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# Scaling of peak ground acceleration and peak ground velocity recorded in the Netherlands

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**Abstract -** Measured accelerations caused by induced and tectonic events in the Netherlands have been made available since 1997. Measured mean horizontal peak ground accelerations reach values of up to 2.2 m/s$^2$ for an induced event of magnitude 3.4 at a hypocentral distance of 2.5 km and with a dominant frequency of 10 Hz. Measured mean peak horizontal ground velocities reach values of up to 4.5 cm/s for a tectonic event of magnitude 3.9 at a hypocentral distance of 4.4 km. These high values are predicted by existing empirical relations for the scaling of peak ground acceleration and peak ground velocity. The best fit for the observations of magnitudes larger than 3.0, taking into account that underestimates should be avoided, is given by Campbell (1997). For the total magnitude range, a new scaling relation for the Netherlands was estimated, based on the attenuation relation determined to calculate local magnitudes for induced events. These relations will be used in updates of seismic hazard studies for the Netherlands.

## 1. Introduction

Although the Netherlands is a low seismicity area, moderate earthquakes do occur and seismic hazard is an issue. The 1992 Roermond earthquake, $M_L$ = 5.8, caused damage to structures in the epicentral area (Berz, 1994), but, unfortunately, no accelerations were measured within a radius of 50 km from the epicentre (Camelbeeck et al., 1994). Since then, accelerometers have been installed in the Netherlands and its surroundings to improve this situation. The presently existing seismic hazard map for the Netherlands of de Crook (1996) is based on expected peak intensities from possible tectonic earthquakes in the southern part of the

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country. The approximate conversion to peak ground acceleration (PGA), based on relations used in Germany and France, needs to be replaced by an attenuation relation based on measured accelerations.

Monitoring induced seismicity in the northern part of the Netherlands (Dost and Haak, 2003) received a high priority. Although the largest recorded induced event in that region had a magnitude of 3.5, damage is often reported for events of magnitude 3 and higher, and for the largest events even intensity VI according to the European Macroseismic Scale (Gruenthal, 1998) was reported. This is due to the fact that the depth of these events is usually around 2-3 km. Therefore, starting in 1996, an accelerometer network, that consists presently of 17 stations

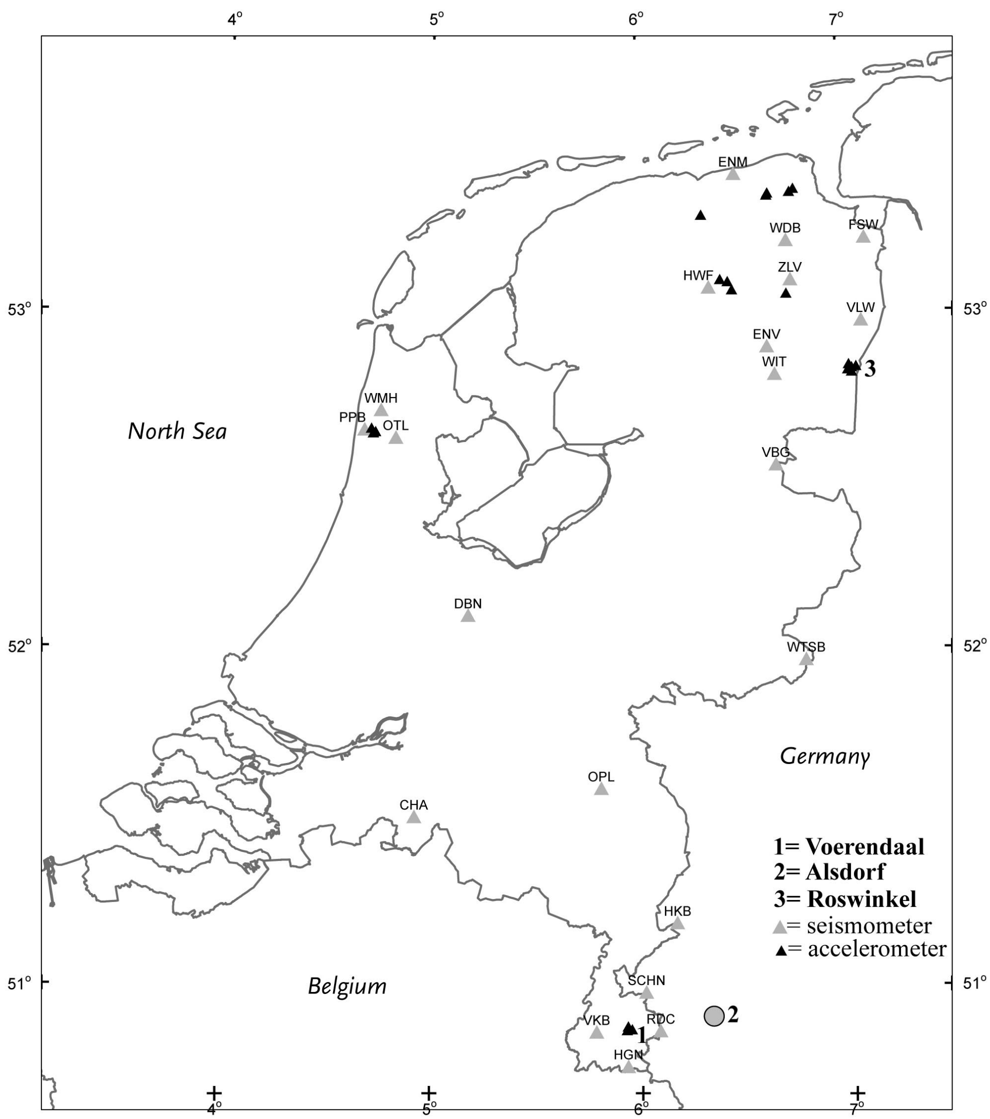


**Fig. 1** - Overview of acceleration stations (black triangles) and other seismic stations (grey triangles) presently deployed by the KNMI in the Netherlands. Earthquake source regions (Voerendaal, Roswinkel and Alsdorf), mentioned in the text, are also shown.

in the northern part of the country (Fig. 1), was built up. By June 2003 this network recorded 60 triaxial accelerograms of seismic events.

