separate) monitoring network, hence this effect is not part of the analysis procedure of this monitoring network. However, the ground-borne vibrations measured by KNMI do provide valuable input for the transfer of the ground-borne vibrations to building-vibrations (step 2).

During the first four analysed earthquakes the sensor network of KNMI was not yet finished. Therefore no transfer functions could be calculated and no analysis could be executed.

For the most recent earthquake, the Hellum earthquake, the distance between the KNMI stations and the nearest by TNO sensors was rather big, so it was also not possible to calculate reliable transfer factors for individual buildings.

<u>Ad 2: Vibration load on buildings</u>

Ground-borne vibrations are (probably) not transferred to the buildings one-to-one. The extent to which the ground-borne vibrations are transferred to buildings is

characterised in practice by a transfer function. The transfer of vibrations depends on several factors, such as local soil conditions, type of foundation, etc.
To obtain insight into the transfer of the vibrations, vibration measurements in buildings (2) are linked to the ground-borne vibrations measured or calculated by the KNMI (1) in order to determine the transfer functions.

<u>Ad 3: Damage caused by vibrations</u>
For all houses of the monitoring network, an initial damage survey is carried out. After each earthquake with a magnitude of M=2.5 or larger, a repetitive damage survey is carried out for houses for which the measured vibration level during the earthquake exceeded the preset trigger of v=1 mm/s. The results of these repetitive damage surveys are compared with the results from the last damage surveys, to determine the damage that is caused by the earthquake.

2.1.2 *Installed sensors*

In the end of 2015, about 300 sensors were part of the monitoring network. Most of the sensors are installed in houses. About 30 sensors are installed in other buildings such as town halls, community centres and offices from local industry. A map with all installed sensors is given in Figure 2.2.

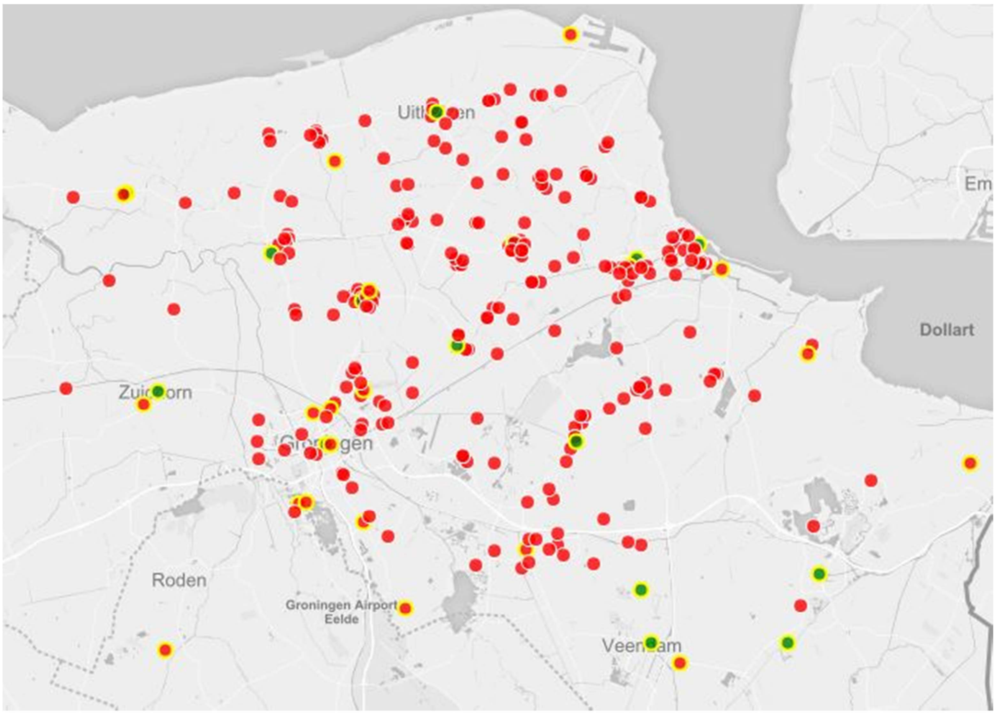

Figure 2.2: Installed sensors dated November 2015 (red = house, red/yellow = no house, green/yellow = town hall).

The houses included in the monitoring network are selected such that they are representative for the majority of the houses in Groningen.
An overview of installed sensors in houses per building type is given in table A.1, Annex A.

The sensors are installed close to foundation level at a rigid location, taking technical and practical conditions into account.

2.2 Framework analyses vibrations

The building sensors measure building vibration accelerations at foundation level in three directions (2 horizontal, 1 vertical). Out of these measured accelerations the sensor systems calculate directly the vibration velocity and these calculated vibration velocities are used to determine if the preset trigger, a vibration velocity of 1 mm/s, is exceeded.
After the preset trigger is exceeded, the sensor system sends the originally measured vibration accelerations to the vibration data center (VDC). These originally measured accelerations are used for the analysis of the building vibrations.

More detailed information about vibration signals and how vibration characteristics are calculated is presented in Annex B.

A few examples of vibration signals are presented in Annex C (accelerations and frequencies) and Annex D (velocities and frequencies).

2.3 Framework analyses building damage

2.3.1 General

During the installation of the sensors, an initial damage survey of the buildings has taken place (see TNO-report “Monitoring Network Building Vibrations”; Chapter 11 (ref [01])). This initial damage survey is used to classify the initial damage state of the buildings according to the EMS-98 “European Seismological Scale” (see Figure 2.3 and Table 2.1). This damage state was used to comply with the setup of the fragility curves for the building stock in the Groningen region (see ARUP report “Seismic Risk Study Earthquake Scenario-Based Risk Assessment” dated 29 November 2013) and because this classification has been used in many other damage studies across Europe.

The initial building damage survey was limited to a survey of the major cracks in the external parts of the building facades, because this information is regarded as sufficient for the categorisation of the building damage according to the EMS-scale.

Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction (very heavy structural damage)** Total or near total collapse.

Figure 2.3: Classification of damage for masonry buildings (EMS-98).

Table 2.1: Damage state of buildings

Damage state	Description
DS 0	No damage
DS 1	Negligible damage (“non-structural”)
DS 2	Moderate damage (“slight structural”)
DS 3	Substantial to heavy damage (“structural”)
DS 4	Very heavy damage
DS 5	Destruction

2.3.2 *Repetitive building survey*

After an earthquake with a magnitude of M=2.5 or larger, all buildings triggered by that earthquake have been surveyed again to see if there are changes.

During this repetitive damage survey, cracks that were already present have been examined to see if:

- the length and/or width has been increased
- they are repaired in the meantime
- repaired cracks have cracked again.

Also new cracks are reported, in the same way as during the initial damage survey.

Based on the results of the repetitive damage survey the damage state of the buildings after the earthquake has been determined again.

2.3.3 *Damage curves*

Based on a comparison of the initial building damage state and the damage state after the earthquake, the effect of the earthquake on the individual buildings can be determined. Subsequently this effect can be related to the measured vibration level of the foundation during the earthquake.

The relation between vibration level and occurred damage can be characterized in different ways. In line with the SBR directive for vibration damage (ref [02]) the vibration level is characterized by the peak velocity of the buildings.
Therefore, damage curves have been setup based on the relation between the peak vibration velocity at foundation level and the damage state after the earthquake.

If sufficient data is available, also other damage curves will be made, based on other characterizations of the vibrations, such as peak ground acceleration (KNMI; in line with the fragility curves) or peak acceleration of the buildings.

In the period between two damage surveys, also other vibrations could have been registered by the sensor. Examples are: vibrations due to other earthquakes with a magnitude less than M=2.5, which took place in the intermediate period, building activities, traffic, etc. If these vibrations were larger than the vibrations during the analysed earthquake, the building owners were asked for the cause for this trigger. If the cause leads to an overall vibration of the building, it was taken into account. If the cause was too local (for instance a bump against the sensor) the measurement of that particular vibration was excluded for analysis.

3 Buildings triggered by earthquakes

For each of the earthquakes, all buildings for which the measured vibration velocity has exceeded the trigger level of 1 mm/s are analysed. This trigger level of 1 mm/s is commonly regarded as the lower limit for damage due to vibrations.

3.1 Garmerwolde earthquake

During the Garmerwolde earthquake, data was gathered from 45 sensors for which the maximum vibration velocity (v_{max}) exceeded 1 mm/s:

- 42 triggered buildings are houses; these are selected for both signal analysis and damage analysis.
- 3 triggered buildings are town halls; these are selected for signal analysis, but excluded from damage analysis.

Figure 3.1 shows the maximum measured, horizontal component of the building vibration velocities at foundation level ($v_{x,y,max}$) of all buildings with respect to the epicentre of the Garmerwolde earthquake as given by KNMI. Note that "non-triggered" sensors represent sensors for which the maximum measured velocity was under 1 mm/s as well as sensors for which there was no data registered.

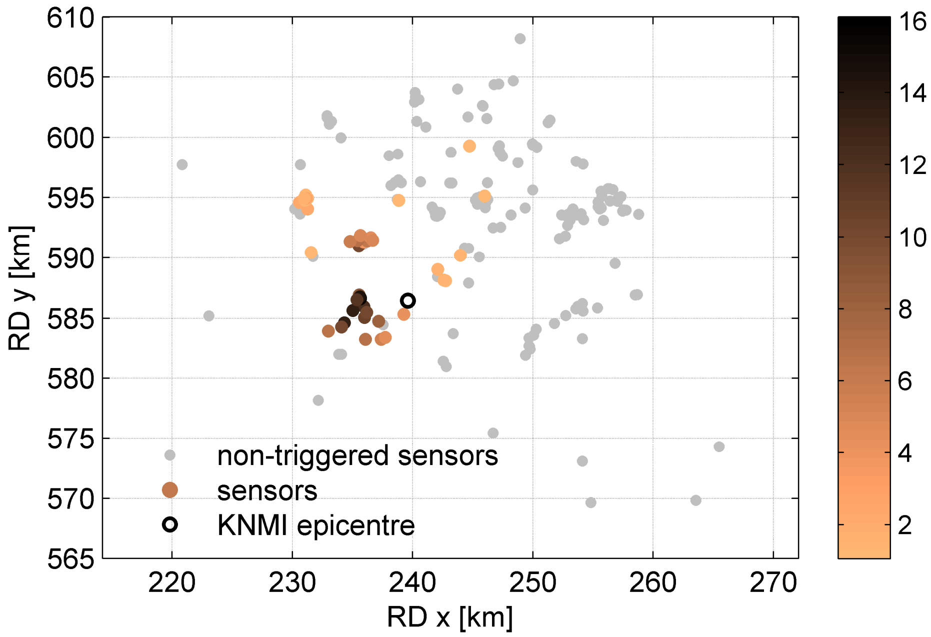

Figure 3.1: Overview of the maximum measured horizontal component of the building vibration velocity at foundation level ($v_{x, y,max}$ mm/s) with respect to the epicentre of the Garmerwolde earthquake.

3.2 Zandeweer earthquake

During the Zandeweer earthquake, data was gathered from 91 sensors for which the maximum vibration velocity (v_{max}) exceeded 1 mm/s:

- 87 triggered buildings are houses; these are selected for both signal analysis and damage analysis.
- 4 triggered buildings are town halls; these are selected for signal analysis, but excluded from damage analysis.
- For 4 of the triggered houses, vibration data was not available during the period of the damage survey, due to long term absence of internet connection. Therefore a damage survey in these buildings has not taken place.
- For 1 triggered house, a damage survey has not taken place due to building activities and repair activities during that time.

Figure 3.2 shows the maximum measured, horizontal component of the building vibration velocities at foundation level ($v_{x,y,max}$) of all buildings with respect to the epicentre of the Zandeweer earthquake as given by KNMI. Note that "non-triggered" sensors represent sensors for which the maximum measured velocity was under 1 mm/s as well as sensors for which there was no data registered.

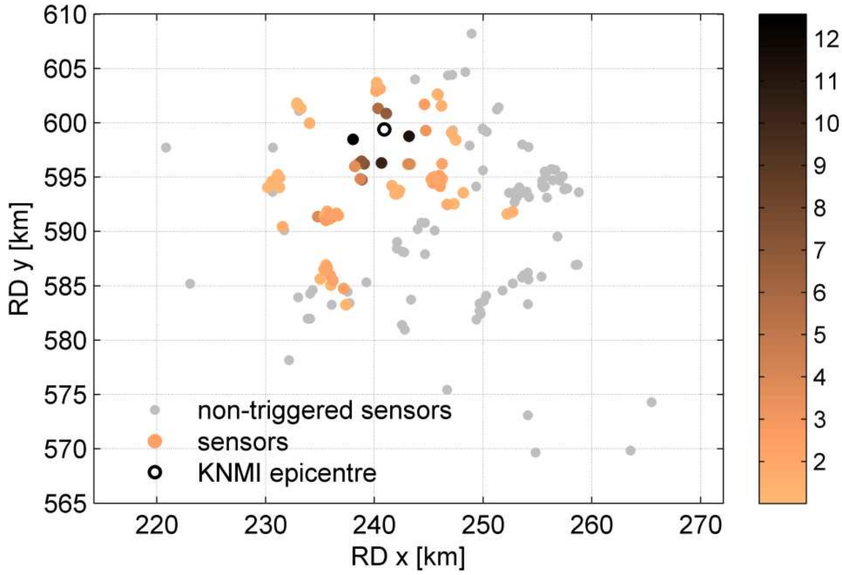

Figure 3.2: Overview of the maximum measured horizontal component of the building vibration velocity at foundation level ($v_{x, y,max}$ mm/s) with respect to the epicentre of the Zandeweer earthquake.

3.3 Woudbloem earthquake

During the Woudbloem earthquake, data was gathered from 23 sensors for which the maximum vibration velocity (v_{max}) exceeded 1 mm/s:

- 22 triggered buildings are houses; these are selected for both signal analysis and damage analysis.
- 1 triggered building is a town hall; this building is selected for signal analysis, but excluded from damage analysis.
- For 1 triggered house, an event file (extensive vibration signal during earthquake) was not generated, because the trigger was just at the trigger level of 1 mm/s. Therefore only a damage analysis is included and not a signal analysis.

Figure 3.3 shows the maximum measured, horizontal component of the building vibration velocities at foundation level ($v_{x,y,max}$) of all buildings with respect to the epicentre of the Woudbloem earthquake as given by KNMI. Note that "non-triggered" sensors represent sensors for which the maximum measured velocity was under 1 mm/s as well as sensors for which there was no data registered.

