NAM

Empirical Ground-Motion Prediction Equations for Peak Ground Velocity from Small-Magnitude Earthquakes in the Groningen Field Using Multiple Definitions of the Horizontal Component of Motion

Updated Model for Application to Smaller Earthquakes

Julian J Bommer, Peter J Stafford & Michail Ntinalexis

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General Introduction

The hazard from induced earthquakes is primarily presented by the ground motion to which buildings and people are subjected. The prediction of ground motion, resulting from the earthquakes in the Groningen area induced by the production of gas, is critical for the assessment and prognosis of building damage and personal risk.

The research into the development of the ground motion prediction methodology started in 2012 and continues as more ground motion data from Groningen earthquakes is collected. The prime goal of these studies has been the assessment of ground motion for risk assessment. This means the focus has primarily been on the prediction of ground acceleration for larger events, extrapolating from the currently available data obtained from earthquakes with magnitude below M=3.6 to earthquakes with magnitude in the range from M=4 to M=5 and up to M_{max} (Ref. 1). The development of these Ground Motion Prediction Models for the assessment of risk has been documented in several reports (Ref. 2, 3, 4, 5 and 6). The current model used in the hazard and risk assessment is GMM version 5 (Ref. 6).

Additionally, a Ground Motion prediction methodology was developed for smaller earthquakes within the range of experience. This empirical methodology was developed for operational use within the context of a new damage protocol. The Ground Motion Model developed in 2016 aimed to accurately predict ground motion for earthquakes in the same range as the historical data base, primarily from M=2.5 to M=3.6. Additional to the peak ground acceleration this methodology also covers peak ground velocity and V_{top}. These last two metrics of ground motion are especially relevant for building damage and comparison with the Guidelines of the SBR (Stichting Bouw Research) (Ref. 7 and 8).

During 2017, the requirement to prediction ground motions for earthquakes smaller than M=2.5 was identified. This empirical methodology has therefore been extended to cover the range of earthquakes with magnitude in the range from M=1.8 to M=3.6.

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9. Empirical Ground-Motion Prediction Equations for Peak Ground Velocity from Small-Magnitude Earthquakes in the Groningen Field Using Multiple Definitions of the Horizontal Component of Motion, Julian J Bommer, Peter J Stafford & Michail Ntinalexis, November 2016

These reports are also available at the study reports page of the website www.namplatform.nl.

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Title	**Empirical Ground-Motion Prediction Equations for Peak Ground Velocity from Small-Magnitude Earthquakes in the Groningen Field Using Multiple Definitions of the Horizontal Component of Motion** **Updated Model for Application to Smaller Earthquakes**	**Date**	November 2017
		Initiator	NAM
Autor(s)	Julian J Bommer, Peter J Stafford & Michail Ntinalexis	**Editors**	Jan van Elk & Dirk Doornhof
Organisation	Researcher primarily from Imperial College, London.	**Organisation**	NAM
Place in the Study and Data Acquisition Plan	<u>Study Theme:</u> Ground Motion Prediction <u>Comment:</u> The prediction of Ground Motion is central to the hazard assessment. This report describes a Ground Motion Prediction methodology for operational use in the damage protocol, covering the magnitude range from M=1.8 to M=3.6.		
Directliy linked research	(1) Hazard Assessment. (2) Building Damage (DS1).		
Used data	Accelerograms from the accelerometers placed in the Groningen field. Description of the shallow geology of Groningen.		
Associated organisation	Imperial College (London).		
Assurance	Internal to the Hazard Team.		

Empirical Ground-Motion Prediction Equations for Peak Ground Velocity from Small-Magnitude Earthquakes in the Groningen Field Using Multiple Definitions of the Horizontal Component of Motion:

Updated Model for Application to Smaller Earthquakes

Julian J Bommer, Peter J Stafford & Michail Ntinalexis

A report to NAM

November 2017

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1. Introduction and Scope

As part of its response to induced earthquakes in the Groningen gas field, NAM has for several years been developing and refining models for the estimation of seismic hazard and risk. An essential component of the hazard and risk estimations is a model for the prediction of ground-motion amplitudes and durations at the ground surface as a result of all potential induced and triggered earthquakes (*e.g.*, Bommer *et al*., 2017a).

In parallel to the ground-motion model (GMM) for spectral accelerations and durations that is applicable for moderate-to-large magnitude earthquakes, an empirical model for the prediction of peak ground velocity (PGV) was developed for applications related to tolerable shaking levels (Bommer *et al*., 2016). The model derived a year ago was based on the same dataset of Groningen ground-motion recordings used in the derivation of the GMM, which covers a magnitude range from M_L 2.5 to 3.6. However, the model has been applied to smaller earthquakes, which implies an extrapolation outside the strict range of applicability of the equations. To address this issue, a new PGV model has been derived that is applicable to a wider range of magnitudes and this new model is presented in this report.

Section 2 of the report presents the expanded database compiled for the purposes of deriving the new model. The derivation of the new model is presented in Section 3 of the report, which also includes comparisons with the previous model. As before, equations are derived for the three different definitions of the horizontal component of motion and the reader is referred to Bommer *et al*. (2016) for additional information regarding these definitions. The report ends with a brief discussion in Section 4.

2. Ground-Motion Database

In this section, the expanded database used to derive the new PGV equations is briefly described, both in terms of its general characteristics and the values of PGV.

The database of recordings used to derive the original PGV prediction equations 178 recordings from 22 earthquakes in the Groningen field, obtained by surface accelerographs operated by KNMI (Bommer *et al*., 2016). As noted earlier, the minimum magnitude was M_L 2.5. For the development of the current (V5) GMM (Bommer *et al*., 2017b), an additional 80 recordings were incorporated from the M_L 2.6 Slochteren earthquake of May 2017, bringing the total database to 258 recordings from 23 earthquakes.

For the extension of the database, the minimum magnitude selected was 1.8, since smaller events than this cannot be of any relevance to impact 0on the built environment and furthermore the signals would be so weak as to make retrieval of useable numbers of reliable amplitudes very challenging.