In December 2000, a tectonic event occurred in the southern part of the Netherlands near the city of Voerendaal. Fifteen years before this region experienced a small earthquake swarm with small ($M_L$ < 3.1) and shallow (3-6 km) events. In anticipation of a new swarm, initially two, and later three, accelerometers were installed near Voerendaal. The swarm that followed counted 139 events up to the end of 2001 with a maximum magnitude of 3.9. Activity continued during 2002 and 2003, but with a much lower rate of occurrence. In summer 2002, an event of magnitude 4.9 occurred near Alsdorf in western Germany, only 20 km from Voerendaal. This event was recorded in all three accelerometer stations around Voerendaal. In total 66 triaxial accelerograms have been recorded.

The purpose of the present paper is to investigate the scaling of the measured horizontal PGAs and derived peak ground velocity (PGV) values from small magnitude events. We compare this with existing empirical attenuation functions for small-magnitude earthquakes and extrapolations of existing empirical attenuation functions based on measured accelerations from larger earthquakes and at larger distances. Finally, we will compare attenuation functions derived from borehole seismometer data in the northern part of the Netherlands with the acceleration scaling.

## 2. Data

The accelerometers deployed are mainly SIG SMACH AC-23 sensors in combination with 16-bit SMACH SM-2-16 recorders. In 2002, also two Kinemetrics epi-sensors with ETNA data loggers were installed. But up to mid-2003, these did not record any accelerations.

In the northern part of the Netherlands, most accelerograms have been obtained from the region around the village of Roswinkel, situated in the northeastern part of the Netherlands and 22 events were recorded on one or more accelerometers in the period 1997-2003. The largest measured PGA is 215 cm/s$^2$ for the 1997 (February 19) $M_L$ 3.4 event at a dominant frequency of 10 Hz. For these events two accelerometer stations are situated at a nearly constant hypocenter distance of 2.3-2.7 km. The high accelerations measured are not uncommon for a combination of low-magnitude events and small distances. Hanks and Johnson (1976) reported PGA values of 100-200 cm/s$^2$ for a magnitude 3.2 event at a source-site distance of 10 km. Fletcher et al. (1983) show examples for induced seismicity near the Monticello dam in South Carolina, where PGAs in access of 200 cm/s$^2$ are measured for events of magnitude 3.0 at a distance around 1 km.

In the southern part of the Netherlands, 44 events are recorded near Voerendaal on one to three accelerometers. The largest event ($M_L$ = 3.9) in this cluster of events produced a PGA of 124 cm/s$^2$ at a 4-km epicentral distance. The largest tectonic event, the event near Alsdorf, recorded by these accelerometers occurred at an epicentre distance of 18-20 km. This Alsdorf event displayed a longer duration and lower frequencies (around 1-2 Hz) as compared to the Voerendaal events.

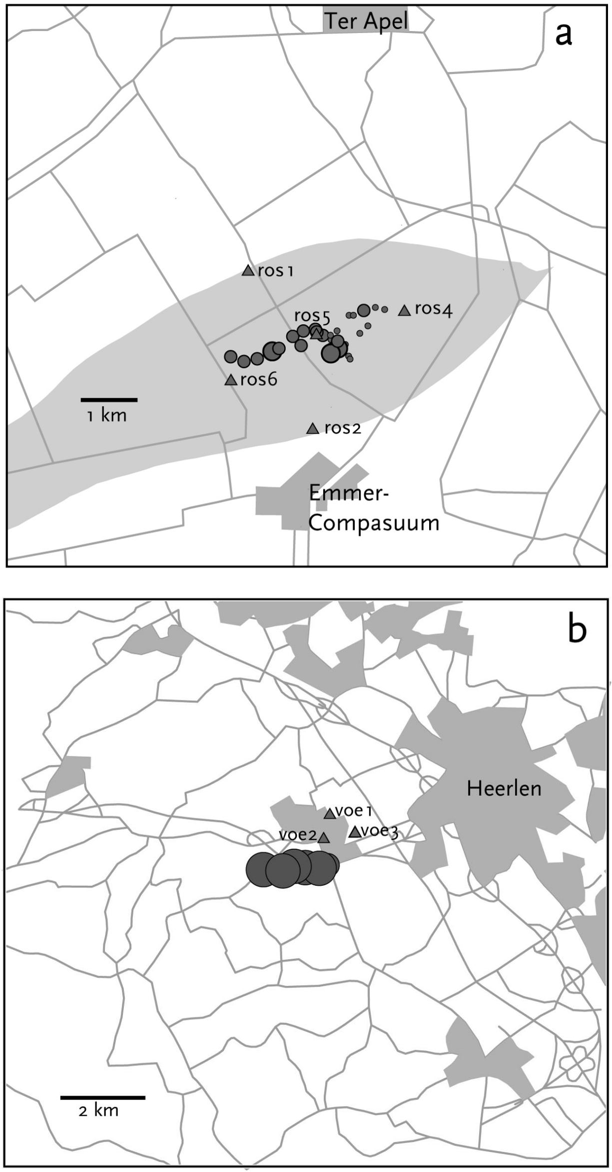


**Fig. 2** - Acceleration stations near Roswinkel (a) and Voerendaal (b). In (a) events are indicated with a circle; magnitudes varying from 0.8-3.4. The Roswinkel gas field is indicated by a shaded contour. In (b) the largest events, magnitudes ≥ 3.0, near Voerendaal are shown. Main roads and cities are indicated.

The majority of the accelerometers are located in garages, cellars or small sheds connected to a one to two-story building. The instruments are anchored to the concrete floors. At one location, where the structure was larger than average, we observed anomalously low PGAs. To investigate the influence of the building, we carried out an experiment comparing the signal of the accelerometer in the building with one of an accelerometer outside, in the free field. Results are shown in Fig. 3. Besides attenuating the higher frequencies, the building seems to introduce SV energy at the vertical component and at the same time reduce SV energy at the radial