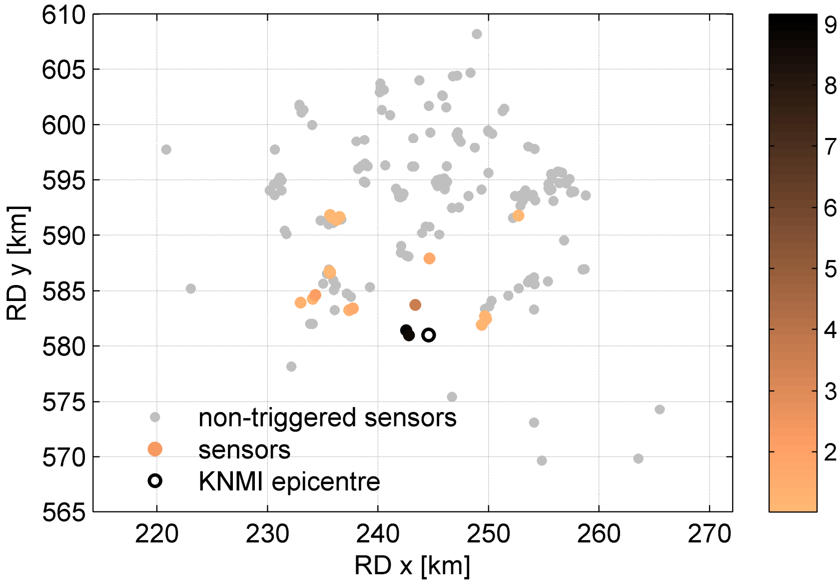

Figure 3.3: Overview of the maximum measured horizontal component of the building vibration velocity at foundation level ($v_{x, y,max}$ mm/s) with respect to the epicentre of the Woudbloem earthquake

3.4 Wirdum earthquake

During the Wirdum earthquake, data was gathered from 38 sensors for which the maximum vibration velocity (v_{max}) exceeded 1 mm/s:

- 37 triggered buildings are houses; these are selected for both signal analysis and damage analysis.
- 1 triggered building is a town hall; this building is selected for signal analysis, but excluded from damage analysis.

Figure 3.4 shows the maximum measured, horizontal component of the building vibration velocities at foundation level ($v_{x,y,max}$) of all buildings with respect to the epicentre of the Wirdum earthquake as given by KNMI. Note that "non-triggered" sensors represent sensors for which the maximum measured velocity was under 1 mm/s as well as sensors for which there was no data registered.

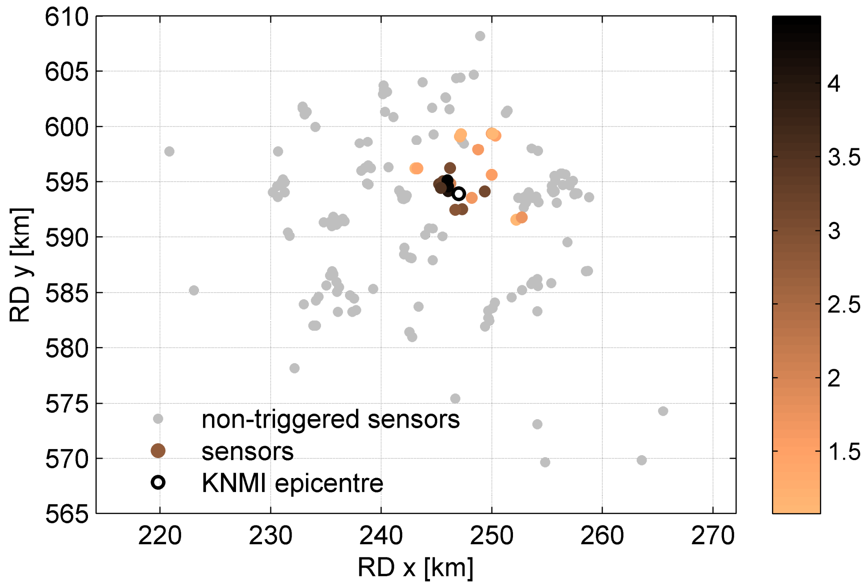

Figure 3.4: Overview of the maximum measured horizontal component of the building vibration velocity at foundation level ($v_{x, y,max}$ mm/s) with respect to the epicentre of the Wirdum earthquake.

3.5 Hellum earthquake

During the Hellum earthquake, data was gathered from 40 sensors for which the maximum vibration velocity (v_{max}) exceeded 1 mm/s:

- 38 triggered buildings are houses; these are selected for both signal analysis and damage analysis.
- 2 triggered buildings are town halls; these are selected for signal analysis, but excluded from damage analysis.
- For 1 triggered house, an event file (extensive vibration signal during earthquake) was not generated, because the trigger was just at the trigger level of 1 mm/s. Therefore only a damage analysis is included and not a signal analysis.
- For 2 houses, vibration data was not available, due to out of order of the measuring equipment. However, based on the vibration data of nearby houses, it is expected that the vibration level in these two houses has exceeded the trigger level. Therefore these two houses are also selected for damage analysis.

Figure 3.5 shows the maximum measured, horizontal component of the building vibration velocities at foundation level ($v_{x,y,max}$) of all buildings with respect to the epicentre of the Hellum earthquake as given by KNMI. Note that “non-triggered” sensors represent sensors for which the maximum measured velocity was under 1 mm/s as well as sensors for which there was no data registered.

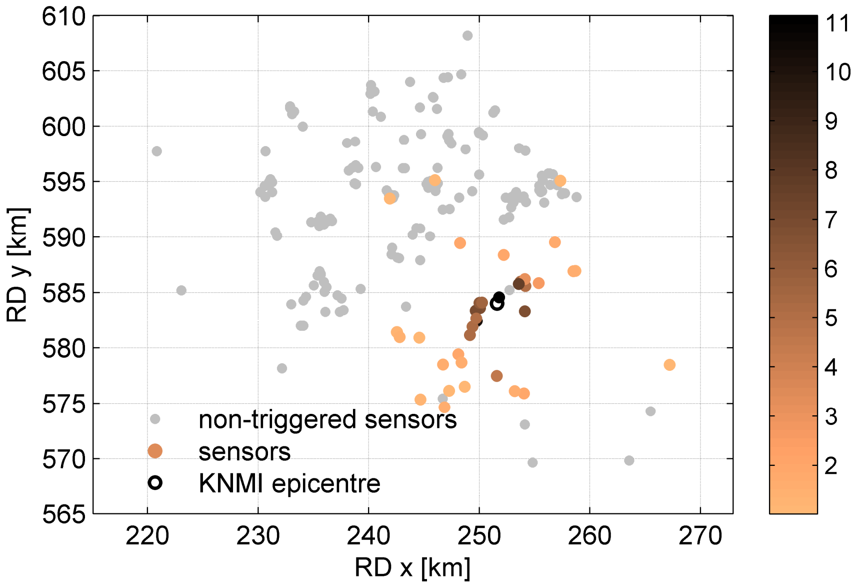

Figure 3.5: Overview of the maximum measured horizontal component of the building vibration velocity at foundation level ($v_{x,y,max}$ mm/s) with respect to the epicentre of the Hellum earthquake.

3.6 Summarised overview

Figure 3.6 shows the maximum measured, horizontal component of the building vibration velocities at foundation level ($v_{x,y,max}$) of all buildings, caused by the five analysed earthquakes. Also, the locations of the epicentres of the earthquakes as given by KNMI, are presented.
In Figure 3.6, "non-triggered" sensors represent sensors

- for which the maximum measured velocity was under 1 mm/s
- for which there was no data registered (internet connection failure)
- that were installed at the time of the last earthquake, but were not installed at the time of an earlier earthquake.

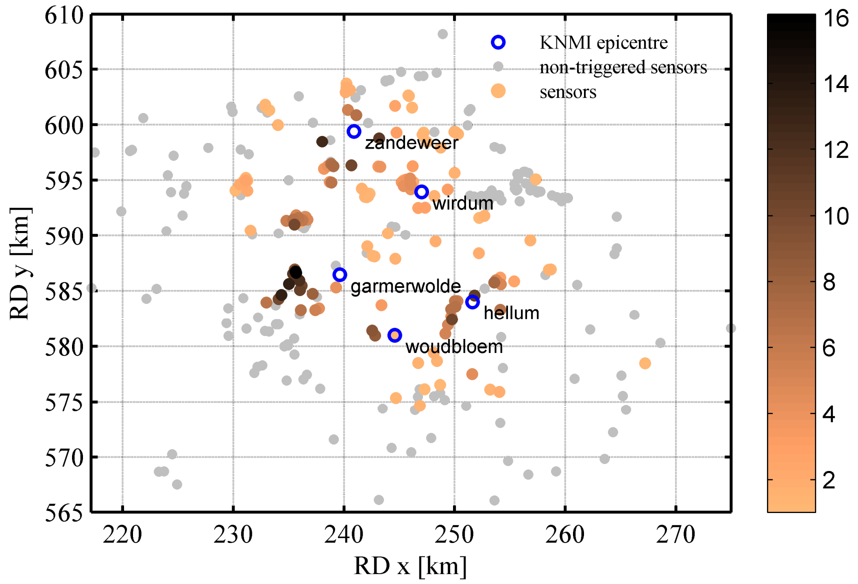

Figure 3.6: Overview of the maximum measured horizontal component of the building vibration velocity at foundation level ($v_{x,\, y,max}$ mm/s) with respect to the epicentre of the 5 earthquakes.

4 Vibration characteristics

The vibration signals of the triggered buildings are recorded for a period of 30 s, about 10 s before and 20 s after the beginning of the vibration signal. These recordings are stored in so-called event files. From 5 earthquakes, a total of 235 event files were gathered and used for analysis.

4.1 General information regarding acceleration

Annex C of this report gives a few examples of the measured vibration acceleration signals. The same Annex also gives graphs of the frequency content of each signal.

4.1.1 Peak accelerations

The calculated vibration characteristics regarding the acceleration of the five earthquakes are summarized in Figure 4.1 – 4.4, presenting the following information:

- The distribution of the peak acceleration in the buildings in horizontal direction, for each of the five earthquakes (Figure 4.1) and for all five earthquakes together (Figure 4.2).
- The distribution of the peak acceleration in the buildings in vertical direction, for each of the five earthquakes (Figure 4.3) and for all five earthquakes together (Figure 4.4).

From the Figures 4.1 – 4.4 the following conclusions can be drawn:

- From all triggered buildings from five earthquakes, 90% of the sensors measured a horizontal peak acceleration of maximum 0.3 m/s^2. The remaining 10% measured a horizontal peak acceleration of 0.3 – 0.6 m/s^2 (9%) and 0.6 – 0.9 m/s^2 (1%). The maximum measured horizontal peak acceleration is 0.7 m/s^2.
- From all triggered buildings from five earthquakes, 94% of the sensors measured a vertical peak acceleration of maximum 0.3 m/s^2. The remaining 6% measured a vertical peak acceleration of 0.3 – 0.6 m/s^2 (4%), 0.9 – 1.2 m/s^2 (1%) and 1.2 – 1.5 m/s^2 (1%). The maximum measured vertical peak acceleration is 1.2 m/s^2.

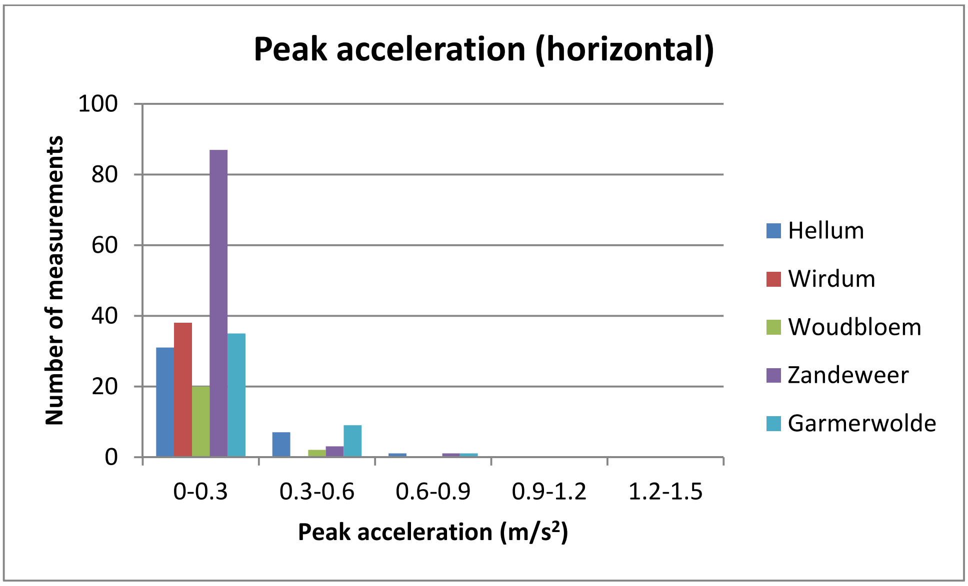

Figure 4.1: Peak vibration acceleration (horizontal) of triggered buildings for each of the five analyzed earthquakes.

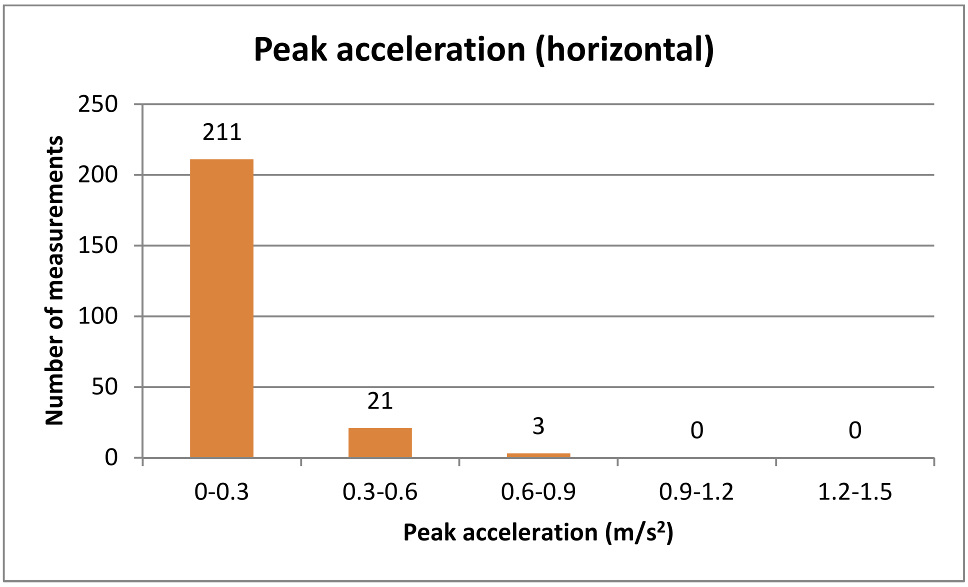

Figure 4.2: Peak vibration acceleration (horizontal) of all triggered buildings combined for the five analysed earthquakes.