The KNMI portal was the primary source of recordings from Groningen, and from this data source recordings for 23 earthquakes of M_L 1.8-2.4 were identified. The portal contains Groningen recordings only after the local accelerograph network upgrade that took place in 2013 and only from upgraded stations and borehole stations; the earliest event in this list, therefore, occurred on 28 September 2013. Since the number of events exactly matched that for the larger magnitude range, it was decided that these data were sufficient and there was no need to attempt the retrieval of earlier recordings. Figure 2.1 shows the epicentres of the earthquakes in the final database.

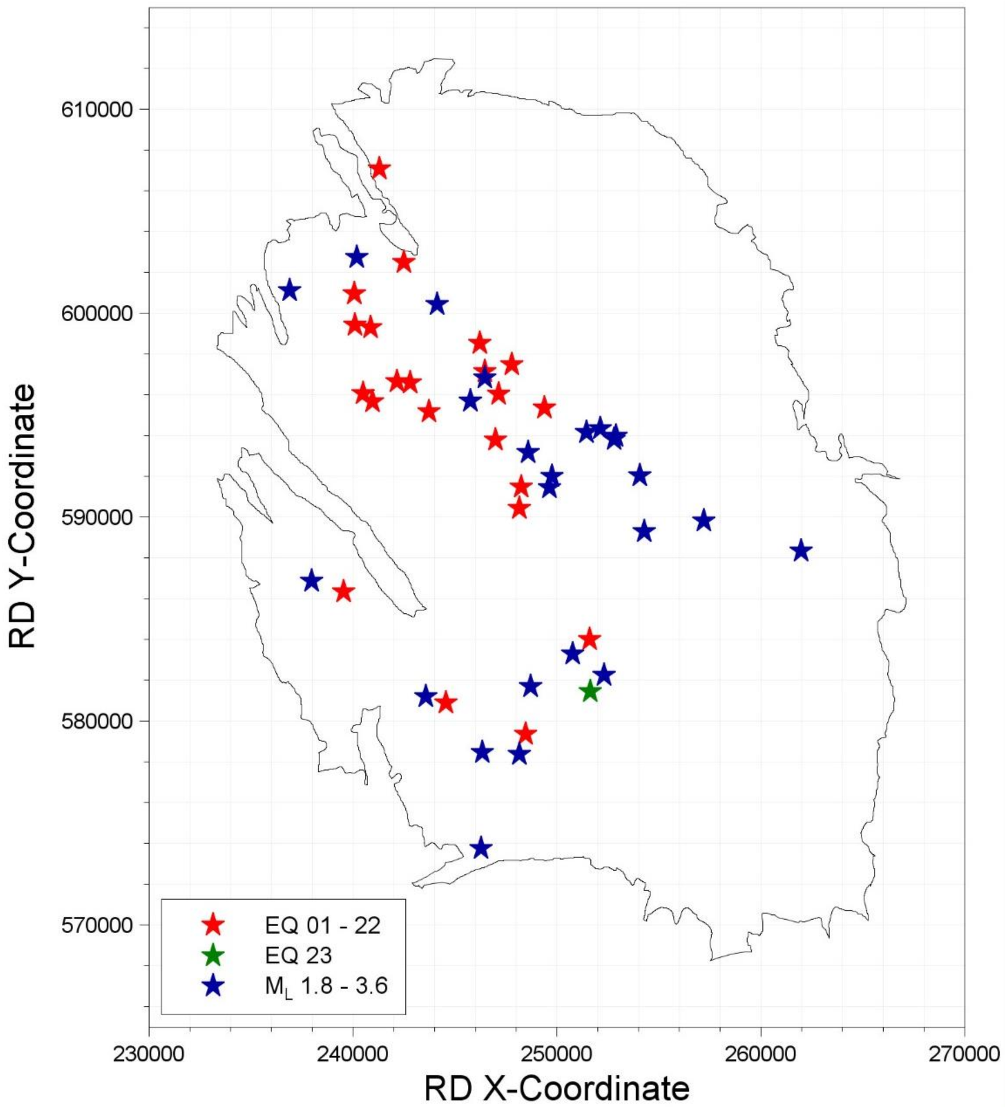

Figure 2.1. Map of the Groningen field; earthquake epicentres are shown in stars

From the records available in the portal for this smaller-magnitude dataset, 756 records were deemed usable for the derivation of the empirical GMPE and were carefully processed. With the addition of the 258 records of the V5 surface database, a total of 1,014 records from magnitudes of M_L 1.8-3.6 and epicentral distances ranging from 0.4 to 32 km constitute the extended database used for the empirical GMPE. The 47 earthquakes included in this database, as well as their main metadata, the local magnitude, epicentral coordinates and date and time of occurrence, are summarised in Table 2.1.

Table 2.1. List and basic metadata of earthquakes included in the extended database