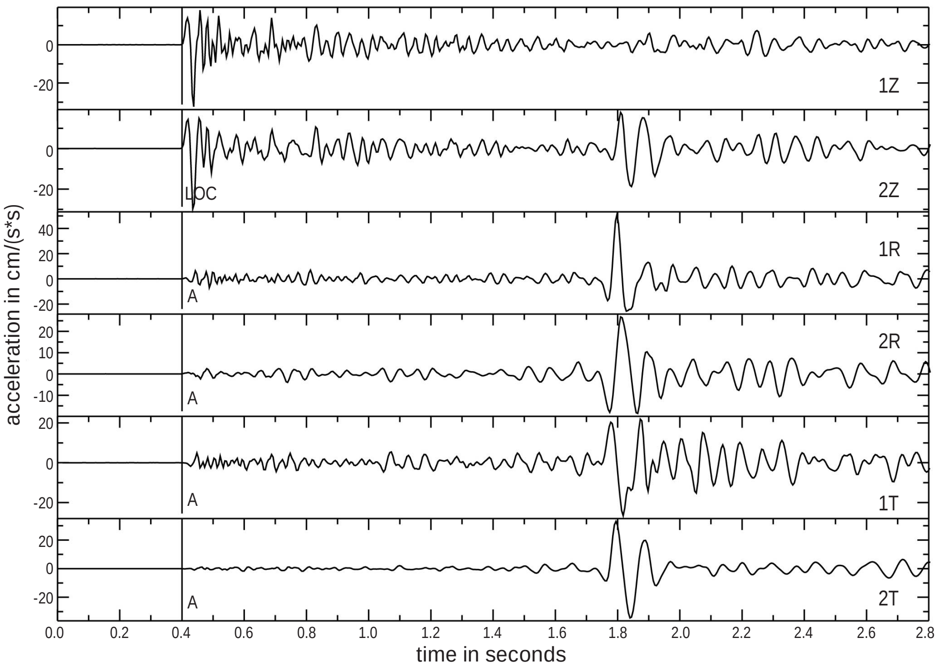


**Fig. 3** - Accelerations for a Roswinkel event (31.12.1999) recorded inside an elongated building (2) and in the free field outside the building (1). From top to bottom, the vertical (Z), radial (R) and transverse (T) components are shown.

component. The PGA at the radial component is reduced by a factor 2, which is considerable and explains partly the observed differences. A source radiation effect and possible site effects are other components.

In this paper, the PGAs are defined as in Campbell (1997) and Campbell and Bozorgnia (2003): the geometric mean of the peaks of the two horizontal components. The horizontal components are rotated to compare radial and transverse components for all events. Since some empirical relations use “recorded” PGAs, i.e. the largest recorded value, instead of an average value, such values have also been measured (see Table 1).

## 3. Waveform characteristics

Events around Roswinkel have a characteristic waveform shape. After instrument correction and conversion to displacement, a simple displacement pulse remains (Fig. 4). A remarkable feature of this displacement pulse is that the pulse duration seems to be stable at approximately 0.1 seconds over the recorded magnitude range of 0.8-3.4. For the larger events the waveform seems to become more complex. This pulse form is clearly visible in station ROS1 and ROS2, where most accelerations are measured. For the Voerendaal regions, this simple waveform has not been observed.