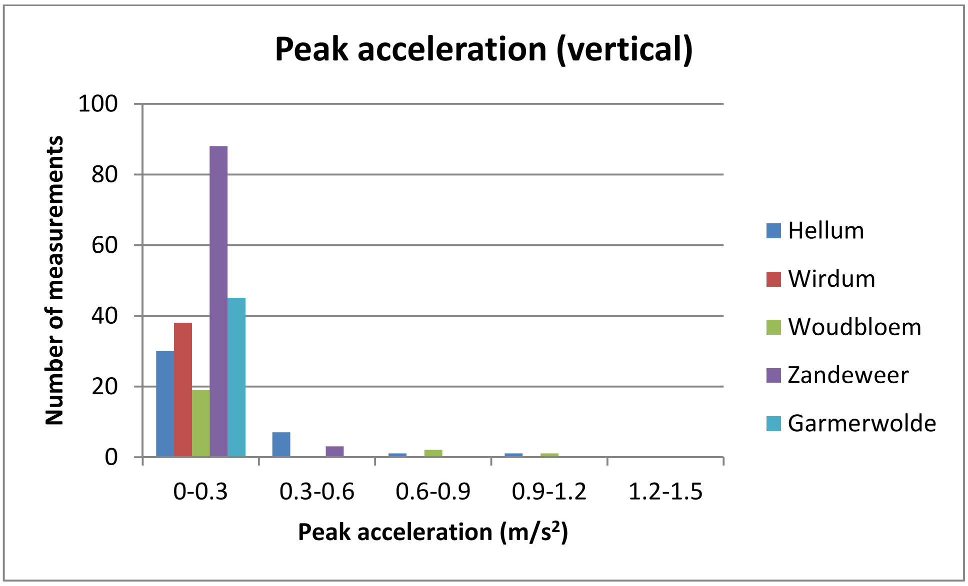

Figure 4.3: Peak vibration acceleration (vertical) of triggered buildings for each of the five analysed earthquakes.

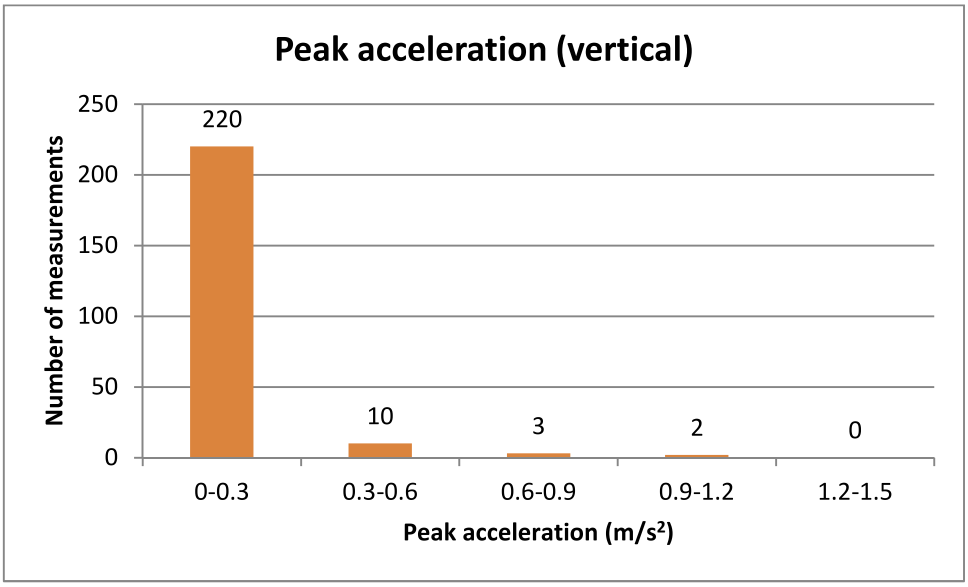

Figure 4.4: Peak vibration acceleration (vertical) of all triggered buildings combined for the five analysed earthquakes.

4.1.2 Dominant frequencies

The distribution of the dominant frequency of the vibration accelerations is analysed to make it possible to compare the dominant frequency of the ground-borne vibrations with the ones of the foundations vibrations. In the acceleration measurements no significant frequency content above 25 Hz is observed for the x and y channels for most sensors. Some sensor records with peak accelerations of 0.4 m/s^2 and higher showed frequency content up to 35-40 Hz for the x and y channels. For the vertical accelerations (the z channel) there is no significant frequency content above 40 Hz in most sensor records. A few sensors registered a frequency content of up to 60 in the vertical channel.

As expected, the frequency spectra show a shift of the content to the lower frequencies with no significant content above 15 Hz for the x- and y-channels and above 25 Hz for the z-channel.

The dominant frequencies are given in Figures 4.5 – 4.6. For the x- and y-channels, the dominant frequencies for acceleration are on average 8 Hz with a 95% upper bound of 12 Hz. For the z-channel the average dominant frequency is 13 Hz and the 95% upper bound is 25 Hz.

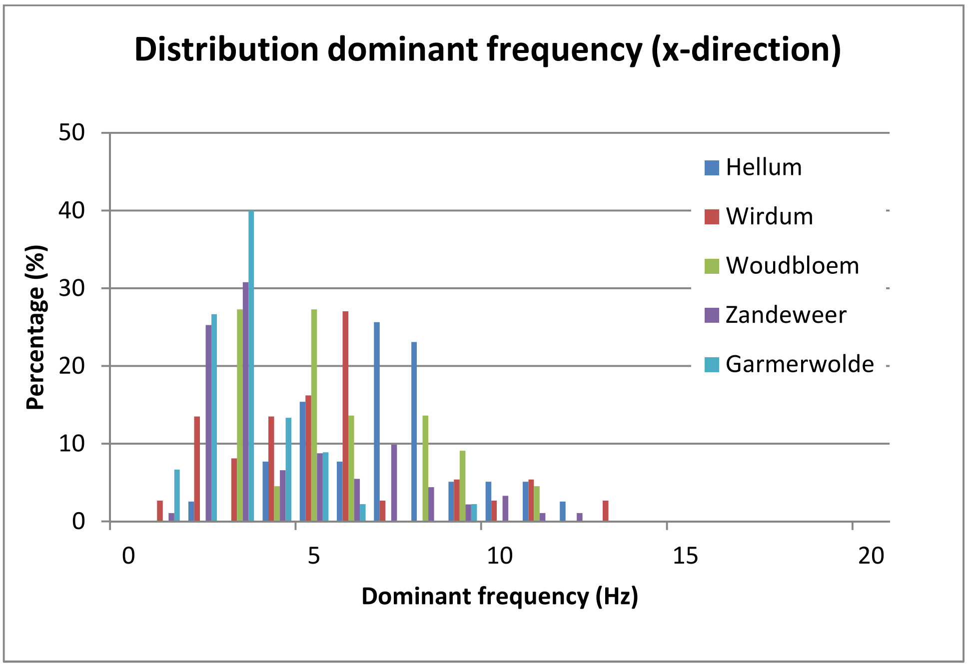

Figure 4.5: Distribution of dominant frequency of the vibration accelerations; x-direction for all buildings triggered by the five earthquakes.

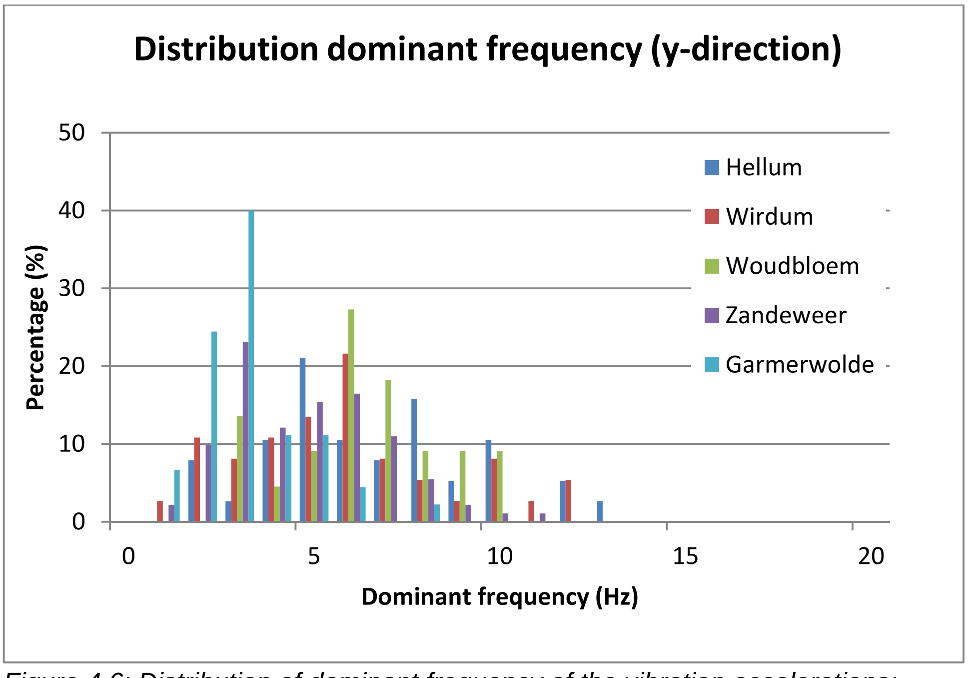

Figure 4.6: Distribution of dominant frequency of the vibration accelerations; y-direction for all buildings triggered by the five earthquakes.

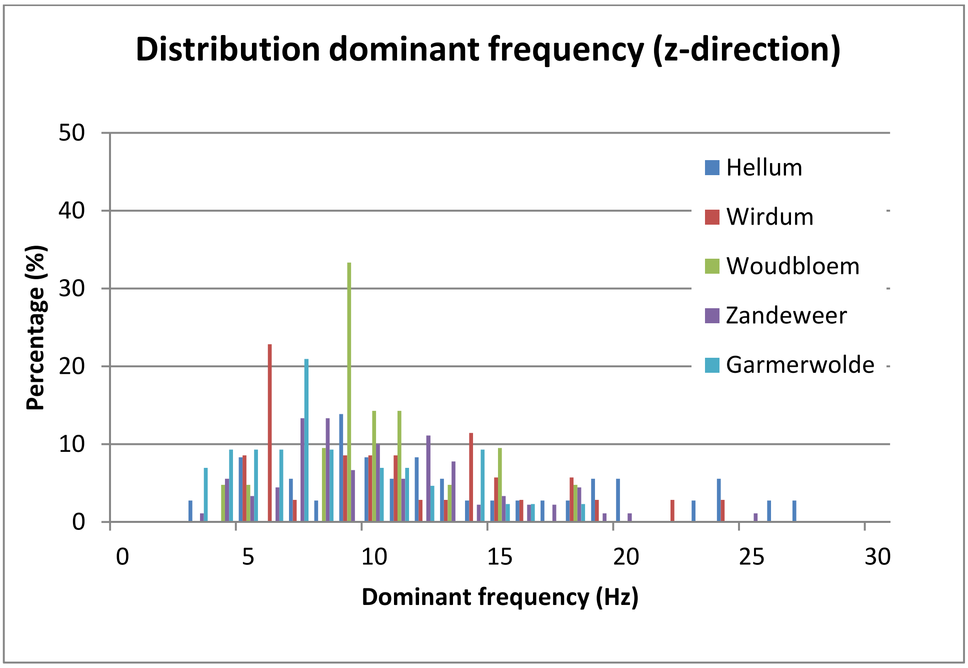

Figure 4.7: Distribution of dominant frequency of the vibration accelerations; z-direction for all buildings triggered by the five earthquakes.

4.2 General information regarding velocity

Annex D of this report gives a few examples of the measured vibration velocity signals.

4.2.1 Peak velocities

The calculated vibration characteristics regarding the velocity of the five earthquakes are summarized in Figure 4.8 – 4.11, presenting the following information:

- The distribution of the peak velocity in the buildings in the horizontal direction, for each of the five earthquakes (Figure 4.8) and for all five earthquakes together (Figure 4.9).
- The distribution of the peak velocity in the buildings in the vertical direction, for each of the five earthquakes (Figure 4.10) and for all five earthquakes together (Figure 4.11).

From Figures 4.8 – 4.11 the following conclusions can be drawn:

- From all triggered buildings from five earthquakes, 75% of the sensors measured a horizontal peak velocity of maximum 4 mm/s. The maximum measured horizontal peak velocity is 16.1 mm/s.
- From all triggered buildings from 5 earthquakes, 96% of the sensors measured a vertical peak velocity of maximum 4 mm/s. The maximum measured vertical peak velocity is 8.6 mm/s.

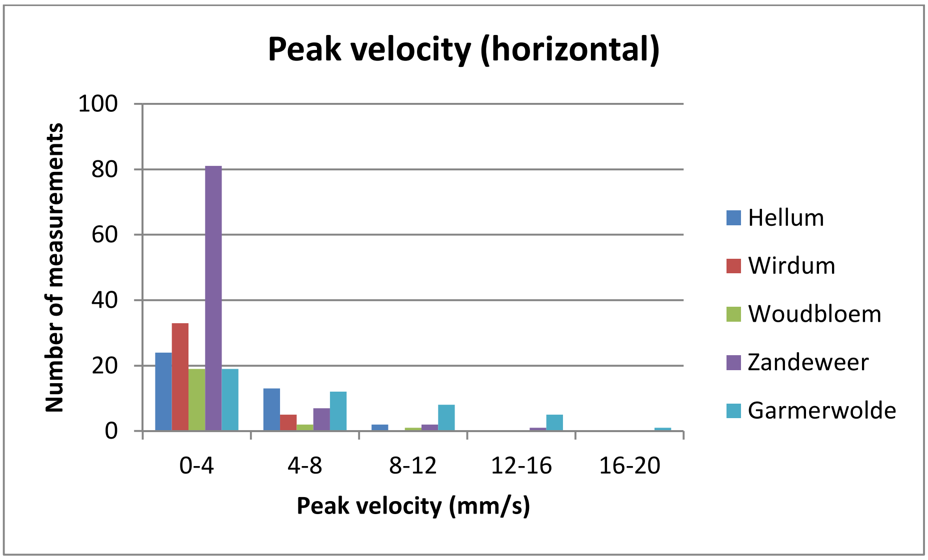

Figure 4.8: Peak vibration velocity (horizontal) of triggered buildings for each of the five analysed earthquakes.