EQ ID	M	RD-X	RD-Y	No. Records	Date & Time
01	3.5	242159	596659	4	2006-08-08-05:04:00
02	2.5	242826	596579	1	2006-08-08-09:49:23
03	3.2	243740	595168	6	2008-10-30-05:54:29
04	2.6	240955	595673	3	2009-04-14-21:05:25
05	3	246479	597129	5	2009-05-08-05:23:11
06	2.5	242496	602509	5	2010-08-14-07:43:20
07	3.2	248253	591487	8	2011-06-27-15:48:09
08	2.5	241305	607070	3	2011-08-31-06:23:57
09	2.5	249399	595368	1	2011-09-06-21:48:10
10	3.6	240504	596073	7	2012-08-16-20:30:33
11	2.7	240112	599405	3	2013-02-07-22:31:58
12	3.2	240085	600945	3	2013-02-07-23:19:08
13	2.7	246230	598516	2	2013-02-09-05:26:10
14	3	248163	590446	2	2013-07-02-23:03:55
15	2.8	247166	596048	5	2013-09-04-01:33:32
16	3	247804	597489	14	2014-02-13-02:13:14
17	2.6	248489	579359	5	2014-09-01-07:17:42
18	2.8	239565	586336	12	2014-09-30-11:42:03
19	2.9	240890	599307	18	2014-11-05-01:12:34
20	2.8	244561	580898	19	2014-12-30-02:37:36
21	2.7	246987	593800	19	2015-01-06-06:55:28
22	3.1	251603	584016	42	2015-09-30-18:05:37
23	2.6	251654	581456	71	2017-05-27-15:29:00
A0	1.9	244131	600435	2	2013-09-28-02:20:41
A1	1.9	248599	593173	2	2013-10-02-20:24:26
A2	2.0	252129	594346	11	2013-11-26-23:54:53
A3	2.3	250795	583309	10	2014-03-11-09:08:23
A4	1.9	254062	592047	9	2014-03-15-19:09:24
A5	2.1	236905	601108	10	2014-03-18-21:15:18
A6	2.1	248709	581699	9	2014-07-02-17:34:16
A7	2.0	251466	594165	9	2014-08-09-15:55:32
B0	1.9	246301	573749	30	2015-02-12-16:05:53
B1	2.3	252916	593972	26	2015-02-25-10:02:56
B2	2.3	252806	593803	12	2015-03-24-13:27:56
B3	2.0	240203	602746	23	2015-05-27-10:52:10
B4	1.9	245771	595702	26	2015-06-06-23:39:15
B5	2.1	237996	586878	31	2015-07-07-03:09:00
B6	2.0	246365	578459	29	2015-08-18-07:06:12
B7	2.3	257224	589809	49	2015-10-30-18:49:01
C0	2.4	248172	578382	58	2016-02-25-22:26:30
C1	2.1	252307	582249	55	2016-09-02-13:16:00
C2	1.9	249653	591435	48	2016-11-01-00:12:28
C3	2.2	249776	591994	52	2016-11-01-00:57:46
C4	2.1	246483	596828	56	2017-03-11-12:52:48
C5	1.8	261993	588355	63	2017-04-04-10:00:44
C6	2.0	243574	581189	68	2017-04-26-13:56:49
C7	1.9	254299	589303	68	2017-09-05-22:08:27

With regard to the first column in Table 2.1, the following ID coding was used: standard numbers are used for earthquakes of $M_L \geq 2.5$, the prefix “A” is used for earthquakes that occurred in 2013 and 2014, before the G-network was online, the prefix “B” is used for 2015, when a part of the G-network was online, and C is used for earthquakes including and after 2016, when most, and almost all, of the G-network has been online. Figure 2.2 the distribution of the entire dataset in terms of magnitude and distance.

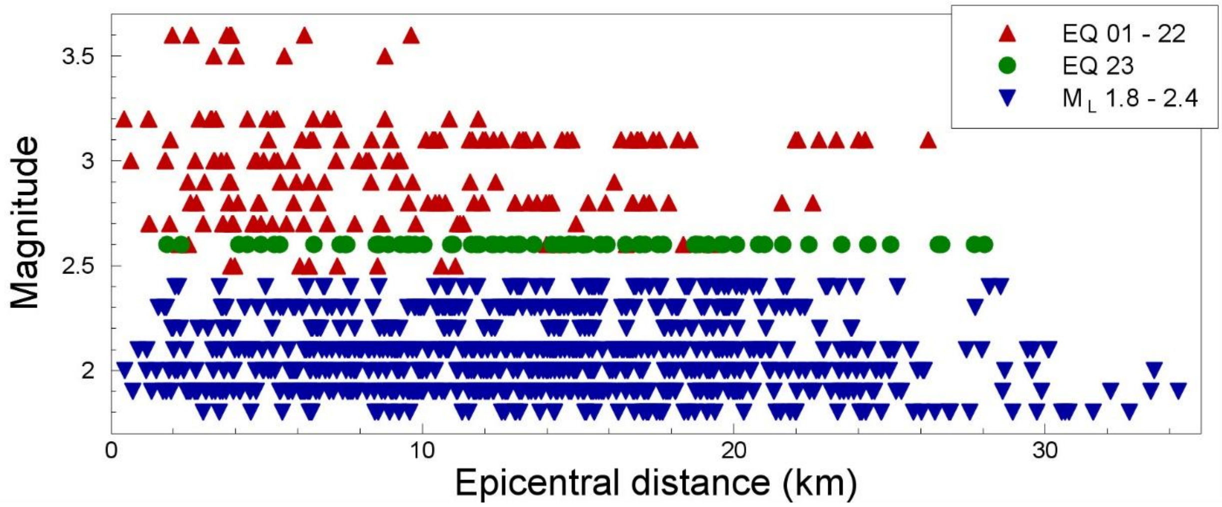

Figure 2.2. Magnitude-distance distribution of the extended database. The red symbols are the records used to derive the previous model and the green symbols the recordings from the Slochteren event; the blue symbols are the small-magnitude data added for the extension of the model’s range of applicability

The largest recorded value of PGV on any single component within the expanded database is still 3.46 cm/s, which was on the NS component of the MID1 recording obtained at 2 km from the epicentre of the 2012 Huizinge M_L 3.6 earthquake. The largest horizontal PGV component from the Slochteren earthquake was just 0.43 cm/s and unsurprisingly, none of the smaller events have generated large amplitude motions: the largest individual horizontal component among the additional data is just 0.37 cm/s. Overall, the amplitudes of the original PGV database were already rather small, with only 14 of the 178 records having a PGV above 1 cm/s and for about half of the data, the recorded PGV values did not exceed 0.1 cm/s. There are still only the same 14 records with PGV values above 1 cm/s, and now only about 10% of the final database have PGV values equal to or exceeding 0.1 cm/s. In fact, about 60% of the recordings have a maximum PGV on the as-recorded traces that is below 0.01 cm/s.

Figure 2.3 shows the PGV values—using the three different treatments of the pairs of horizontal components—plotted against distance. The consistently low amplitudes of the additional small-magnitude recordings are immediately apparent.