**Table 1** - Event list and measured PGA and PGV values.

| event time | station | R [km] | $M_L$ | PGA [m/s$^2$] radial | PGA [m/s$^2$] transverse | PGA [m/s$^2$] average | PGV [cm/s] radial | PGV [cm/s] transverse | PGV [cm/s] average |
|---|---|---|---|---|---|---|---|---|---|
| 970519_1543 | ROS1 | 2.6 | 1.3 | 0.06 | 0..06 | 0.06 | 0.08 | 0.06 | 0.07 |
| 990312_1806 | ROS1 | 2.6 | 1.3 | 0.07 | 0.08 | 0.08 | 0.09 | 0.07 | 0.08 |
| 990515_1928 | ROS1 | 2.6 | 1.4 | 0.08 | 0.07 | 0.07 | 0.11 | 0.07 | 0.09 |
| 990317_2314 | ROS1 | 2.7 | 1.5 | 0.16 | 0.16 | 0.16 | 0.23 | 0.15 | 0.18 |
| 970818_0442 | ROS1 | 2.3 | 1.6 | 0.18 | 0.05 | 0.10 | 0.17 | 0.07 | 0.11 |
| 990514_1830 | ROS1 | 2.6 | 1.7 | 0.14 | 0.15 | 0.14 | 0.23 | 0.14 | 0.18 |
| 970620_0045 | ROS1 | 2.8 | 1.8 | 0.20 | 0.11 | 0.15 | 0.27 | 0.14 | 0.19 |
| 980128_2234 | ROS1 | 2.3 | 2.0 | 0.28 | 0.14 | 0.20 | 0.39 | 0.19 | 0.27 |
| 970818_0517 | ROS1 | 2.4 | 2.1 | 0.25 | 0.18 | 0.21 | 0.42 | 0.23 | 0.31 |
| 020214_1701 | ROS1 | 2.3 | 2.1 | 0.46 | 0.41 | 0.43 | 0.68 | 0.37 | 0.50 |
| 970116_0012 | ROS1 | 2.6 | 2.4 | 0.39 | 0.15 | 0.24 | 0.50 | 0.15 | 0.27 |
| 010428_2300 | ROS1 | 2.4 | 2.4 | 0.42 | 0.52 | 0.47 | 0.55 | 0.41 | 0.47 |
| 980128_2133 | ROS1 | 2.4 | 2.7 | 0.75 | 0.54 | 0.63 | 1.18 | 0.66 | 0.97 |
| 991231_1100 | ROS1 | 2.4 | 2.8 | 1.23 | 0.72 | 0.95 | 1.83 | 0.73 | 1.16 |
| 001025_1810 | ROS1 | 2.7 | 3.2 | 1.53 | 0.81 | 1.11 | 2.94 | 0.93 | 1.75 |
| 980714_1212 | ROS1 | 2.7 | 3.3 | 2.81 | 0.87 | 1.58 | 4.89 | 1.18 | 2.41 |
| 970219_2153 | ROS1 | 2.4 | 3.4 | 3.04 | 1.51 | 2.15 | 5.52 | 2.07 | 3.38 |
| 000327_1023 | ROS2 | 2.3 | 0.8 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| 021014_2345 | ROS2 | 2.4 | 0.9 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 |
| 000107_1419 | ROS2 | 2.3 | 1.1 | 0.04 | 0.02 | 0.03 | 0.05 | 0.02 | 0.03 |
| 990506_1813 | ROS2 | 2.6 | 1.4 | 0.06 | 0.07 | 0.07 | 0.08 | 0.06 | 0.07 |
| 990515_1928 | ROS2 | 2.5 | 1.4 | 0.06 | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 |
| 021224_0257 | ROS2 | 2.4 | 1.4 | 0.02 | 0.03 | 0.03 | 0.05 | 0.05 | 0.05 |
| 990317_2314 | ROS2 | 2.3 | 1.5 | 0.13 | 0.07 | 0.10 | 0.15 | 0.08 | 0.11 |
| 970818_0442 | ROS2 | 2.4 | 1.6 | 0.07 | 0.08 | 0.08 | 0.10 | 0.06 | 0.08 |
| 990514_1830 | ROS2 | 2.5 | 1.7 | 0.10 | 0.06 | 0.08 | 0.13 | 0.06 | 0.09 |
| 980128_2234 | ROS2 | 2.4 | 2.0 | 0.29 | 0.18 | 0.23 | 0.34 | 0.27 | 0.30 |
| 970818_0517 | ROS2 | 2.5 | 2.1 | 0.20 | 0.15 | 0.17 | 0.36 | 0.19 | 0.26 |
| 020214_1701 | ROS2 | 2.4 | 2.1 | 0.42 | 0.21 | 0.30 | 0.55 | 0.25 | 0.37 |
| 010428_2300 | ROS2 | 2.4 | 2.4 | 0.16 | 0.08 | 0.12 | 0.33 | 0.10 | 0.18 |
| 980128_2133 | ROS2 | 2.4 | 2.7 | 0.38 | 0.24 | 0.31 | 0.93 | 0.34 | 0.56 |
| 991231_1100 | ROS2 | 2.5 | 2.8 | 0.56 | 1.13 | 0.80 | 2.21 | 0.76 | 1.28 |
| 001025_1810 | ROS2 | 2.3 | 3.2 | 0.46 | 0.24 | 0.33 | 1.48 | 0.45 | 0.82 |
| 980714_1212 | ROS2 | 2.4 | 3.3 | 0.91 | 0.58 | 0.73 | 1.88 | 0.59 | 1.05 |
| 010428_2300 | ROS4 | 2.4 | 2.4 | 0.32 | 0.10 | 0.18 | 0.32 | 0.12 | 0.20 |
| 991231_1100 | ROS4 | 2.3 | 2.8 | 0.51 | 0.27 | 0.37 | 0.66 | 0.53 | 0.59 |
| 001025_1810 | ROS4 | 2.4 | 3.2 | 0.35 | 0.12 | 0.20 | 0.39 | 0.17 | 0.26 |
| 020214_1701 | ROS5 | 2.1 | 2.1 | 0.07 | 0.05 | 0.06 | 0.10 | 0.07 | 0.08 |
| 010428_2300 | ROS5 | 2.0 | 2.4 | 0.11 | 0.08 | 0.09 | 0.15 | 0.13 | 0.14 |
| 001025_1810 | ROS5 | 2.0 | 3.2 | 0.22 | 0.50 | 0.33 | 0.30 | 0.65 | 0.44 |
| 021224_0257 | ROS6 | 2.2 | 1.4 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| 020214_1701 | ROS6 | 2.1 | 2.1 | 0.21 | 0.29 | 0.25 | 0.25 | 0.44 | 0.33 |
| 010428_2300 | ROS6 | 2.6 | 2.4 | 0.07 | 0.09 | 0.08 | 0.17 | 0.11 | 0.14 |
| 010623_0140 | VOE1 | 4.4 | 3.9 | 1.18 | 1.80 | 1.46 | 3.24 | 6.23 | 4.48 |
| 010623_0153 | VOE1 | 4.1 | 3.5 | 0.57 | 0.94 | 0.73 | 0.79 | 1.53 | 1.11 |
| 010623_0202 | VOE1 | 4.0 | 3.2 | 0.28 | 0.42 | 0.34 | 0.41 | 0.95 | 0.63 |
| 010307_0917 | VOE1 | 4.5 | 3.1 | 0.16 | 0.17 | 0.17 | 0.33 | 0.49 | 0.40 |
| 010307_1104 | VOE1 | 4.5 | 3.1 | 0.52 | 0.18 | 0.31 | 0.74 | 0.57 | 0.65 |
| 010307_1029 | VOE1 | 4.5 | 3.0 | 0.39 | 0.17 | 0.26 | 1.02 | 0.47 | 0.69 |
| 020722_0545 | VOE1 | 23.2 | 4.9 | 0.52 | 0.23 | 0.35 | 3.44 | 1.45 | 2.23 |
| 010623_0140 | VOE2 | 4.2 | 3.9 | 1.83 | 0.83 | 1.23 | 8.58 | 1.74 | 3.86 |
| 010623_0153 | VOE2 | 3.9 | 3.5 | 0.25 | 0.33 | 0.29 | 1.06 | 0.98 | 1.02 |
| 010623_0202 | VOE2 | 3.7 | 3.2 | 0.35 | 0.23 | 0.28 | 0.82 | 0.64 | 0.72 |
| 010307_0917 | VOE2 | 4.3 | 3.1 | 0.17 | 0.15 | 0.16 | 0.64 | 0.54 | 0.58 |
| 010307_1104 | VOE2 | 4.3 | 3.1 | 0.29 | 0.15 | 0.21 | 0.56 | 0.54 | 0.55 |
| 010307_1029 | VOE2 | 4.2 | 3.0 | 0.19 | 0.15 | 0.17 | 0.54 | 0.49 | 0.52 |
| 020722_0545 | VOE2 | 23.4 | 4.9 | 0.33 | 0.28 | 0.31 | 2.40 | 1.67 | 2.00 |

## 4. Scaling relations

We compared our data with four published empirical PGA relations and two empirical PGV relations. In addition, an attenuation function, derived for local magnitude determination in the northern part of the Netherlands, is used as a basis to determine new regional scaling relations. The relations are briefly presented below.

Different types of empirical attenuation relations have been constructed over the years; see a special issue of Seismological Research Letters (Abrahamson and Shedlock, 1997) for a recent overview. Few studies provide scaling relations for smaller earthquakes (e.g. Campbell, 1989; Ambraseys, 1995). We further selected scaling relations obtained by Campbell (1997, errata 2000, 2001) from near source data from shallow crustal events, as in our case. Campbell (1997) uses a global dataset. Relations derived by Ambraseys (1995) are based on European events for a large range of magnitudes. A study by Sabetta and Pugliese (1987) focussing on Italian strong motion data has also been used for comparison. Both the Campbell (1997) and Sabetta and Pugliese (1987) relations are derived for magnitudes much larger than the events we show in this study. However, we are interested in how well these relations behave if extrapolated to the lower magnitudes.