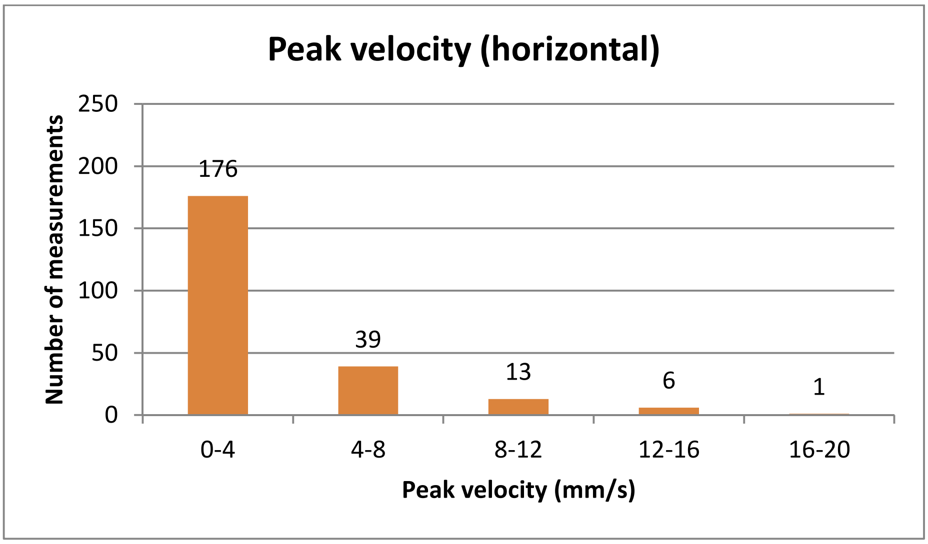

Figure 4.9: Peak vibration velocity (horizontal) of all triggered buildings combined for the five analysed earthquakes.

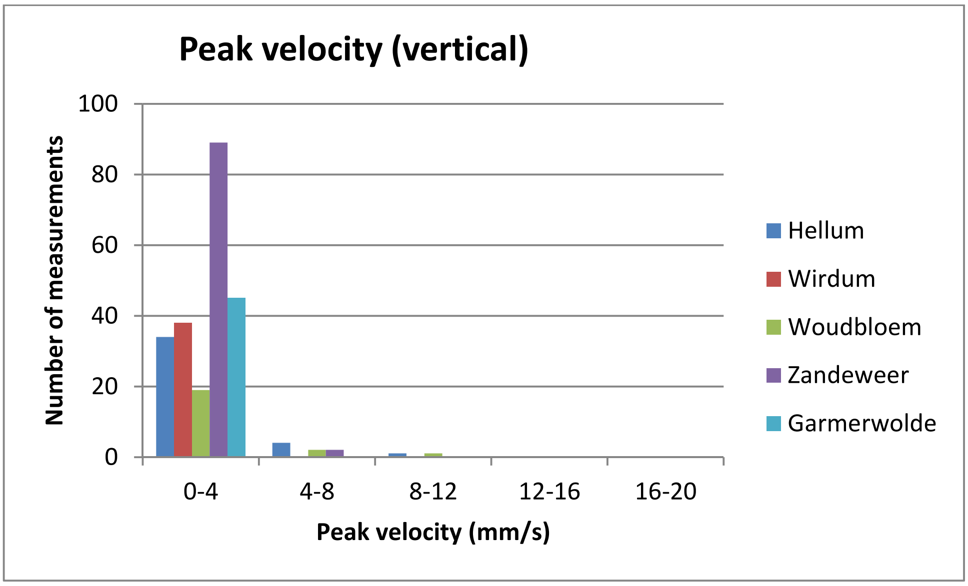

Figure 4.10: Peak vibration velocity (vertical) of triggered buildings for each of the five analysed earthquakes.

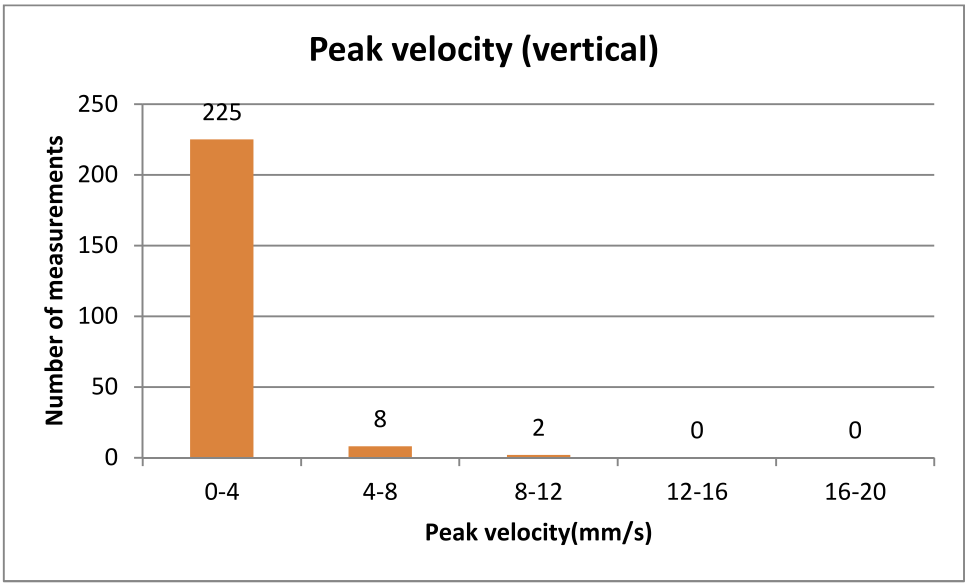

Figure 4.11: Peak vibration velocity (vertical) of triggered buildings combined for the five analysed earthquakes.

4.2.2 Dominant frequencies

The distribution of the dominant frequency of the vibration velocities is analysed . As expected, the frequency spectra of the velocities show a shift of the content to the lower frequencies with no significant content above 10 Hz for the x- and y-channels and above 15 Hz for the z-channel.

The dominant frequencies are given in Figures 4.12 – 4.14. For the x- and y-channels, the dominant frequencies for velocity are on average 5 Hz. For the z-channel the average dominant frequency is 5 Hz.

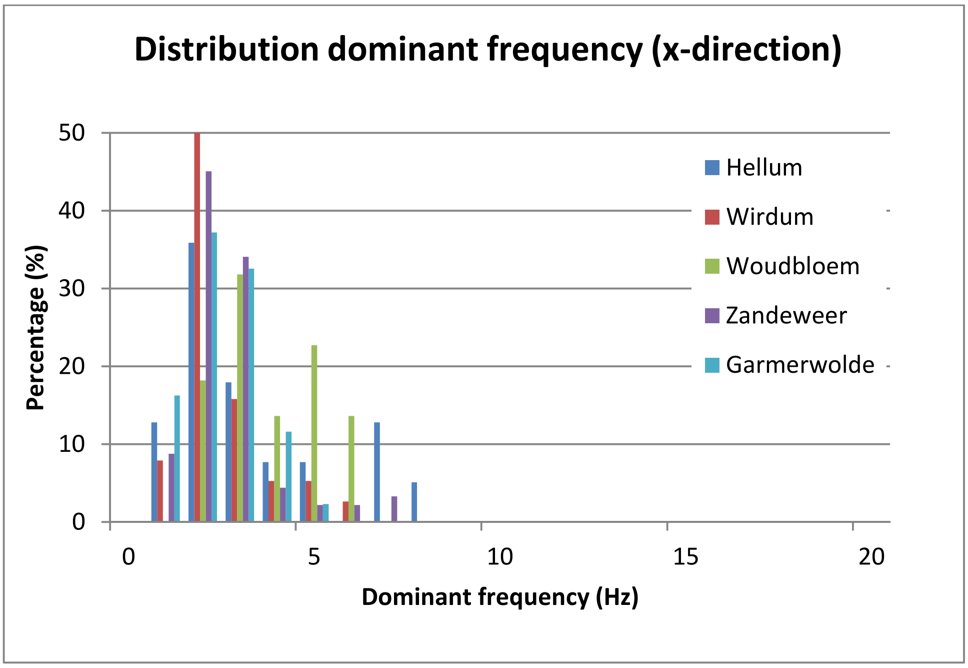

Figure 4.12: Distribution of dominant frequency of the vibration velocity; x-direction for all buildings triggered by the five earthquakes.

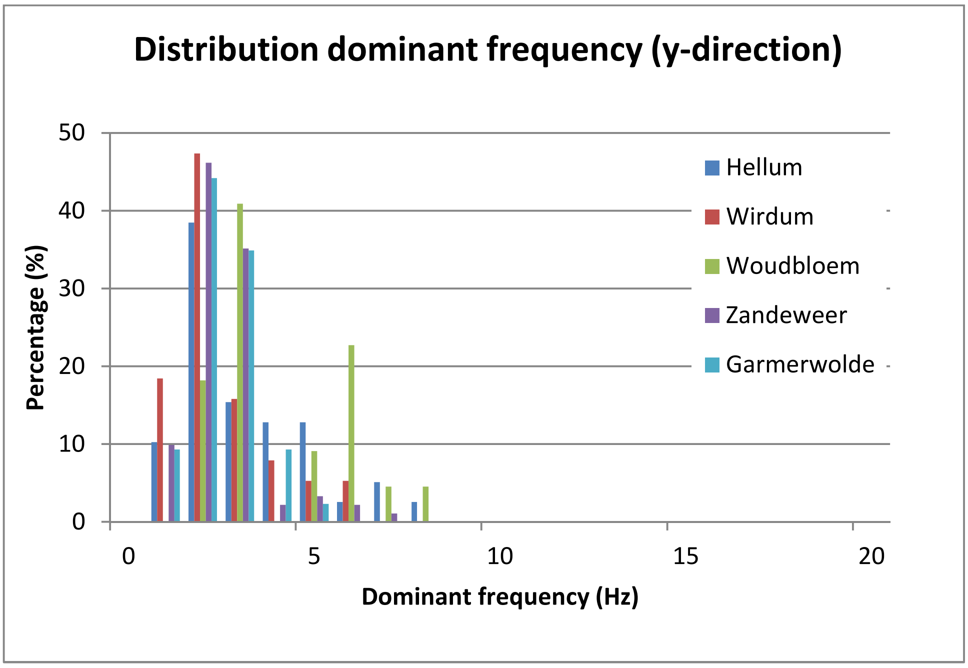

Figure 4.13: Distribution of dominant frequency of the vibration velocity; y-direction for all buildings triggered by the five earthquakes.

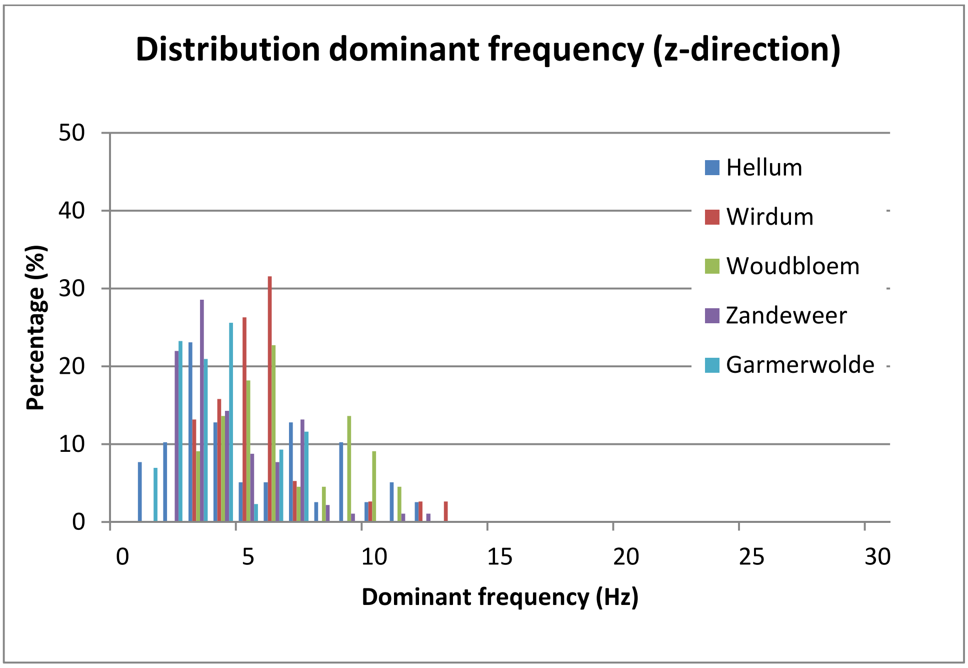

Figure 4.14: Distribution of dominant frequency of the vibration velocity; z-direction for all buildings triggered by the five earthquakes.

5 Analysis vibration characteristics

5.1 Horizontal versus vertical component of the vibrations

The horizontal and the vertical component of the vibration of each triggered building are compared, to see which direction gives the highest vibrations. This is done for both the peak acceleration (Figure 5.1) and the peak velocity (Figure 5.2).
From these figures it can be concluded that the horizontal component of the acceleration is dominant over the vertical component for about 70% of the measured vibrations. In case of the velocity the horizontal component is almost always dominant over the vertical component.

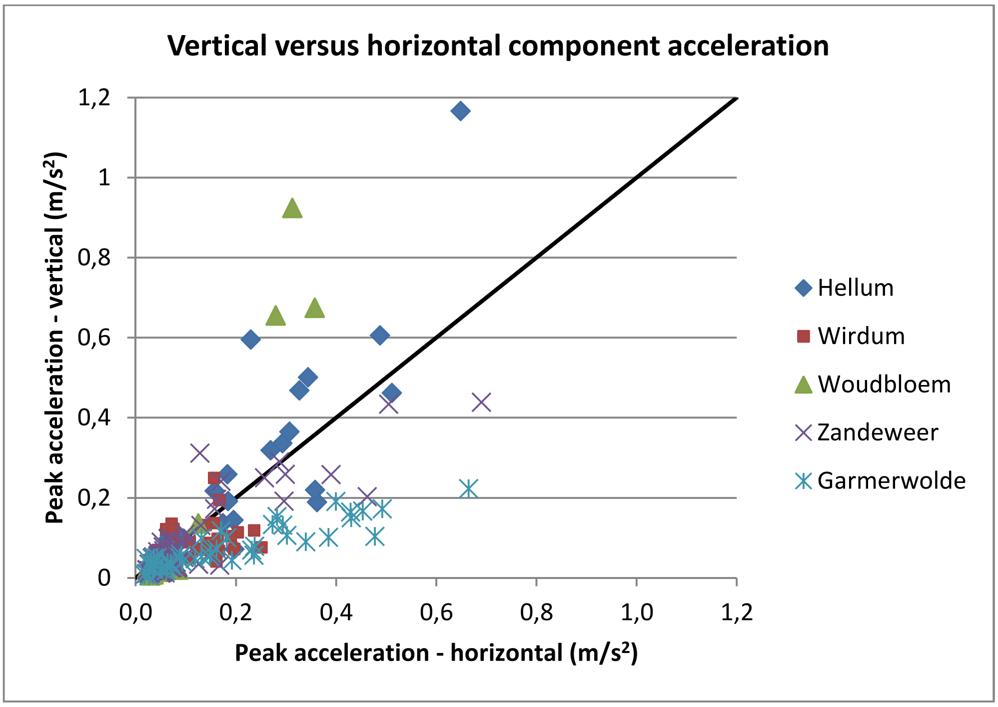

Figure 5.1: Horizontal versus vertical component of peak acceleration for all buildings triggered by the five analysed earthquakes.