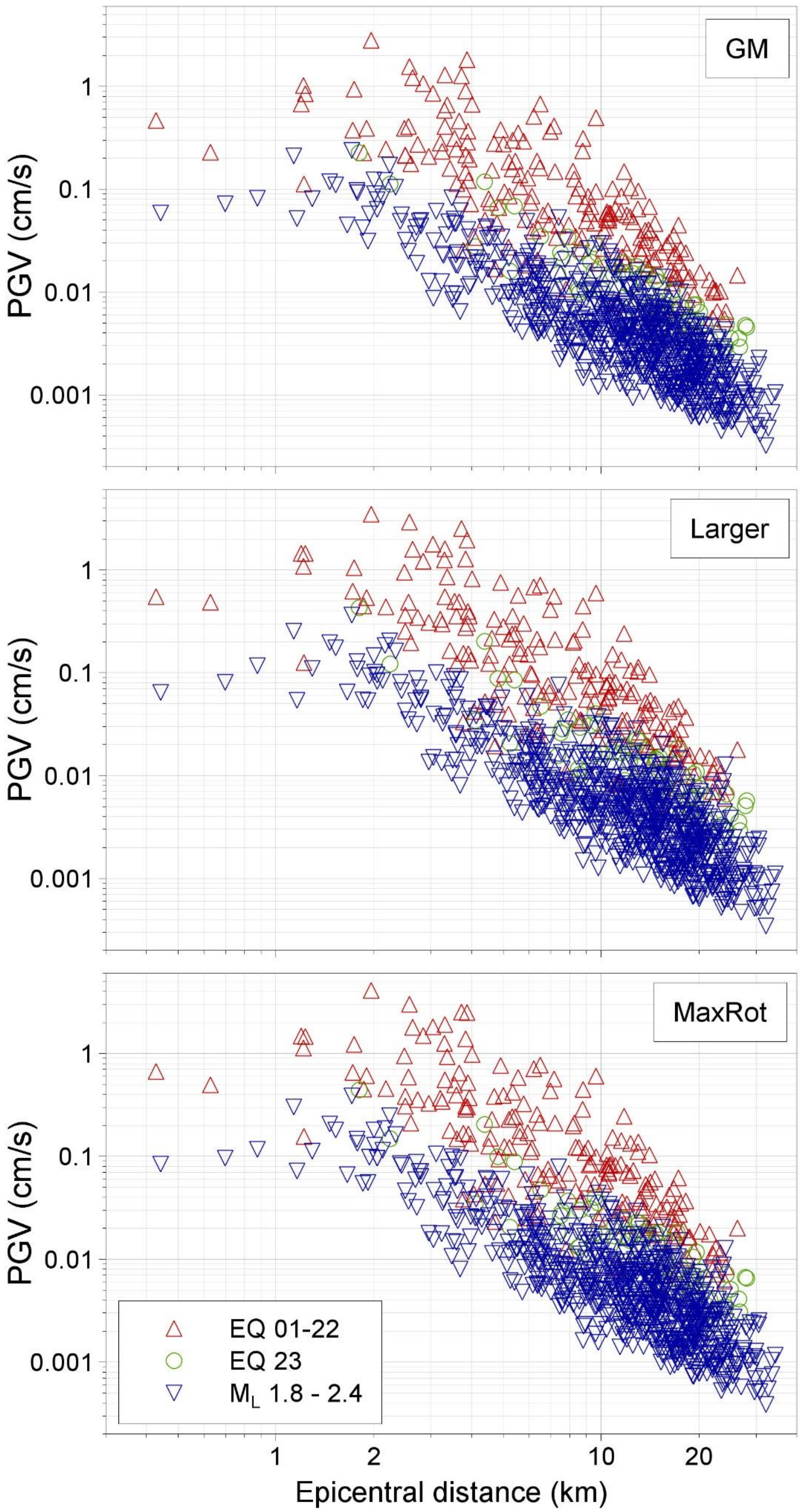

Figure 2.3. Values of PGV in the extended database plotted against distance

3. Empirical Equations for PGV

The new equations have been derived in exactly the same way as the 2016 empirical models for PGV.

3.1. Functional form

The extended database has not required any changes to the basic functional form used previously:

$$\ln(PGV) = c_1 + c_2 M + g(R) \tag{3.1}$$

with PGV in cm/s, M being local magnitude, M_L, determined by KNMI and the distance term, R, is defined as in Eq.(3.2), which defines the magnitude-dependent near-source saturation of the attenuation curve:

$$R = \sqrt{R_{epi}^2 + [\exp(0.4233M - 0.6083)]^2} \tag{3.2}$$

The magnitude-dependent distance saturation term in Eq.(3.2) was obtained from regressions on Groningen recordings. The geometrical spreading term is segmented over three distances:

$$g(R) = c_4 \ln(R) \qquad R \leq 6.32km \tag{3.3a}$$

$$g(R) = c_4 \ln(6.32) + c_{4a} \ln\left(\frac{R}{6.32}\right) \qquad 6.32 < R \leq 11.62km \tag{3.3b}$$

$$g(R) = c_4 \ln(6.32) + c_{4a} \ln\left(\frac{11.62}{6.32}\right) + c_{4b} \ln\left(\frac{R}{11.62}\right) \qquad R > 11.62km \tag{3.3c}$$

All of these equations are unchanged from the previous empirical model for PGV; they are included here only for ease of reference and to facilitate implementation of the model without reference to Bommer et al. (2016). However, for additional background to the derivation of the model, the reader may wish to consult the earlier report; this document is intended as a supplementary update and the complete documentation of the model should be considered as both reports taken together.

3.2. Regression analyses and residuals

Maximum likelihood regression was performed to find the coefficients of the functional form present in Section 3.1 for all three PGV definitions. The results are summarized in Table 3.1.

Table 3.1. Coefficients of Eqs. (3.1-3.3) for the prediction of PGV

Coefficient	PGV_{GM}	PGV_{Larger}	PGV_{MaxRot}
c_1	-5.9357	-5.6419	-5.4801
c_2	2.4036	2.4613	2.4509
c_4	-1.8819	-2.0024	-2.0385
c_{4a}	-1.2274	-1.2137	-1.195
c_{4b}	-1.7343	-1.7721	-1.7878

Analysis of the residuals for all three equations, separated into event-terms (earthquake-to-earthquake variability) and within-event residuals, were examined with respect to magnitude and distance, respectively (Figure 3.2). No discernible trends were identified in the residuals, which suggests that the model provides an unbiased fit to the data and that the functional form, therefore, is appropriate.