Campbell (1989) derived an attenuation relationship for events in the (local) magnitude range $2.5 \leq M_L \leq 5.0$:

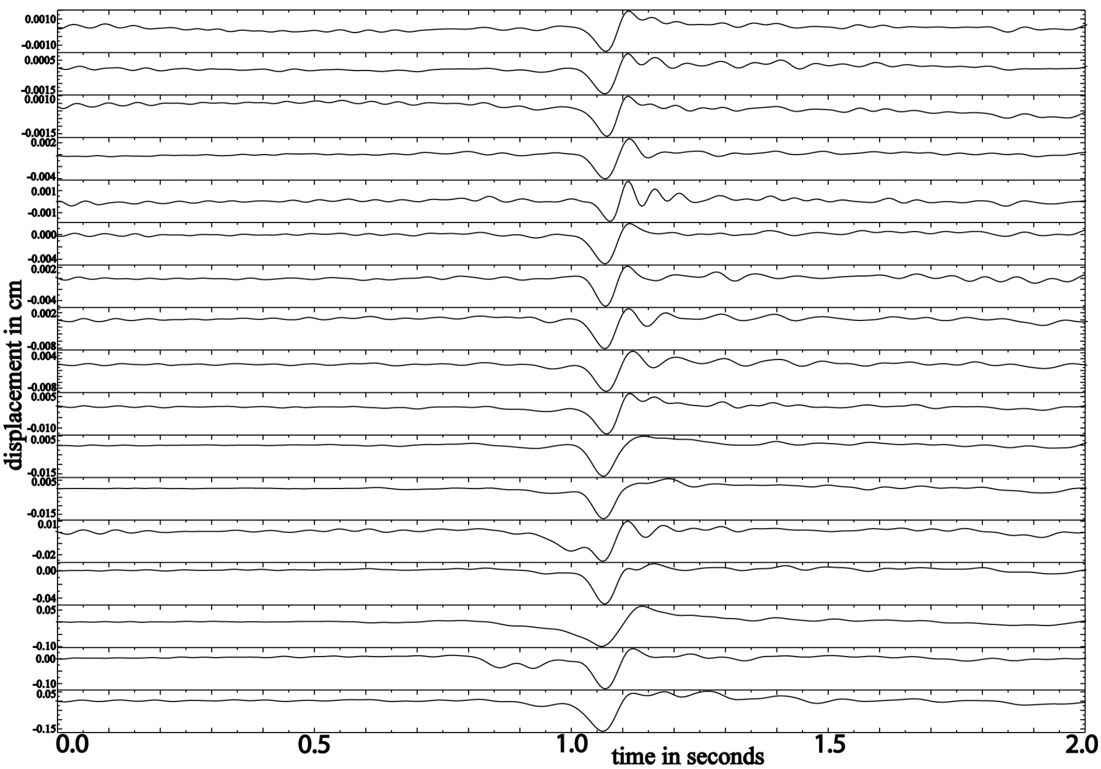


**Fig. 4** - Radial displacement component of Roswinkel events recorded in station ROS1. Acceleration has been converted to displacement. From top to bottom magnitude increases from $M_L = 1.1$ to 3.4.

$$\ln A_h = -2.501 + 0.623\, M_L - 1.0 \ln (R + 7.28) \tag{1}$$

where $A_h$ is the mean of the two horizontal components, PGA in units of g (1 g = 981 cm/s$^2$) and $R$ the epicentral distance. The standard deviation $\sigma$ in this relation is estimated at 0.506. The relation is based on 171 near-source accelerograms, mainly from events in California.

Campbell's (1997) attenuation relations, based on events in the (moment) magnitude range $4.7 \leq M_W \leq 8.0$ , consist of a basic equation and additions for e.g. different styles of faulting and local site conditions. For firm soil and strike-slip these additions are equal to zero and the relation becomes:

$$\ln A_h = -3.1512 + 0.904\, M_w - 1.328 \ln \sqrt{r^2 + (0.149 e^{0.647\, M_w})^2}, \tag{2}$$

where $A_h$ is the mean horizontal PGA in units of $g$ and $r$ the source-to-site distance. Source mechanisms determined in the southern part of the Netherlands are dominated by normal faulting, which is underrepresented in the Campbell (1997) relations. Normal faulting is also the main structural feature in the northern part of the country where induced seismicity dominates, although there are also indications for shallow-dipping thrust events. Campbell (1997) originally suggested using something between a strike-slip and thrust faulting for normal faulting. Later, in the first erratum (Campbell, 2000) the author recommends the use of the strike-slip description instead and this suggestion is followed here. In a recent update of these relations by Campbell and Bozorgnia (2003) the new basic relation is slightly modified:

$$\ln A_h = -2.896 + 0.812\, M_w - 1.328 \ln \sqrt{r^2 + (0.187 e^{0.616\, M_w})^2}. \tag{3}$$

In their paper, the authors also argue that normal faulting in extensional stress regimes have lower median predicted ground motion and can be modelled together with the strike-slip events. The standard deviation in the empirical relations is of considerable importance, especially if these relations are used in hazard estimates. These are explicitly mentioned in the aforementioned papers and are given as a function of the horizontal PGA (Campbell, 1997):

$$\text{for } A_h < 0.068\, g\text{: } \sigma = 0.55,$$

$$\text{for } 0.068\, g \leq A_h \leq 0.21\, g\text{: } \sigma = 0.173 - 0.140 \cdot \ln A_h,$$

$$\text{for } A_h > 0.21\, g\text{: } \sigma = 0.39.$$

Campbell and Bozorgnia (2003) give a similar relation with slightly adjusted parameter values.

From Ambraseys (1995), we selected a relation that includes the effect of focal depth and is based on data for a magnitude range of $2.0 \leq M_S \leq 7.3$ . The data set used consists of 1253 triaxial records:

$$\log A_h = -1.151 + 0.266\, M_S - 0.00022\, r - 1.024 \log (r), \tag{4}$$

where $A_h$ is the "recorded" horizontal PGA in units of g, not the geometric mean as used by Campbell (1989, 1997). The distance r is defined as hypocentral distance. The magnitude is $M_S$, which for low magnitudes, is systematically lower as compared to $M_L$. The standard deviation $\sigma = 0.27$ on the logarithmic unit, is comparable to the values used by Campbell (1989, 1997). When Eq. (4) is used for a fixed distance, investigating horizontal PGA as a function of magnitude, no "saturation" is built in for the higher magnitudes. This is one of the main differences between Eqs. (3) and (4).