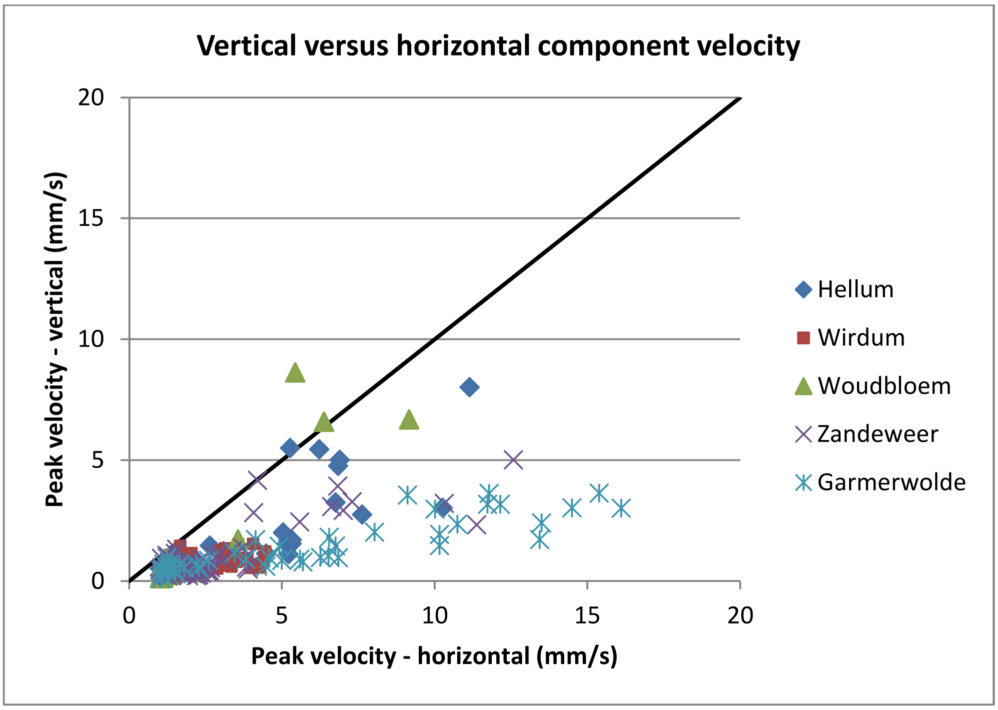

Figure 5.2: Horizontal versus vertical component of peak velocity for all buildings triggered by the five analysed earthquakes

To find out if the comparison of the horizontal and the vertical component of the vibration is depending on the distance to the epicentre of the earthquake, the ratio between the components is presented in relation to the distance to the epicentre. This is done for both the peak acceleration (Figure 5.3) and the peak velocity (Figure 5.4).
From these figures it can be concluded that higher vertical/horizontal-ratios are observed near the epicentre and that these ratios are decreasing with the distance to the epicentre.

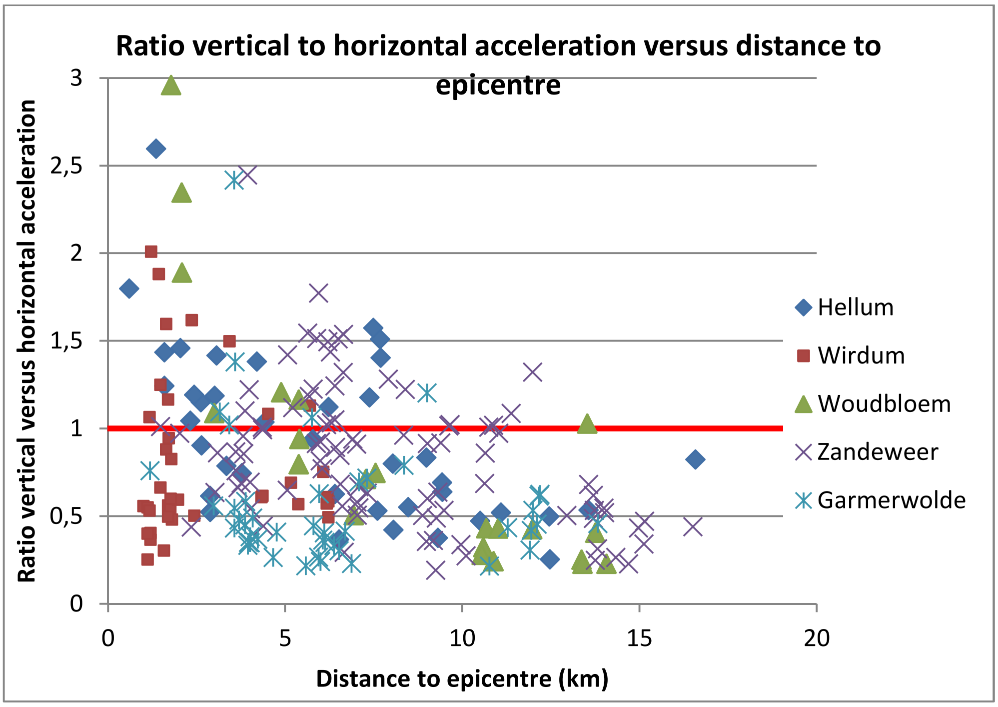

Figure 5.3: Ratio of vertical to horizontal peak acceleration versus the distance to the epicenter for all buildings triggered by the five analysed earthquakes.

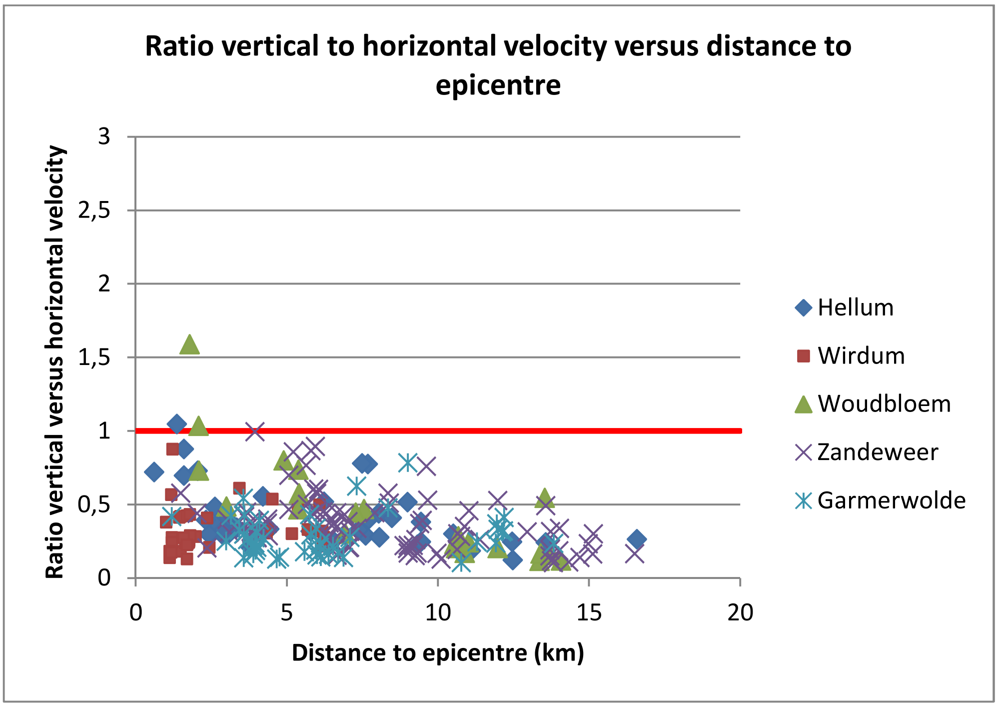

Figure 5.4: Ratio of vertical to horizontal peak velocity versus the distance to the epicenter for all buildings triggered by the five analysed earthquakes.

5.2 Vibration acceleration versus velocity

The peak acceleration and the peak velocity are compared to each other to look for the relation between these two characteristics. The results of this comparison are given in Figure 5.5 and 5.6 for respectively the horizontal and the vertical direction. These figures show a rather linear relation between the peak acceleration and the peak velocity for most of the buildings.

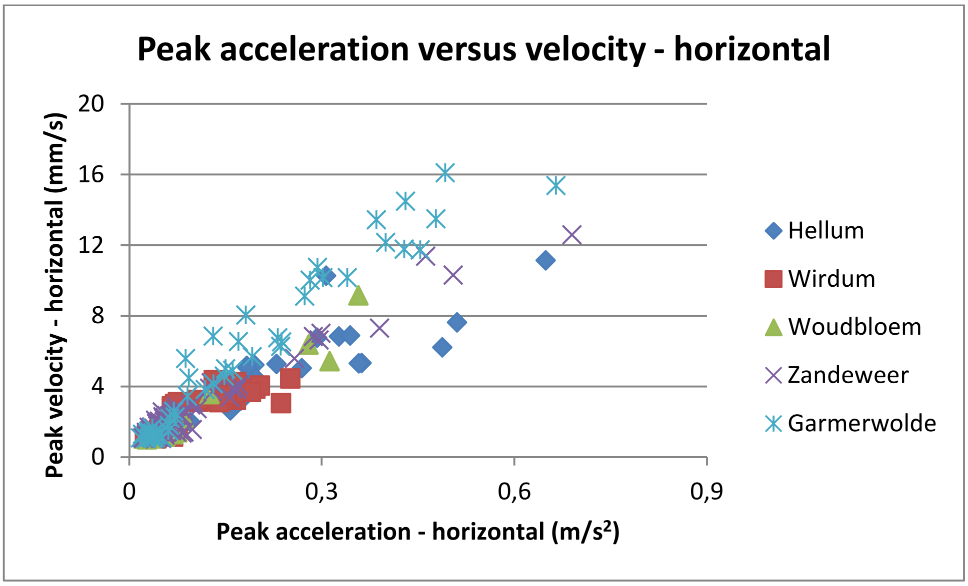

Figure 5.5: Peak acceleration versus the peak velocity (horizontal) for all buildings triggered by the five analysed earthquakes.

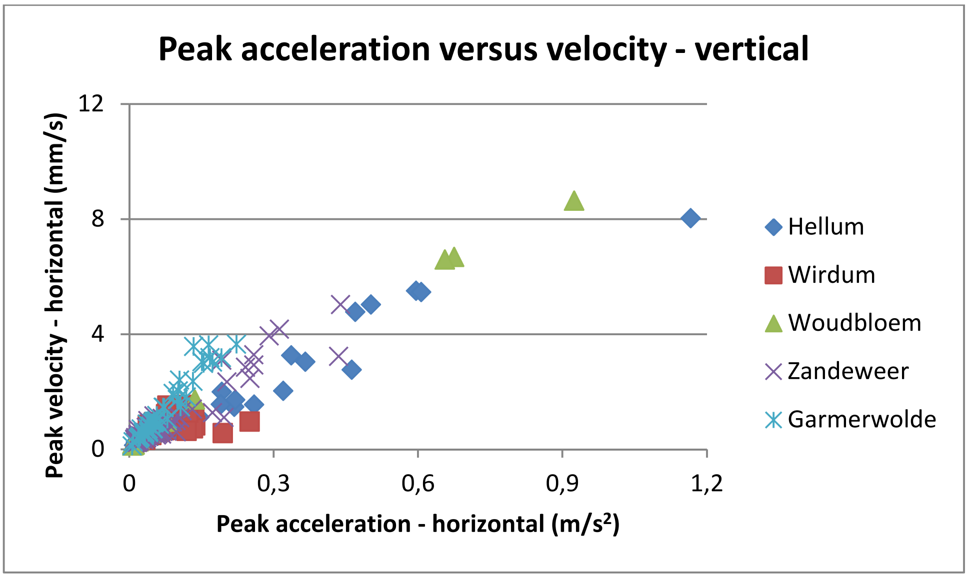

Figure 5.6: Peak acceleration versus the peak velocity (vertical) for all buildings triggered by the five analysed earthquakes.

6 Repetitive damage surveys

6.1 General

The houses for which the measured vibration velocity had exceeded the trigger level of 1 mm/s at the time of an earthquake were visited to carry out a repetitive damage survey. As a result of these five earthquakes, a total of 167 repetitive damage surveys have been carried out. The total number of surveys is less than the total number of event files as described in chapters 4 and 5, for the following reasons:

- Only triggered houses are selected for damage analysis. Other triggered buildings, such as town halls, are excluded from damage analysis.
- Some houses have exceeded the trigger level twice in the period between two surveys, due to two successive earthquakes.
- For some houses, a repetitive damage survey has not taken place because of ongoing building activities during the period of the repetitive damage surveys.
- For some houses, vibration data was not yet available during the period of the damage surveys, due to long term absence of internet connection.

The total of 167 surveys was subdivided as follows:

- 145 individual houses with a first repetitive damage survey
- 21 of these houses with also a second repetitive damage survey
- 1 of these houses with also a third repetitive damage survey.

6.2 Normative vibration velocity

In order to relate damage to a vibration level, it is necessary to know whether the houses were also subject to vibrations caused by other sources. For the period between the last damage survey and the repetitive damage survey, houses triggered by an earthquake have been scanned for other triggers. In addition, building owners were asked for a possible explanation.

For some buildings, the vibration level caused by another source was higher than that caused by an earthquake. In case of a local source, such as mounting the sensor’s cover lit, these registered vibrations are excluded. In case of a (external) source for which it is likely that it resulted in a vibration of the whole building, its vibration level is taken into account.

An overview of mentioned sources, with for each source if it is taken into account yes or no, is given in table 6.1.