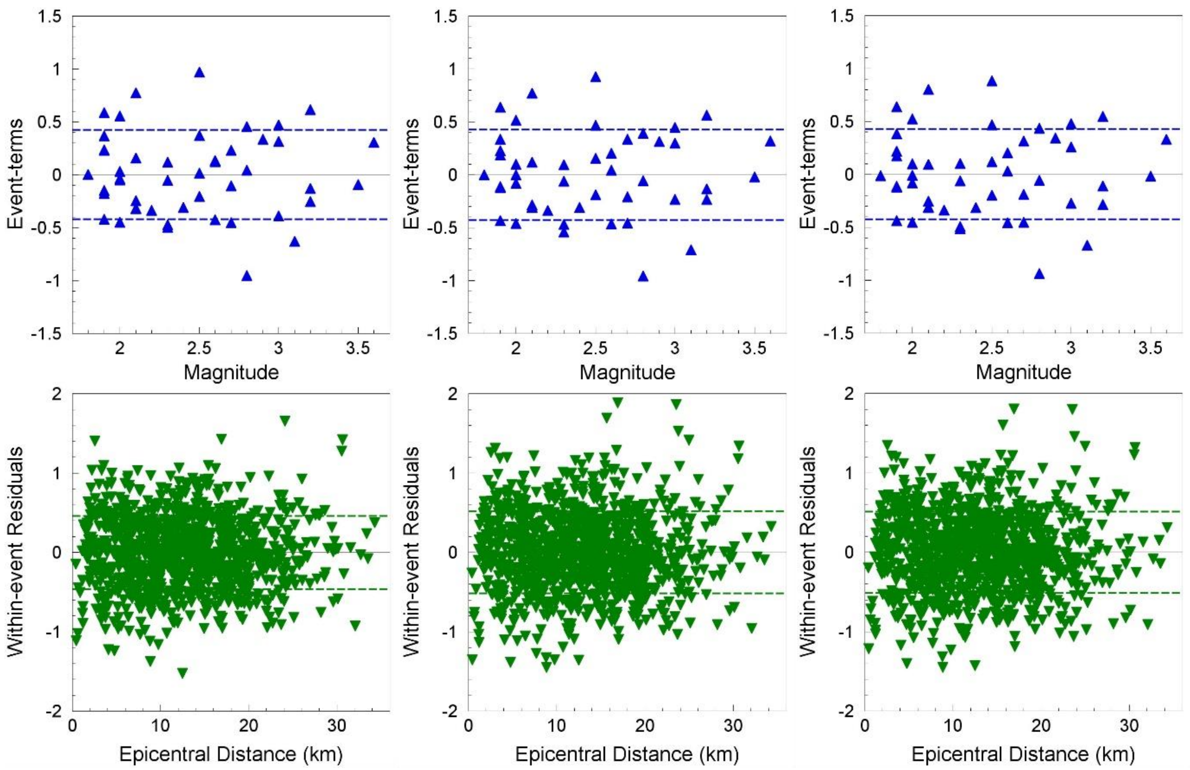

Figure 3.2. Logarithmic residuals of PGV: inter-event residuals against magnitude (*upper*) and intra-event residuals against distance (*lower*). From left to right: geometric mean components, larger recorded components, maximum rotated components.

The standard deviations of the residuals are an integral part of the equations, which predict probabilistic distributions of PGV rather than deterministic estimates of unique values. The total standard deviation, σ, is decomposed into a between-earthquake component, τ, and a within-earthquake component, ϕ; these are related as follows:

$$\sigma = \sqrt{\tau^2 + \phi^2} \tag{3.4}$$

The values of the standard deviations are reported in Table 3.2.

Table 3.2. Standard deviations of the PGV prediction models

Coefficient	PGV_{GM}	PGV_{Larger}	PGV_{MaxRot}
τ	0.4226	0.428	0.4264
ϕ	0.4607	0.5167	0.5115
σ	0.6252	0.671	0.6659

The event terms of the individual earthquakes are listed in Table 3.3. The event terms are plotted against the date of the earthquake in Figure 3.3, from which it can be observed that there has been a tendency towards smaller event terms for more recent earthquakes.

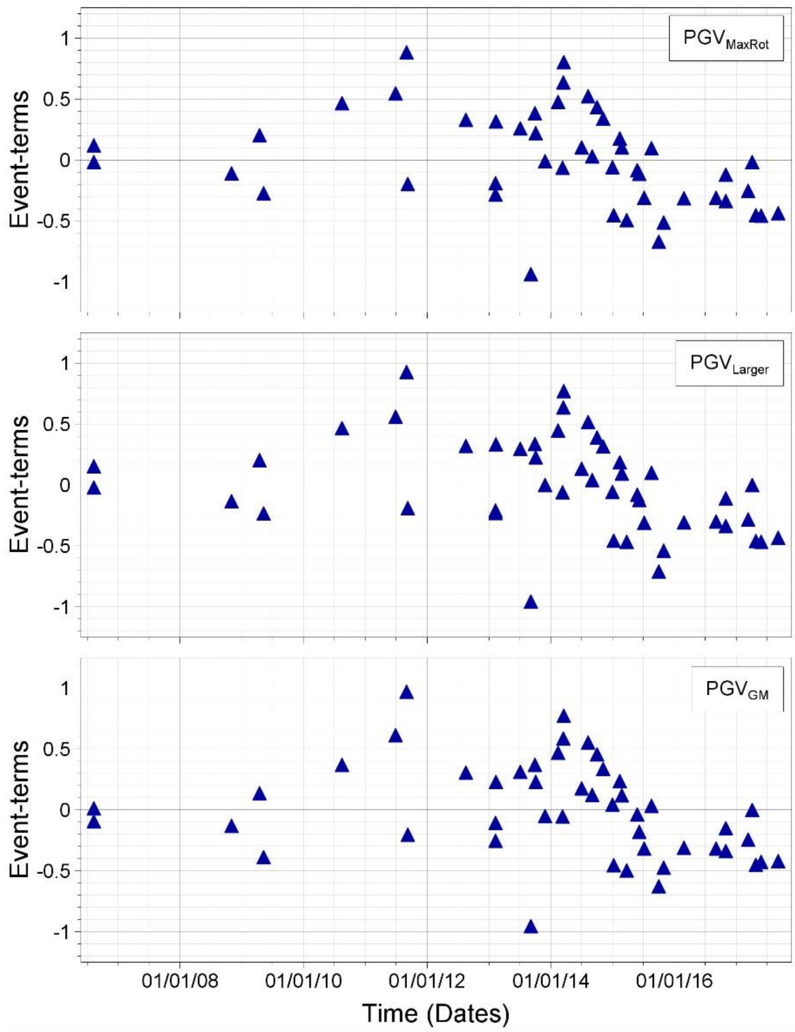

Figure 3.3. Event terms plotted against date of the earthquake.