Sabetta and Pugliese (1987) determined an attenuation relation based on Italian strong motion data:

$$\log A_h = -1.562 + 0.306\, M - \log \sqrt{R^2 + 5.8^2} + 0.169\, S. \tag{5}$$

As in Eq. (4), $A_h$ is the "recorded" horizontal PGA in units of $g$. $M = M_L$ for magnitudes less than 5.5, which is our range of interest. Distance $R$ is defined as the closest distance to the surface projection of the fault. The factor $S$ (either 1 or 0) takes the local site geology into account. In our application we are dealing with deep soil, which means that $S = 0$.

Magnitudes of induced events in the Netherlands have been calibrated using a network of boreholes in the region (Dost and Haak, 2002). The sensor at a depth of 200 m was used to simulate a Wood-Anderson instrument and an attenuation function was derived and magnitude determined by:

$$M_L = \log A_{wa} - \log A_0 = \log A_{wa} + 1.33 \log (r) + 0.00139\, r + 0.924, \tag{6}$$

where $A_{wa}$ is the maximum averaged horizontal (displacement) amplitude of a simulated Wood-Anderson instrument in mm and $r$ is the hypocentral distance. Due to an error in the sensitivity of the borehole sensor, the displacement values in Eq. (6) should be corrected by addition of a factor -0.50.

First, assuming a dominant frequency of 10 Hz for the S-pulse over the measured magnitude range, which has been observed for the induced events, a simple conversion from displacement to acceleration can be made and Eq. (6) can be re-written in the form:

$$\log A_h = -0.27 + M_L - 0.00139\, r - 1.33 \log (r). \tag{7}$$

In Eq. (7), the factor $A_h$ is given in mm/s$^2$ and the free surface effect has not yet been taken into account. Adding a factor 2, we can use this equation to compare the acceleration scaling with the local attenuation derived from a different type of network/instrument. A difference in dominant frequency should show up as a slope in the residues as a function of magnitude. If this is the case, we could look for a better fit.

In addition, we considered two empirical relations to scale the PGV and compared these relations to our data set. Campbell (1997) gives one based on the PGA equations:

$$\begin{aligned} \ln V_h = \ln A_h + 0.26 + 0.29\, M_w - 1.44 \ln [r + 0.0203 e^{0.958\, M_w}] + \\ 1.89 \ln [r + 0.361 e^{0.576\, M_w}] + (0.0001 - 0.000565\, M_w) r. \end{aligned} \tag{8}$$

Again, this equation is shown without the terms for type of fault and soil and is based on the PGA as defined in Eq. (2). Parameter $V_h$ is given in cm/s. Sabetta and Pugliese (1987) also give an equation for the attenuation of PGV:

$$\log V_h = -0.710 + 0.455\, M_L - \log\sqrt{(R^2 + 3.6^2)} + 0.133\, S, \tag{9}$$

where $V_h$ in cm/s and the other parameters as defined in Eq. (5).

Finally, similarly to Eq. (7), the relation for horizontal PGV for the northern part of the Netherlands becomes:

$$\log V_h = -2.07 + M_L - 0.00139\, r - 1.33 \log(r), \tag{10}$$

with $V_h$ in cm/s.

## 5. Results

Since the available horizontal PGA and PGV measurements sample only a few points in distance (Table 1), we concentrate on the magnitude scaling. In order to compare the different empirical relations with the measurements, the differences between observations and model values are normalised by dividing the residual by the standard deviation of the model (see Campbell, 1997).

Since 1995, induced events near Roswinkel (Fig. 2a) have been located using a borehole network in the northern part of the Netherlands (Fig. 1). As waveforms for the different events show a high waveform correlation, high precision, relative locations could be estimated. These locations were related to absolute locations estimated on the basis of accelerometer data for events that occurred since 1997. The depth of the events is assumed to be 2 km. A separate survey with a down-hole seismic tool, carried out by contractors for the Nederlandse Aardolie Maatschappij (NAM) revealed a set of micro events at reservoir level that coincided with the locations of the larger events within an epicentral distance of less than 0.1 km and confirmed the depth of 2 km (with an error of 0.2 km). Therefore, the location of the events is assumed to be known with an accuracy that allows a comparison with empirical scaling functions.

In the series of tectonic events near Voerendaal, 44 are recorded in the accelerometers deployed. Magnitude ranges from 1.1 to 3.9 at an hypocentral distance of approximately 4-6 km. Detailed locations are not yet available, but the locations for the larger events are fairly reliable (Fig. 2b). Therefore, we restrict the current data set to events of magnitude of 3.0 and larger in this study, resulting in a total of 6 triaxial recordings in two stations each.

In Fig. 5a, the measured PGAs are shown as a function of magnitude and compared to the Campbell (1997) relation [Eq. (2)], which gives a good overall fit to the data. For the Roswinkel events, recorded in stations ROS1 and ROS2, an average hypocentral distance of 2.5 km is assumed. ROS1 accelerations at the higher magnitudes ($M_L > 2.8$) fall within the predicted range, for the lower magnitudes, Eq. (2) gives an overestimate. Measured PGAs do not (yet)