Table 6.1: Triggers caused by other sources than the earthquake

Trigger (mm/s)	Source	Into account
1 - 4	Building activities in surrounding area	yes
1 - 6	Road construction activities	yes
2	Traffic (speed hump)	yes
2 - 8	Heavy building activities, a.o.: use of heavy drilling equipment, demolition activities, tree falling	yes
7	Trains (goods transport)	yes
1 - 10	unknown	yes
1 - 35	Local building activities, close to sensor's location such as: changing cables, replacing a window frame, installing a converter for solar panels, cavity wall insulation, repair activities	no
2 - 8	Slamming doors, kicking shoes to wall nearby sensor.	no
10 - 80	unknown	no
20 - 140	mounting cover lit on sensor, bump against sensor	no

6.3 Recorded cracks

A total of 167 repetitive damage surveys resulted in the following information:

- In the initial/previous damage survey, a total amount of 1364 cracks was reported. The repetitive damage surveys have shown that 16 of these cracks have increased in crack width and/or in crack length (about 1%).
- The total amount of new reported cracks is 579.
- Most of the new reported cracks were relatively small and short and belong to crack width category A.

The purpose of the initial survey was to detect and record major cracks, in order to determine the damage state (DS) of the buildings. At that time it was not intended to carry out a total survey, including also the smallest cracks.
During the first repetitive surveys, questions raised - mainly about small cracks - whether these crack were already present or were caused by the earthquake. For this reason it was then decided to record also minor cracks. As a consequence of this decision, the first repetitive surveys show relatively more cracks than the initial survey.

6.4 Repair activities

At 21 houses, repair activities have been taken place between two damage surveys, resulting in one or more repaired cracks. For the individual repaired cracks, it was verified whether or not they had cracked again. About 2% of the repaired cracks was cracked again after the earthquake.

7 Analysis repetitive damage survey

7.1 Initial damage survey

Based on the results from the initial damage survey, all houses are categorised in damage states as described in Chapter 2.3. Table 7.1 provides an overview of the damage state distribution for all houses of the monitoring network dated November 2015. From this Table it can be concluded that the major part of the buildings of the monitoring network had already cracks in the outer facades.

Table 7.1: Initial damage state of the houses of the monitoring network

Damage state after initial damage survey	
DS 0	15%
DS 1	60%
DS 2	24%
DS 3	1%

7.2 Damage curves

Based on the photos and results from the repetitive damage surveys, the damage state of the houses after an earthquake has been categorized again according to the following scheme:

<u>Buildings categorized in DS 0 at previous survey</u>
- DS 0→DS 0 = remained in DS 0
- DS 0→DS 1 = damage stated increased to DS 1
- DS 0→DS 2 = damage stated increased to DS 2

<u>Buildings categorized in DS 1 at previous survey</u>
- DS 1→DS 0 = repaired to DS 0 and remained in DS 0
- DS 1→DS 1 = remained in DS 1
- DS 1→DS 1’ = remained in DS 1, but increase in amount and/or length and/or width of cracks
- DS 1→DS 2 = damage state increased to DS 2

<u>Buildings categorized in DS 2</u>
- DS 2→DS 1 = repaired to DS 1 and remained in DS 1
- DS 2→DS 2 = remained in DS 2
- DS 2→DS 2’ = remained in DS 2, but increase in amount and/or length and/or width of cracks
- DS 2→DS 3 = damage state increased to DS 3

<u>Buildings categorized in DS 3</u>
- DS 3→DS 3 = remained in DS 3
- DS 3→DS 3’ = remained in DS 3, but increase in amount and/or length and/or width of cracks

The results from the categorization of the damage state before and after the five earthquakes are presented in Table 7.2.

Table 7.2: Change in damage state (DS)

Before	After	Total
DS 0	DS 0	3
	DS 1	19
	DS 2	0
DS 1	DS 0	3
	DS 1	44
	DS 1'	70
	DS 2	0
	DS 3	0
DS 2	DS 1	3
	DS 2	2
	DS 2'	22
	DS 3	0
DS 3	DS 3	0
	DS 3'	1
Total		167

The results of the damage state changes are presented in Figures 7.1 – 7.3 for damage state categories DS0, DS1 and DS2. Category DS 3 consists of 1 house, so no graph is made for this category.
The horizontal axis in Figures 7.1 – 7.3 shows the maximum registered vibration velocity in horizontal direction in the period between the previous and the repetitive damage survey. The vertical axis shows the damage state after the repetitive damage survey. Again, two subsets are made: a subset with results from just the first repetitive damage survey and a subset with results from the second and third damage surveys together.

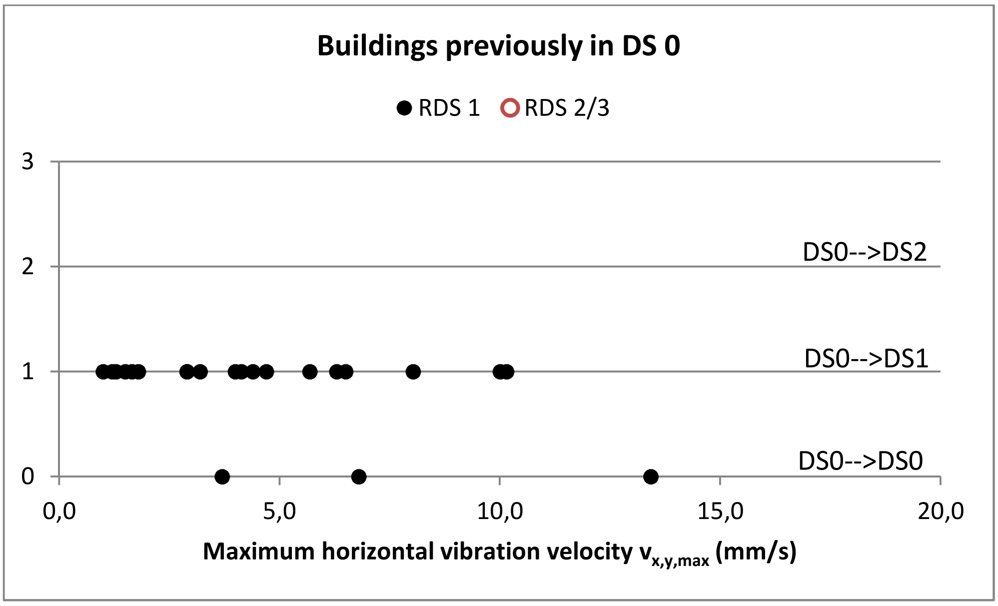

Figure 7.1: Damage state for houses categorised in DS 0 at last survey (RDS1 is first repetitive damage survey; RDS2/3 the second and third one).

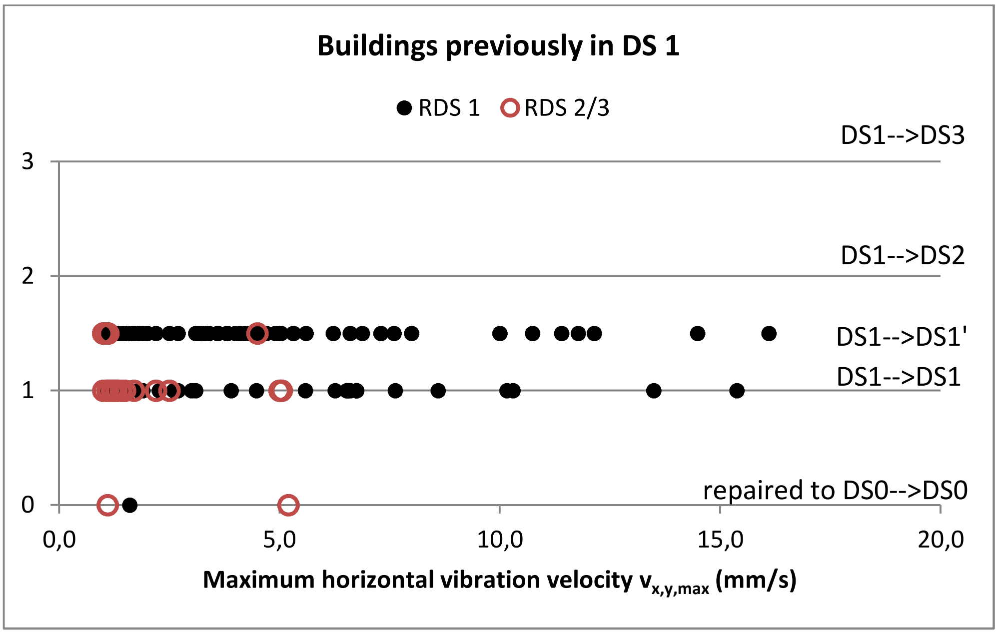

Figure 7.2: Damage state for houses categorised in DS 1 at last survey (RDS1 is first repetitive damage survey; RDS2/3 the second and third one).

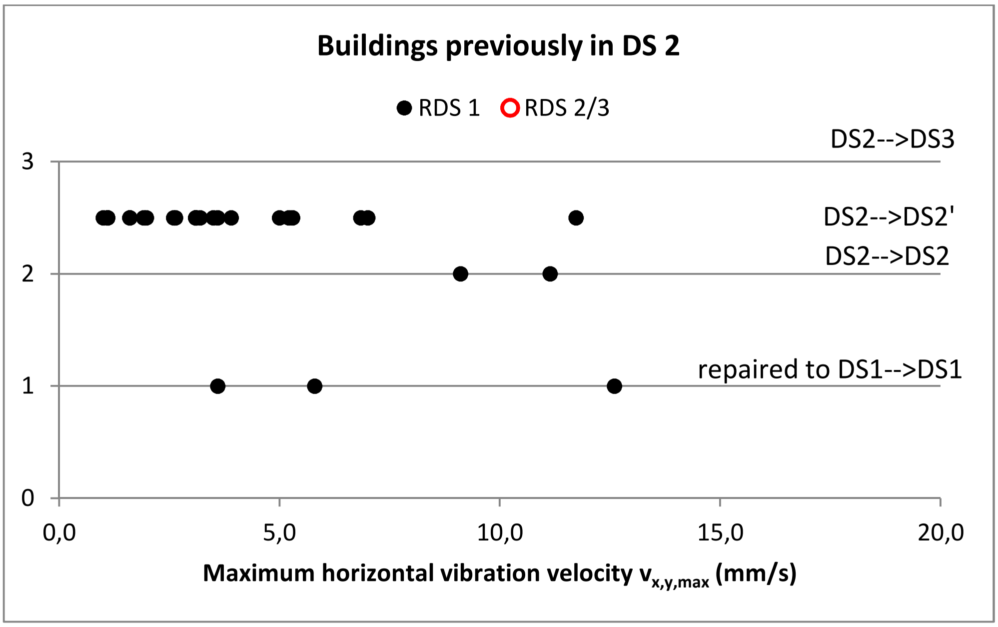

Figure 7.3: Damage state for houses categorised in DS 2 at last survey (RDS1 is first repetitive damage survey; RDS2/3 the second and third one).

7.3 Conclusions

From the results presented in the former Paragraph the following conclusions can be drawn:

- The graphs show no clear relation between the level of the vibration velocity and the increase in damage.
- All 2nd and 3rd repetitive surveys relate to houses which were previously categorized as DS 1. So far, there are no 2nd and 3rd repetitive damage surveys for houses in the other categories.
- For most of the houses that were categorised in damage state DS 0, having no reported cracks, one or more new cracks were reported. Consequently, these houses are categorised into a higher damage state (DS 1). All surveys in this damage state are first repetitive surveys. As mentioned already in Chapter 6, several of the new reported cracks at first damage surveys were already present at the time of the initial damages survey. Therefore, it could not be verified if these buildings were initially already in DS 1 or not.
- For all houses categorized in damage state DS 1 and DS 2, the earthquakes didn’t result in an increase of damage state. This means that potentially missed cracks at the initial or previous damage survey had no influence on the previous categorization of the damage state of the houses.
- For 21 houses, repair activities have taken place in between two surveys. For 3 houses (all in DS 1), these repair activities were substantial, resulting in no recorded cracks after the repetitive damage survey. As a consequence, the damage state of these 3 houses has “improved” to DS 0. For the other houses, the repair activities were not substantial enough in order to decrease the building’s damage state.

8 Conclusions

TNO has analysed the signals and the effects of five earthquakes between 30th September 2014 and September 30th 2015 (all M>2,5) on the buildings of the monitoring network. The analysis has resulted in the following conclusions.

Building vibrations

1. Over five earthquakes, a total of 235 event files were gathered for analysis, consisting of 224 files from sensors installed in houses and 11 files from sensors installed in “other buildings”. An event file is generated when the maximum building vibration velocity of the foundation exceeds the preset trigger of 1 mm/s.

2. Regarding the maximum horizontal peak acceleration at foundation level ($a_{x,y,max}$) 90% of the measurements is smaller than 0.3 mm/s^2. The maximum measured horizontal peak acceleration is 0.7 m/s^2.

3. Regarding the maximum vertical peak acceleration at foundation level ($a_{z,max}$) 94% of the measurements is smaller than 0.3 mm/s^2. The maximum measured vertical peak acceleration is 1.2 m/s^2.

4. Regarding the maximum horizontal peak velocity at foundation level ($v_{x,y,max}$) 75% of the measurements is smaller than 4 mm/s. The maximum measured horizontal peak velocity is 16.1 mm/s.

5. Regarding the maximum vertical peak velocity at foundation level ($v_{z,max}$) 96% of the measurements is smaller than 4 mm/s. The maximum measured vertical peak velocity is 8.6 mm/s.

6. The dominant frequencies for acceleration are on average 8 Hz with a 95% upper bound of 12 Hz, for the x- and y- channels. For the z-channel the average dominant frequency is 13 Hz and the 95% upper bound is 25 Hz.

7. The analysis of the transfer of the accelerations from the soil (KNMI stations) to the foundation of the triggered buildings (TNO sensors) has shown that the distance between the KNMI stations and the nearest by TNO sensors is rather big, so it is not possible to calculate reliable transfer factors for individual buildings.

Repetitive damage survey

8. Over five earthquakes a total of 167 damage surveys were carried out, including 145 first repetitive surveys, 21 second repetitive surveys and 1 third survey.

9. The number of cracks with an increase in crack width and/or crack length is about 1 % of the total amount of initially reported cracks.

10. A major part of the newly reported cracks was already present but not reported at the initial damage survey.

11. At 21 houses cracks were repaired between the last and the repetitive damage survey. About 2% of the repaired cracks was cracked again after the earthquake.

12. For most of the houses that were categorised in damage state DS 0, having no reported cracks, one or more new cracks were reported. Consequently, these houses are categorised into a higher damage state (DS 1). Several of the new reported cracks were already present at the time of the initial damages survey, therefore, it could not be verified if these buildings were initially already in DS 1 or not.

13. For all houses categorized in damage state DS 1 and DS 2, the earthquakes didn’t result in an increase of damage state.