Table 3.3. Event-terms for the PGV ground-motion model

EQ ID	M_L	PGV_{GM}	PGV_{Larger}	PGV_{MaxRot}
1	3.5	-0.0935	-0.0197	-0.0172
2	2.5	0.0135	0.1533	0.1211
3	3.2	-0.1284	-0.1319	-0.1087
4	2.6	0.1361	0.2028	0.204
5	3	-0.3878	-0.2321	-0.2738
6	2.5	0.3715	0.4675	0.468
7	3.2	0.6142	0.5612	0.5467
8	2.5	0.9711	0.9262	0.8836
9	2.5	-0.204	-0.1894	-0.1955
10	3.6	0.3085	0.32	0.3317
11	2.7	-0.1064	-0.2093	-0.19
12	3.2	-0.2544	-0.2313	-0.2838
13	2.7	0.2306	0.334	0.3167
14	3	0.3142	0.298	0.2586
15	2.8	-0.9533	-0.9551	-0.936
16	3	0.4711	0.4464	0.4782
17	2.6	0.1241	0.0416	0.031
18	2.8	0.4557	0.391	0.4337
19	2.9	0.3353	0.3163	0.3416
20	2.8	0.0423	-0.0569	-0.0583
21	2.7	-0.4528	-0.4572	-0.4544
22	3.1	-0.6278	-0.7093	-0.6708
23	2.6	-0.4262	-0.4648	-0.4553
A0	1.9	0.3687	0.3357	0.3851
A1	1.9	0.2294	0.2279	0.2198
A2	2	-0.0505	0.0005	-0.0093
A3	2.3	-0.0524	-0.0596	-0.0627
A4	1.9	0.5863	0.6384	0.6376
A5	2.1	0.7742	0.7696	0.8024
A6	2.1	0.176	0.133	0.1035
A7	2	0.5549	0.5164	0.5234
B0	1.9	0.2363	0.1876	0.1764
B1	2.3	0.121	0.094	0.103
B2	2.3	-0.4968	-0.4671	-0.4937
B3	2	-0.0358	-0.0793	-0.0829
B4	1.9	-0.1787	-0.1216	-0.1142
B5	2.1	-0.317	-0.3104	-0.3093
B6	2	0.0321	0.1007	0.0983
B7	2.3	-0.4745	-0.5399	-0.5148
C0	2.4	-0.3101	-0.308	-0.3135
C1	2.1	-0.3168	-0.2983	-0.3084
C2	1.9	-0.1503	-0.1108	-0.1195
C3	2.2	-0.3349	-0.3353	-0.335
C4	2.1	-0.2442	-0.2838	-0.2534
C5	1.8	0.0013	0.0013	-0.0149
C6	2	-0.4505	-0.4589	-0.4519
C7	1.9	-0.4213	-0.4333	-0.4372

3.3. Predictions of PGV

Figure 3.4 shows predicted median values of PGV from the three equations as a function of epicentral distance for three magnitudes that cover the likely range of application of these equations. The relative amplitudes obtained with the three different horizontal component definitions continue to be exactly as expected.

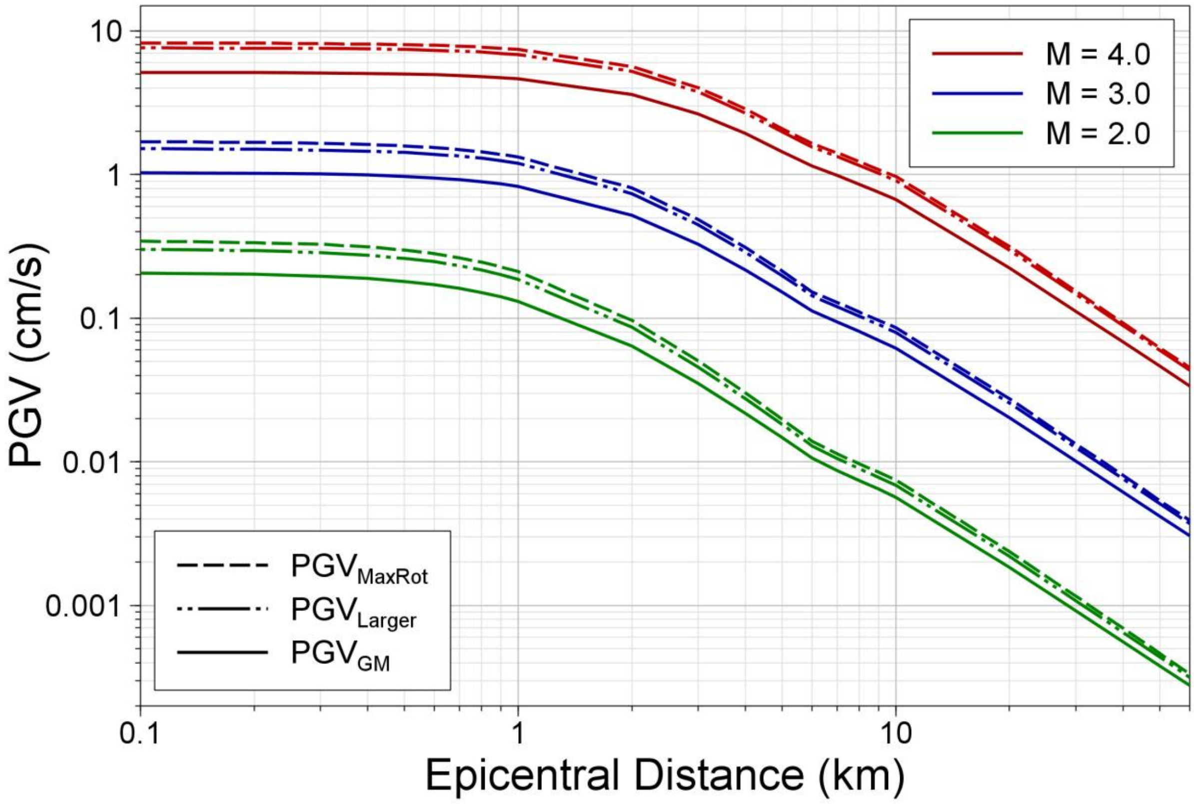

Figure 3.4. Predicted median PGV values against distance for three magnitudes

The new equations predict slightly lower amplitudes than the previous model at smaller magnitudes, as shown by the comparisons in Figure 3.5. This is to be expected in view of the scaling of ground-motion amplitudes with magnitude (*e.g.*, Douglas & Jousset, 2011; Baltay & Hanks, 2014) and the consequent tendency of the extrapolated 2016 model to overestimate the PGV values at smaller magnitudes (Figure 3.6). However, this adjustment also leads to a slightly steeper scaling with magnitude, leading to values that are a little higher at M_L = 4 in the new model as compared to the older model (Figures 3.5 and 3.6). However, it must be borne in mind that this magnitude lies beyond the strict upper limit of applicability of the model and hence is an extrapolation.