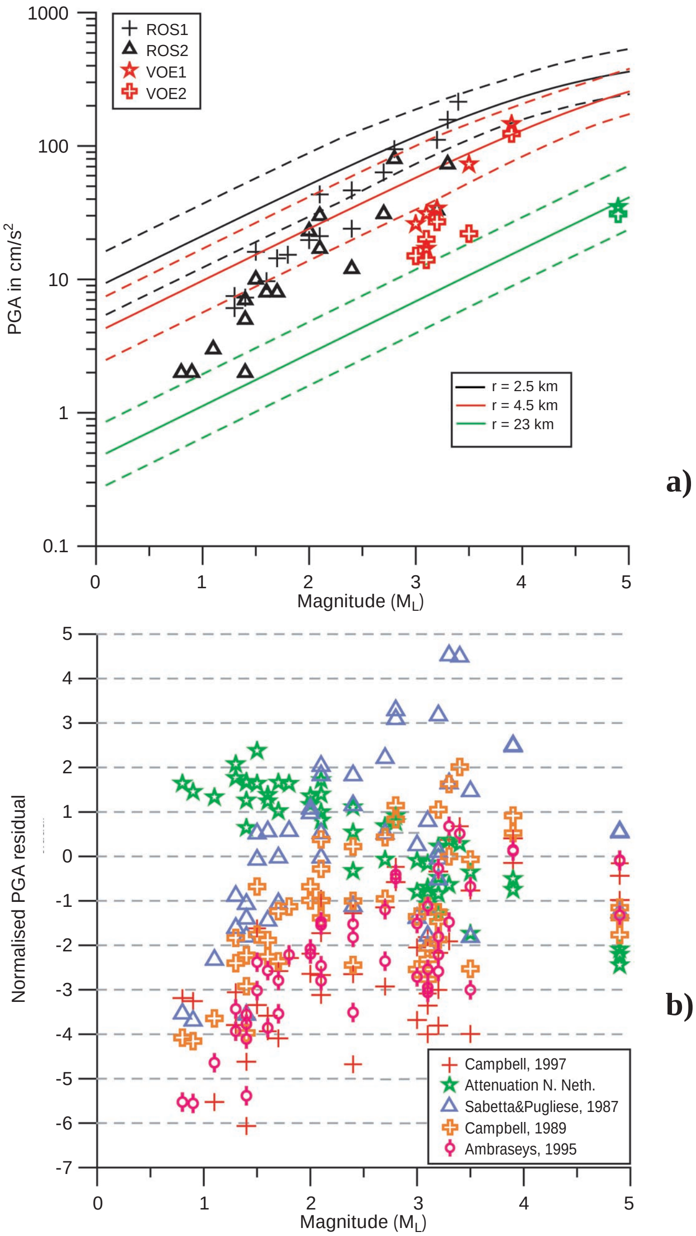


**Fig. 5** - Absolute (a) and normalised (b) scaling of PGA as a function of magnitude. Measurements are compared to a) Campbell (1997) and b) empirical relations mentioned in the text. In a) the solid line indicates the predicted mean value and the broken lines the mean + $\sigma$ and the mean – $\sigma$ predictions. The line colours refer to different source-to-site distances (see legend). In b) the y-axis indicates multiples of the standard deviations. ROS1 and ROS2 refer to accelerometer sites near Roswinkel (see text), VOE1 and VOE2 refer to accelerometer sites near Voerendaal (see text).

show saturation. ROS2 shows a systematic lower PGA as compared to ROS1, which may be due to site effects and the influence of the source mechanism. For tectonic events we note, similar to an induced-events situation, an overestimate of the lower magnitudes and a better fit for the larger magnitudes. However, the fit starts to improve at much higher magnitudes ($M_L > 3.4$).

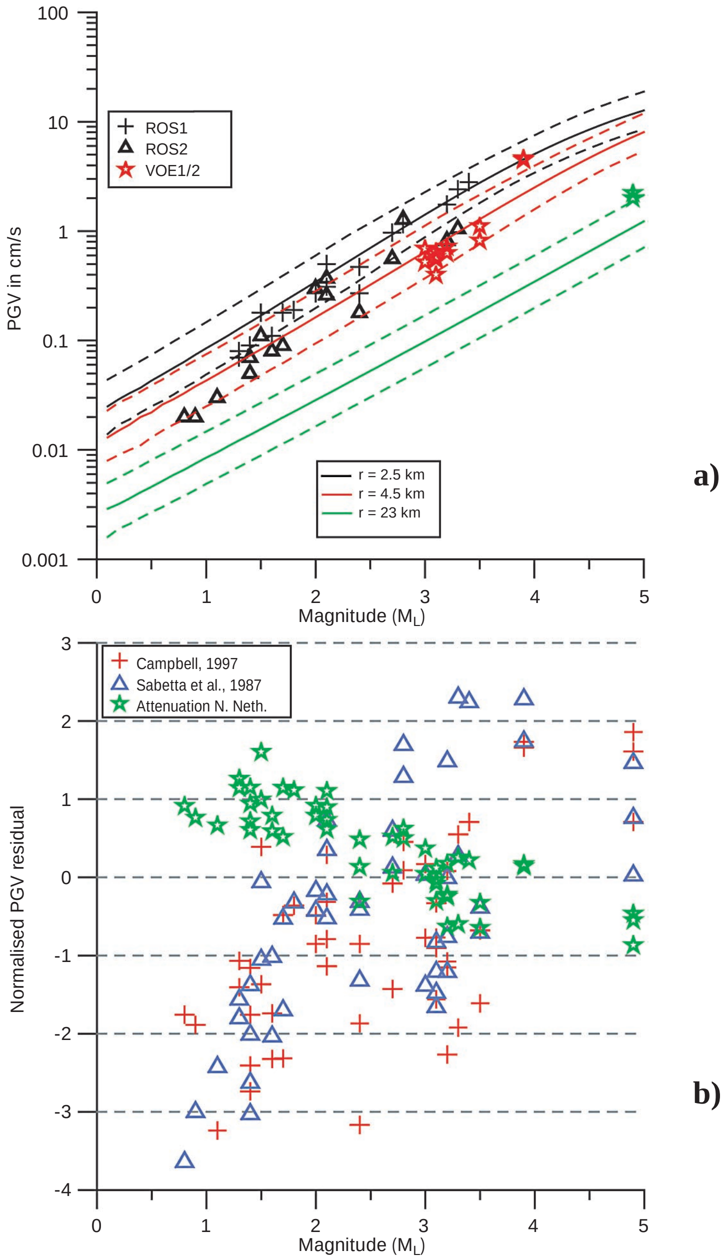


**Fig. 6** - Absolute (a) and normalised (b) scaling of PGV as a function of magnitude. Otherwise see description of Fig. 5.

In Fig. 5b, results of the normalised residual PGA is shown for all attenuation relations mentioned. All published relations, Eqs. (1)-(5), show an overestimate of the PGA for magnitudes less than 2.0. At higher magnitudes, the Sabetta and Pugliese (1987) relation shows a serious underestimate of the PGAs. The Campbell (1989) relation shows an improvement over the Campbell (1997) relation for the lower magnitudes, $M_L < 2.5$ , but not for the higher magnitudes and the relation of Ambraseys (1995) gives results comparable to Campbell's (1997). Since Ambraseys (1995) model is based on $M_S$ instead of $M_L$, the model by Campbell