9 References

[01] TNO-report 2015 R10501 “Monitoring Network Building Vibrations”

[02] SBR guide line A: “Trillingen: meet- en beoordelingsrichtlijnen. Schade aan gebouwen, 2002”

[03] SBR guide line B: “Meet- en beoordelingsrichtlijn. Hinder voor personen in gebouwen, 2002”

10 Signature

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A Building types

Table A.1: Installed sensors per building type (November 2015)

Building type		Amount	Foundation	Ground level floor	Amount
1	Terraced - corner	15	--	--	--
		--	Piles	Concrete	2
		--	Piles	Other	3
		--	No piles	--	5
		--	Unknown	--	5
2	Terraced - no corner	18	--	--	--
		--	Piles	Concrete	5
		--	No piles	--	5
		--	Unknown	--	8
3	Semi-detached	40	--	--	--
		--	Piles	Concrete	28
		--	No piles	--	10
		--	Unknown	--	2
4/5/6	Detached <1940	98	--	--	--
4		--	No piles	Combination wood/concrete	47
5		--	No piles	Wood	16
6		--	No piles	Concrete	19
4/5/6		--	Unknown	--	16
7	Detached 1941-1975	31	--	--	--
			No piles	--	22
			Piles	--	2
		--	Unknown	--	7
8/9	Detached >1975	70	--	--	--
8		--	Piles	Concrete	36
9			No piles	Concrete	25
8/9			No piles	--	5
		--	Unknown	--	4
Subtotal	Houses	272			
0	Other (not houses)	27			
Total	All buildings	299			

B Framework analysis building vibrations

General

The building sensors measure building vibration accelerations at foundation level. Out of these measured accelerations the sensor systems calculate directly the vibration velocity and these calculated vibration velocities are used to determine if the pre set trigger, a vibration velocity of 1 mm/s, is exceeded.
After the pre set trigger is exceeded, the sensor system sends the originally measured vibration accelerations to the vibration data center (VDC). These originally measured accelerations are used for the analysis of the building vibrations.

Vibration characteristics

For each building the measured acceleration signal by the building sensor is analysed as follows (Figure B.1):

- Two time-domain signals are calculated:
  - The raw measured acceleration signal a(t) is used after removal of the offset.
  - After filtering the signal is integrated to a velocity signal v(t).
- The frequency spectrum is calculated for the acceleration and the velocity signals.
- Individual signal characteristics are calculated for each of the three signal directions per sensor (two in horizontal direction (x and y) and one in vertical direction (z)):
  - Acceleration [a]; this value is used in international earthquake guidelines and is of interest for structural calculations. Calculated values are: $a_{x, max}$, $a_{y, max}$, $a_{z, max}$ and $a_{x,y,max}$ (=peak acceleration in horizontal direction).
  - Velocity [*v*]; this value is used in the Dutch guidelines (SBR ref [02]) for relations between building vibrations and the probability of damage. Calculated values are: $v_{x, max}$, $v_{y, max}$, $v_{z, max.}$ and $v_{x,y,max}$ (=peak velocity in horizontal direction).
  - Effective velocity [$v_{eff,max}$]; this value is mostly used to express a relation between the vibration and the hindrance for people (ref [03]).
  - Dominant frequency of acceleration [$f_{a,dom}$] and velocity [$f_{v,dom}$]; these values are of interest for the transfer of the ground-borne vibrations to the building vibrations.
  - The vectorial maximum of the acceleration ($|a(t)|_{max}$) and the velocity ($|v(t)|_{max}$) are calculated ($|a(t)| = \sqrt{(a_x(t))^2 + (a_y(t))^2 + (a_z(t))^2}$). These are absolute values of the acceleration and the velocity, independent from the orientation of the sensor.
- The Arias Intensity. For the x-channel this is given by $I_{A,x} = \frac{\pi}{2g}\int_0^T a_x(t)^2 dt$ with T the length of the time trace. The y- and z-channels are calculated in a similar way.
- The Total Arias Intensity. This is given by $I_{A,total} = I_{A,x} + I_{A,y} + I_{A,y}$.
- The Cumulative Absolute Velocity (CAV). For the x-channel this is given by: $CAV_x = \int_0^T |a_x(t)| dt$ and similar for the y- and z- channels.

- The Total Cumulative Absolute Velocity. This is given by $CAV_{total} = CAV_x + CAV_y + CAV_z$.
- The Standardized Cumulative Absolute Velocity $CAV_{STD.}$ This is calculated in a similar fashion as the CAV but here the signal is divided into 1 second long sections and a section is only taken into account if there is a moment in the section where the absolute acceleration is above a certain threshold. Currently this threshold is set to 0.001g. This prevents the CAV_{STD} from keeping accumulating after the event contrary to the CAV can do.

The calculation of the Arias Intensity, CAV and CAV_{STD} is performed on the raw acceleration signal after offset removal. No filtering is applied. Tests show that results differ less than 1% for the current events. Larger events are likely to have a lower frequency content which is perhaps partly affected by the filter, so it has been chosen to perform the calculations on the unfiltered signal.

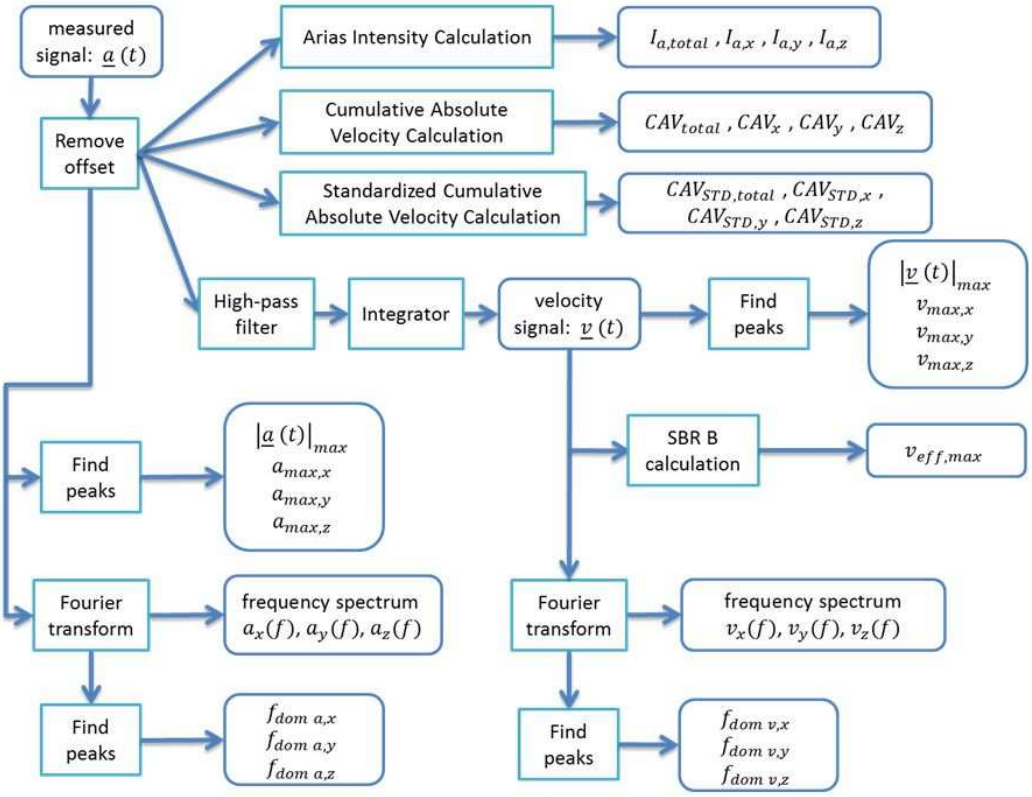


Figure B.1: Flow chart for analysing signal characteristics.

Transfer functions

There are three main sources of information along the chain from the epicenter of an earthquake to the exposed buildings, namely:

(i) the magnitude and location of the earthquake
(ii) the free-field signal characteristics at the KNMI instrument points
(iii) the foundation signal characteristics in the buildings.

The first two sources are covered by KNMI. KNMI has installed free-field sensors in a grid of 6 km within the area of the monitoring network, to measure the free field characteristics. The relationship between the vibration signal characteristics at the KNMI free-field points (ii) and the ones measured on the building foundations (iii) will be calculated as part of the monitoring network building vibrations. For each building, the KNMI free-field data at the KNMI point closest to the building and the measured foundation signals will be used to calculate the transfer function of the ground-borne vibrations to the building vibrations at foundation level.

For each building triggered the closest by KNMI free-field sensor has been selected. The signal from this free-field sensor has been analyzed in the same way as the signal from the building sensors.
Since the horizontal vibration components of the free-field sensors are given in the direction of the epicenter and perpendicular to that direction, these values cannot be compared to the horizontal components of the building sensors directly. The horizontal components of the free-field sensors have to be rotated to the x- and y-direction of the individual buildings.

The transfer of ground-borne vibrations to building vibrations will be determined for each of the individual signal characteristics, as a transfer factor: ratio between the comparable single-figures. This will be done for all three measuring directions.
As an example, the transfer factor for the peak velocity can be determined as follows:

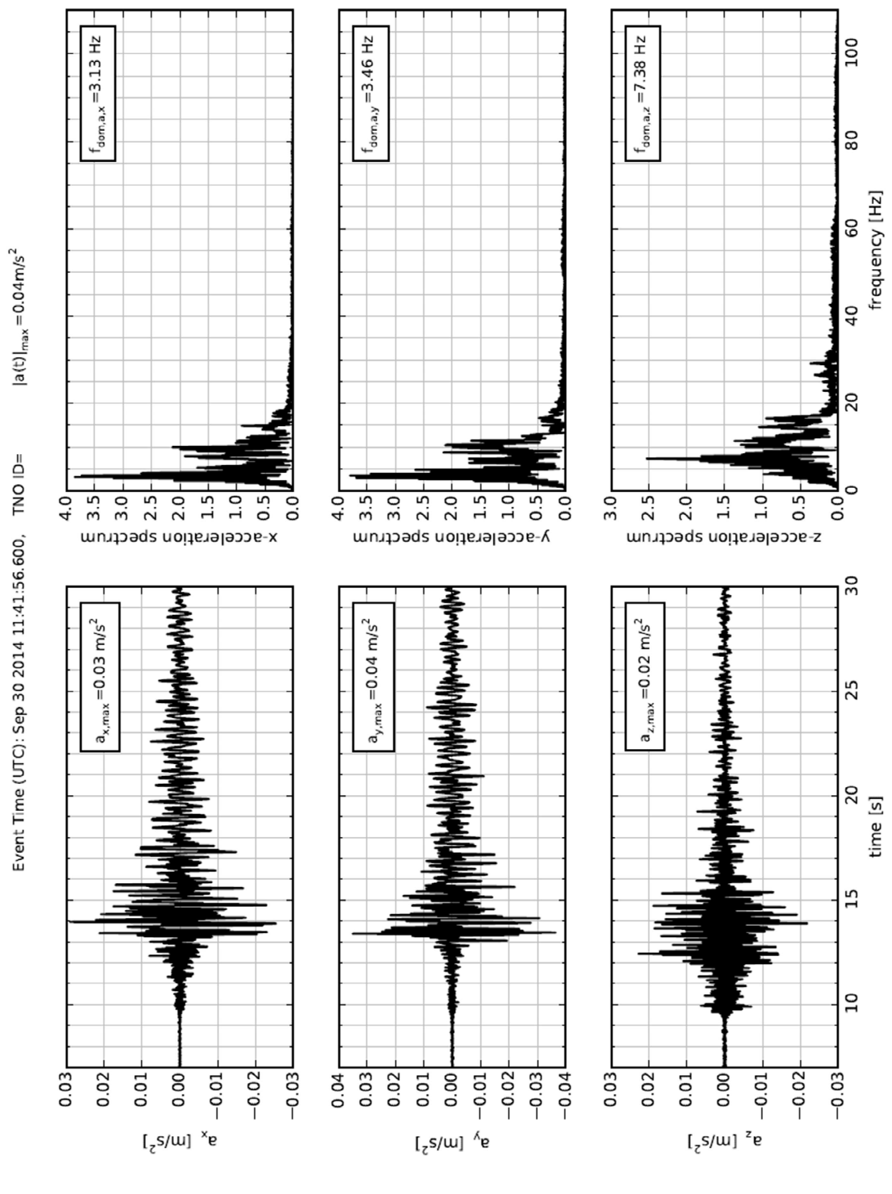
- Peak ground velocity in three directions (i=1,2,3): $v_{max,ground\text{-}borne,i}$
- Peak foundation velocity in three directions (i=1,2,3): $v_{max,building,i}$
- Transfer factor in three directions (i=1,2,3): T_i

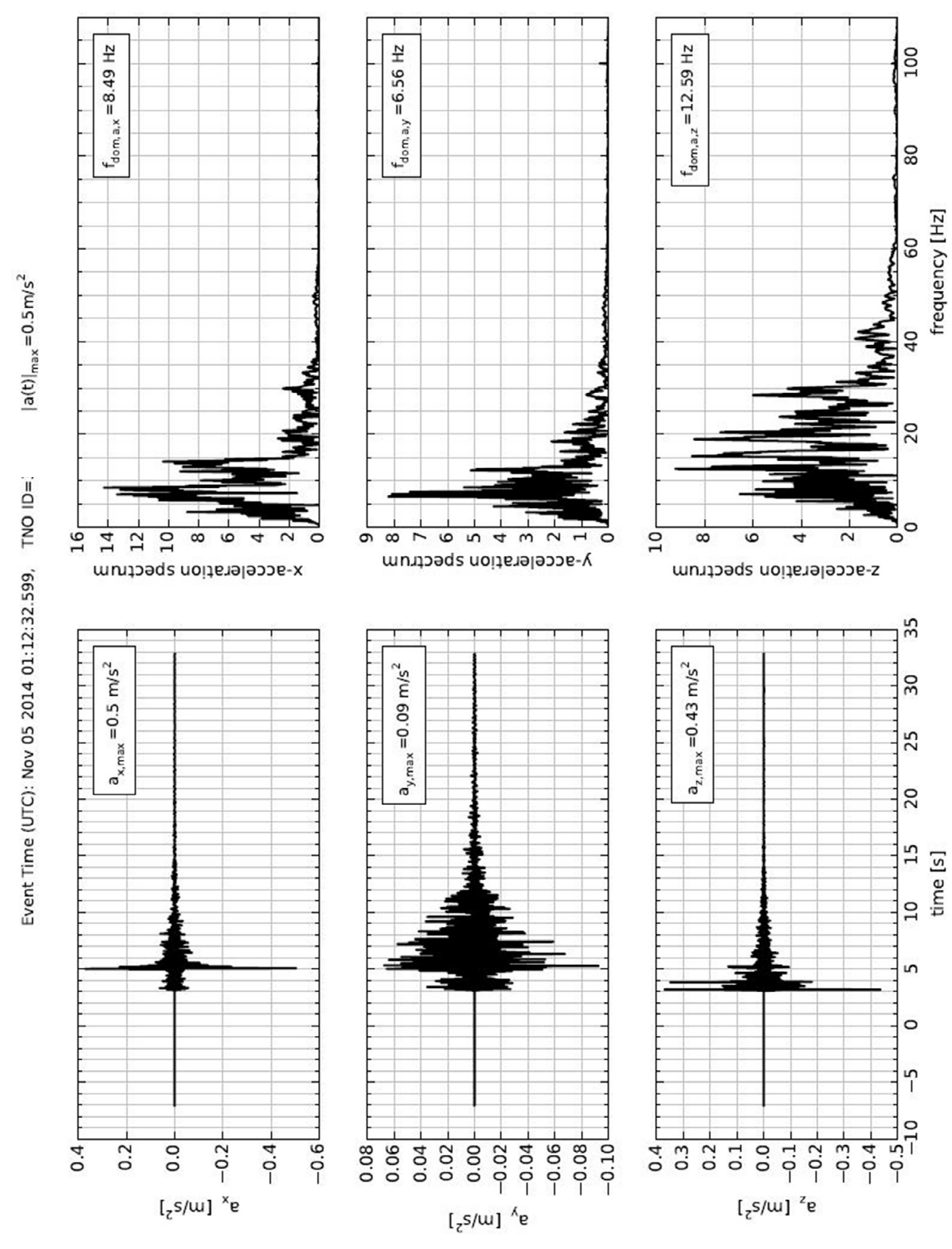
$$T_{v_{max},i} = \frac{v_{max,foundation,i}}{v_{max,ground-borne,i}}$$