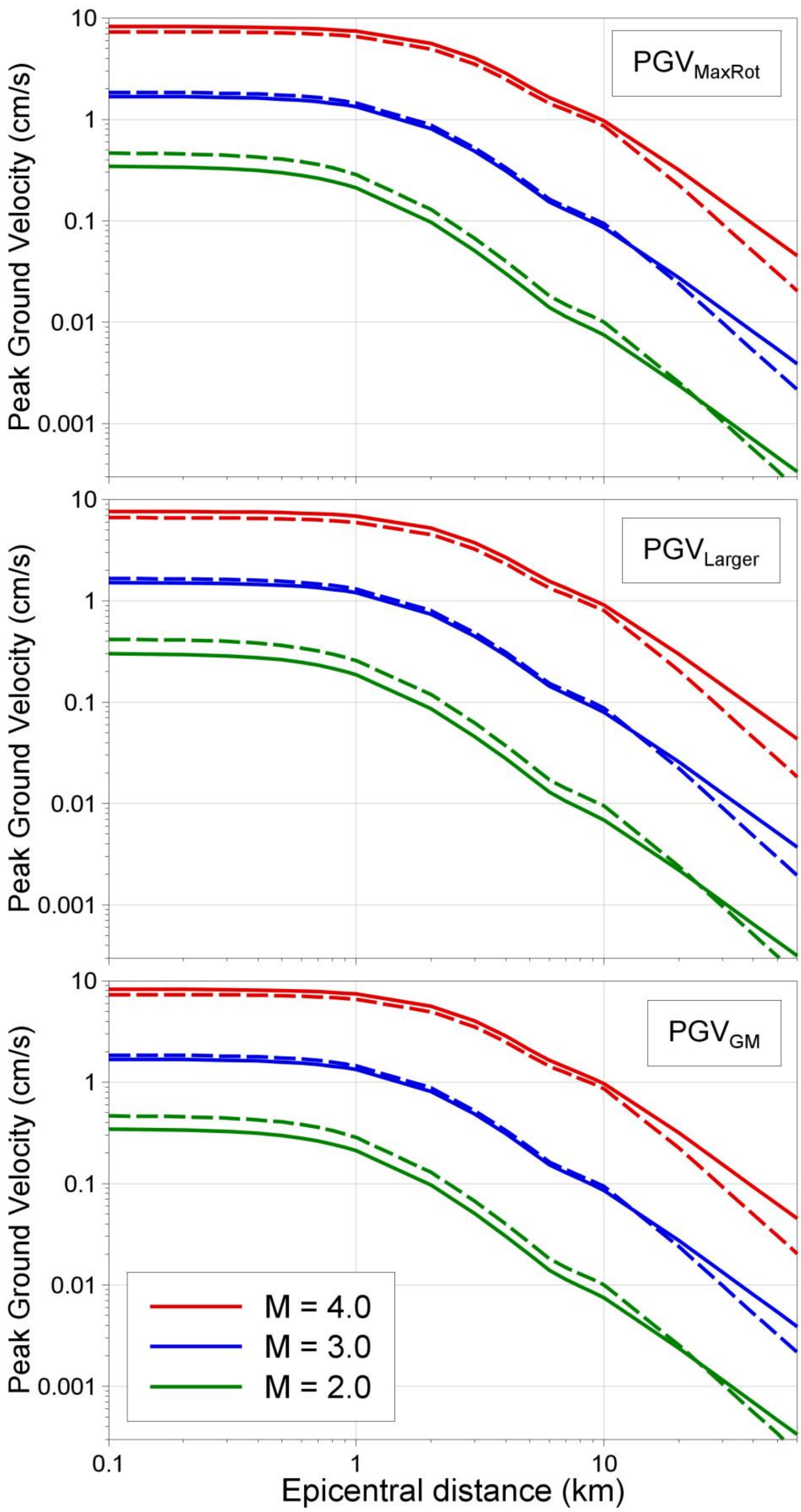

Figure 3.5. Predicted median PGV values from the old and new models against distance for magnitudes M_L 2, 3 and 4