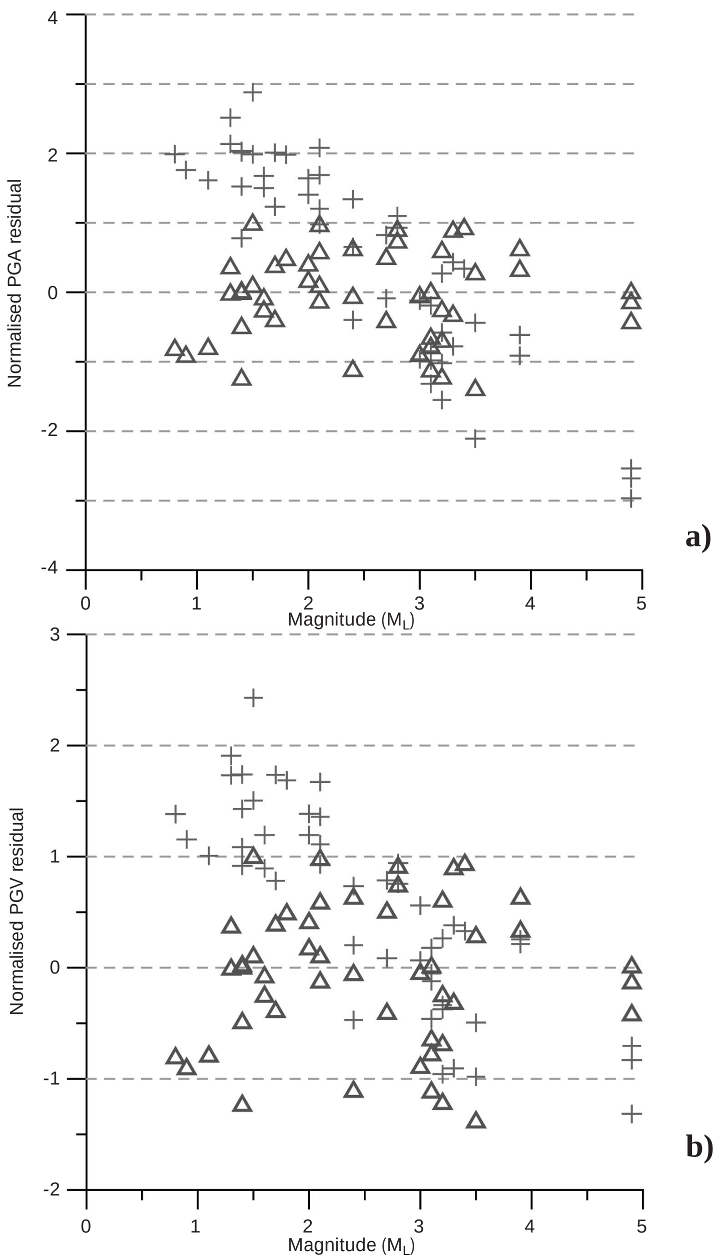


**Fig. 7** - Normalised scaling of PGA (a) and PGV (b) as a function of magnitude. Reference model is the model based on the attenuation function for the northern part of the Netherlands. The crosses represent the fit to the model before adjustment of the magnitude dependence [Eqs. (7) and (10)], the triangles after adjustment [Eqs. (11) and (12)].

(1997) is to be preferred. The updated relation by Campbell and Bozorgnia (2003) provides an even larger overestimate of the PGA compared to the Campbell (1997) relation and is, therefore, not pursued further. It should be noted that in Fig. 5 both induced and tectonic events are mixed, although events with local magnitudes smaller than 3.0 are all induced.

PGV measurements, obtained after integration of the original accelerometer data, are shown in Fig. 6a and residuals with respect to Eqs. (8) and (9) in Fig. 6b. The trend in the PGV values follows the empirical functions closely. Due to an increased standard deviation, peak velocities seem to fit better. However, one would expect an improved scaling for velocity due to the fact that source pulses in displacement are simple one-sided pulses, as also observed and discussed by Rovelli et al. (1991). Again, there is an indication for a systematic difference between the two stations ROS1 and ROS2.

Finally, we will discuss the results for the residual with respect to the attenuation relation based on the magnitude calibration for the northern part of the Netherlands [Eq. (7)], which gives a good fit with a maximum deviation of ± 1 $\sigma$, for $2.3 < M_L < 3.9$ (Fig. 7). At lower magnitudes the relation gives an underestimate, for higher magnitudes an overestimate. This is to be expected from the assumption of a dominant frequency of 10 Hz in the conversion from displacement to acceleration. In the comparison between the borehole amplitudes and the peak accelerations at the surface, we assume not only a factor 2 for the free surface effect, but also an additional factor 2 simulating an average site effect. Estimating the best fit by adapting the slope in the magnitude in Eq. (7) and adding a constant, gives the following equation:

$$\log A_h = -1.41 + 0.57\, M_L - 0.00139\, r - 1.33 \log(r), \qquad (11)$$

with $A_h$ in m/s$^2$. The fit to this equation, with an estimated $\sigma = 0.33$, is shown in Fig. 7a.

Similar to the PGAs, we could modify the attenuation relation for PGV based on the attenuation curves for the northern part of the Netherlands. This leads to the equation:

$$\log V_h = -1.53 + 0.74\, M_L - 0.00139\, r - 1.33 \log(r), \qquad (12)$$

with $V_h$ in m/s. The fit to this equation, with also an estimated $\sigma = 0.33$, is shown in Fig. 7b. Both Eqs. (11) and (12) show the best overall fit to the total data set and may be used in hazard studies in the region. However, these relations do not show a “flattening” of the PGA or PGV at the higher magnitudes, as is the case in Campbell’s (1997) model. The standard deviation in Eqs. (11) and (12) is rather high, 0.33, compared to a value of 0.27 in Eq. (4), but for a first estimate with a small data set it is acceptable.  Future accumulation of data is expected to lower the standard deviation.

## 6. Conclusion

The installation of an accelerometer network in the Netherlands at the end of 1996, coinciding with an increased activity of induced events and later followed by a swarm of shallow tectonic events gives the unique opportunity of studying scaling of PGAs in the region. Since the distance to the source was less than 5 km for most events, scaling could be studied mainly as a function of magnitude. For small magnitudes ($M_L < 3.0$), existing empirical relations overestimated the measured peak accelerations and peak velocities. For larger magnitudes ($3.0 < M_L < 5.0$) existing relations like Campbell’s (1997) do predict the measurements well. However, applying the attenuation function derived for the northern part of the Netherlands to calculate local magnitudes, and based on 200 m-deep borehole short period instruments, improves these existing relations. New attenuation relations for small magnitude events ($1 < M_L < 5$) could be derived for PGA and PGV in the Netherlands. Although the standard deviations of these relations are currently high, they will be used in the analysis of seismic hazard in the country and are expected to improve the accuracy of the present hazard estimates.

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