C Vibration signals - acceleration

This Annex gives an example of the measured vibration acceleration signals. For three different buildings, with different levels of acceleration, during different earthquakes, the following graphs are given:

- Measured acceleration (a_x, a_y, a_z)
- Distribution of the frequency ($f_{dom,a,x}$,$f_{dom,a,y}$,$f_{dom,a,z}$)

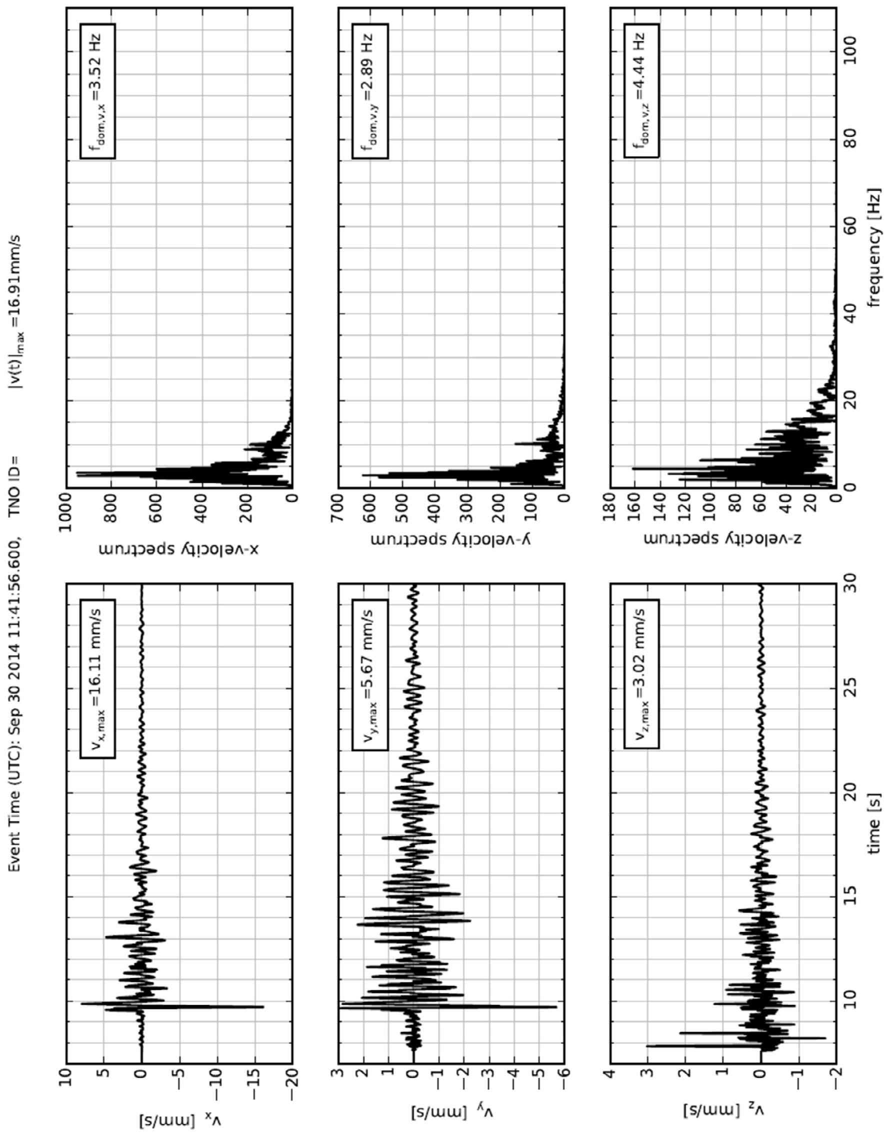


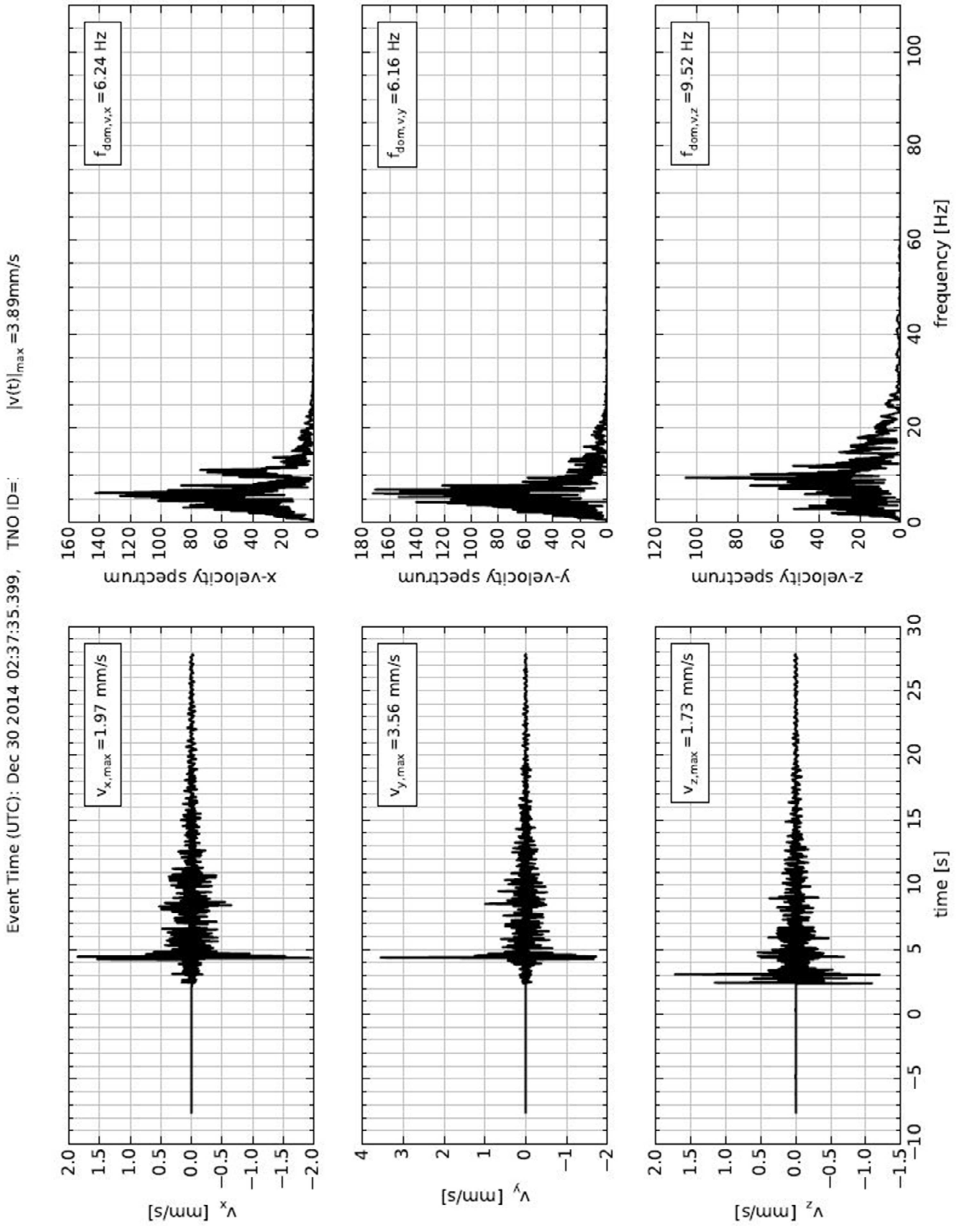

Event Time (UTC): Nov 05 2014 01:12:32.599, TNO ID=: $|a(t)|_{max}$=0.5m/s^2
$a_{x,max}$=0.5 m/s^2
$a_{y,max}$=0.09 m/s^2
$a_{z,max}$=0.43 m/s^2
a_x [m/s^2]
a_y [m/s^2]
a_z [m/s^2]
time [s]
$f_{dom,a,x}$=8.49 Hz
$f_{dom,a,y}$=6.56 Hz
$f_{dom,a,z}$=12.59 Hz
x-acceleration spectrum
y-acceleration spectrum
z-acceleration spectrum
frequency [Hz]

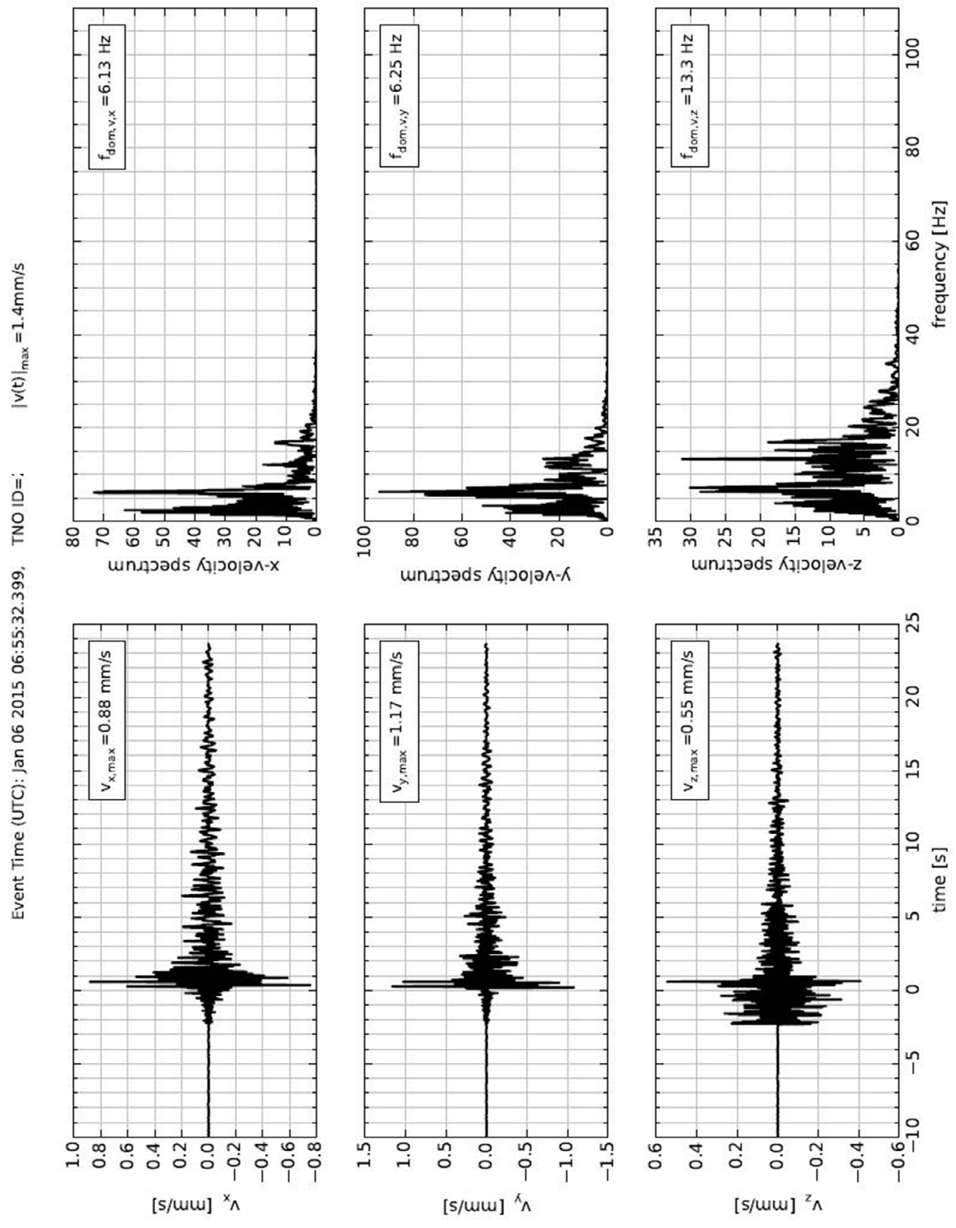
D Vibration signals – velocity

This Annex gives an example of the vibration velocity signals. For three different buildings, with different levels of acceleration, during different earthquakes, the following graphs are given:

- Measured velocity (v_x, v_y, v_z)
- Distribution of the frequency ($f_{dom,v,x}$,$f_{dom,v,y}$,$f_{dom,v,z}$)




Event Time (UTC): Dec 30 2014 02:37:35.399, TNO ID= |v(t)|max =3.89mm/s
v x,max =1.97 mm/s
v y,max =3.56 mm/s
v z,max =1.73 mm/s
f dom,v,x =6.24 Hz
f dom,v,y =6.16 Hz
f dom,v,z =9.52 Hz
v x [mm/s]
v y [mm/s]
v z [mm/s]
x-velocity spectrum
y-velocity spectrum
z-velocity spectrum
time [s]
frequency [Hz]


Event Time (UTC): Jan 06 2015 06:55:32.399, TNO ID=; |v(t)|max =1.4mm/s
vx,max =0.88 mm/s
vy,max =1.17 mm/s
vz,max =0.55 mm/s
fdom,v,x =6.13 Hz
fdom,v,y =6.25 Hz
fdom,v,z =13.3 Hz
vx [mm/s]
vy [mm/s]
vz [mm/s]
x-velocity spectrum
y-velocity spectrum
z-velocity spectrum
time [s]
frequency [Hz]