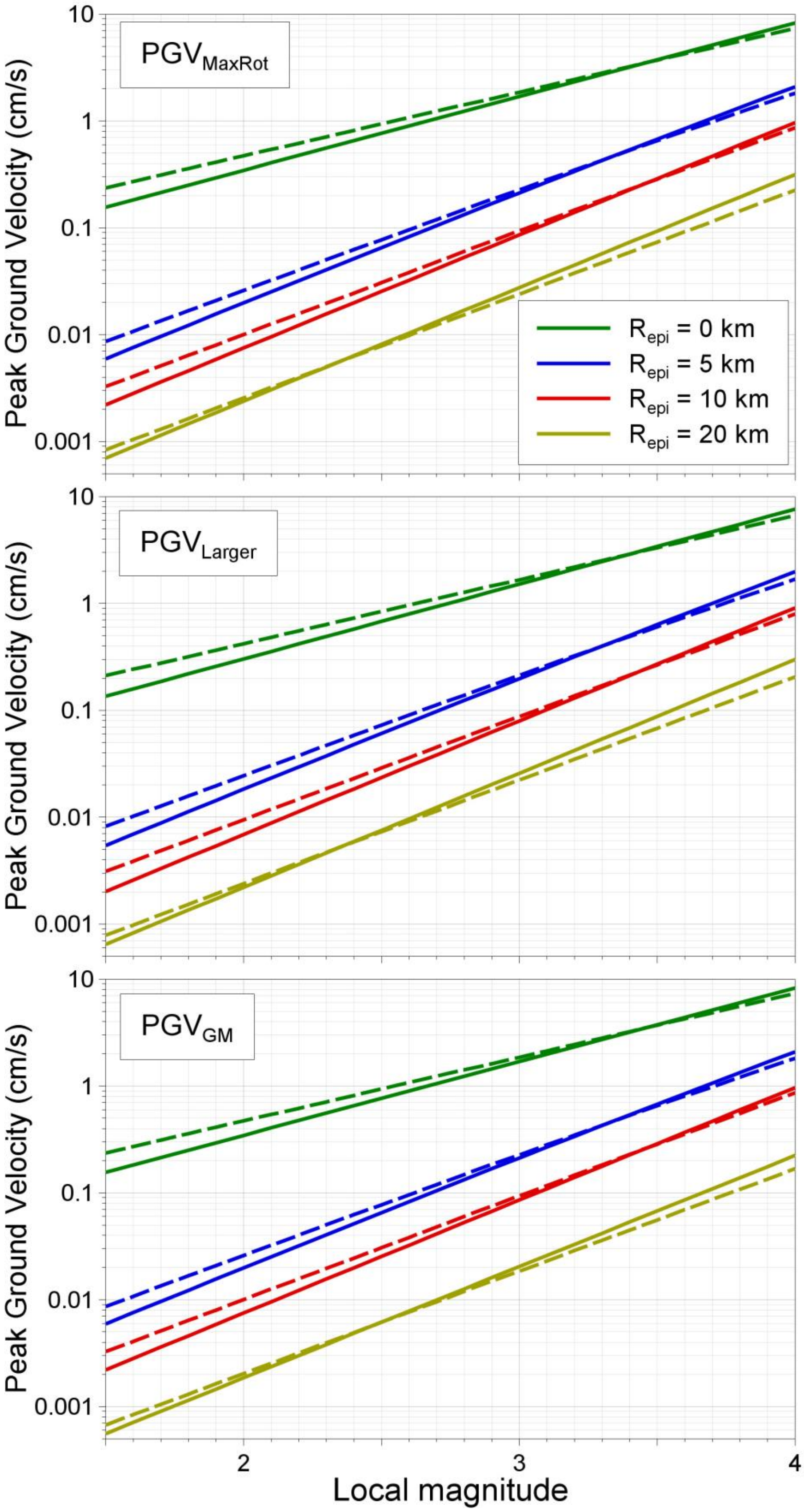

Figure 3.6. Predicted median PGV values from the old and new models against magnitude at four different values of epicentral distance

Finally, Figure 3.7 compares the standard deviations associated with the two models, from which it can be appreciated that the variability associated with the new model is slightly lower. The reduction in the overall sigma value is a consequence of smaller between-earthquake variability, since the within-event sigma value is practically unchanged.

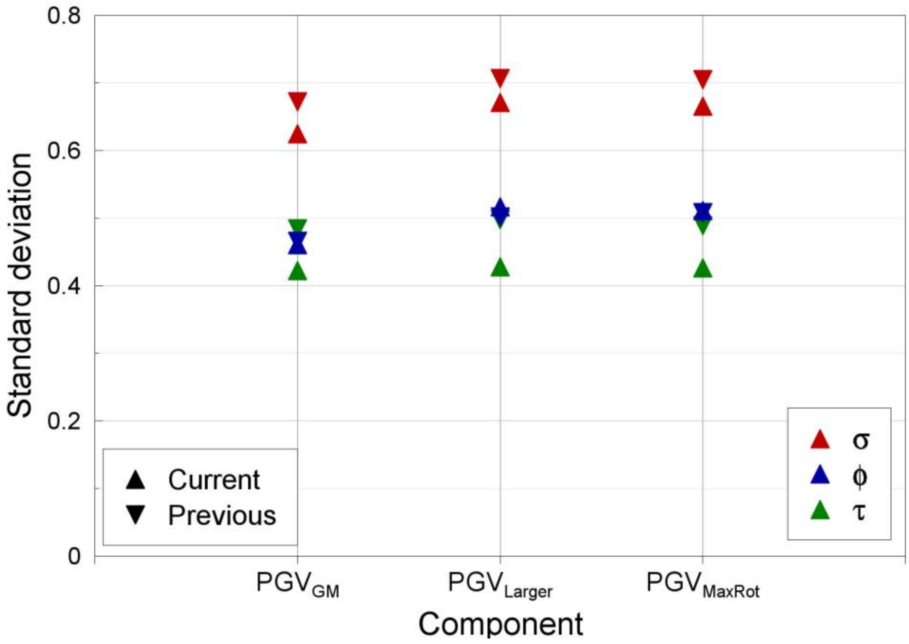

Figure 3.7. Comparison of variability components for the old and new PGV models

4. Concluding Remarks

New empirical PGV equations calibrated to the Groningen field have been derived, using three different definitions of the horizontal component of motion: the geometric mean of the two horizontal components, the larger of the two horizontal components, and the maximum component identified by rotation of the recorded traces. These models are now applicable for earthquakes with magnitudes between M_L 1.8 and M_L 3.6 and at epicentral distances of up to about 35 km. A small extrapolation to larger distances, perhaps to about 50 km, can be made with reasonable confidence but the equation should not be applied outside the Groningen field. Extrapolation to smaller or larger magnitudes is not advisable.

These new equations predict slightly lower amplitudes than the previous models issued in November 2016, with the magnitude range of applicability, particularly at lower magnitudes. This is likely to be due to the fact that the previous model will have overestimated ground-motion amplitudes when extrapolated below ML 2.5, but it may also have been influenced by the low-amplitude recordings of the Slochteren event, which are also considered to have caused a 10% reduction in the amplitudes of the GMM used in the hazard and risk modelling compared to earlier versions (Bommer *et al.*, 2017b). The results have also shown that the more recent events have tended to display smaller event terms. Whether this is due to different source characteristics of these events or the fact that they have overwhelmingly be recorded by the surface accelerographs associated with the borehole network (G-network) is not known at this time.

5. References

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