Ground motion parameters of the July 22, 2002 M_L 4.9 Alsdorf (Germany) earthquake

K.-G. Hinzen

Division of Earthquake Geology, University of Cologne, Bergisch Gladbach, Germany

(Received December 12, 2004; accepted April 1, 2005)

ABSTRACT Ground motion parameters from soft rock stations of the July 22, 2002 Alsdorf, Germany earthquake with local magnitude 4.9 at epicentral distances between ca. 15 and 54 km are analyzed. Peak ground accelerations (PGAs) exceed 20 cm/s^2. Empirical scaling relations given by Dost *et al*. (2004) describe a good upper bound to the observed PGAs of the horizontal components. The maximum acceleration response amplitudes of the geometric mean spectra are 0.213 m/s^2 at 8.0 Hz and 0.205 m/s^2 at 7.1 Hz for the vertical and horizontal component, respectively. At frequencies above 7 Hz, the mean response amplitudes of the vertical component are larger than those of the horizontal components. At 10 Hz the attenuation of the acceleration response is well described by the SEA99 model (Spudich *et al*., 1999; Pankow and Pechmann, 2004); however, at lower frequencies this model tends to overestimate the observations. While the Arias intensity shows a strong correlation with the PGA, strong motion durations do not show a clear systematic change with distance.

1. Introduction

Attenuation relations for both peak ground motions and response spectral amplitudes, play an essential role in probabilistic (PSHA) and deterministic (DSHA) seismic hazard analysis. Large uncertainties in ground motion amplitudes are introduced if empirical attenuation laws, based on data measured in other seismic regimes, are adopted for a certain area (Scherbaum *et al*., 2004). This causes problems for areas of low-to-moderate seismic activity, such as the intraplate seismicity in the European Cenozoic rift system, which includes the Lower Rhine Embayment (LRE). The number of strong ground motion records measured in Germany is still very limited. Design earthquakes for sites in German earthquake zones are mainly based on records from other regions, i.e. Friuli (Italy), California (Hosser, 1987), and model calculations. Recently installed strong motion stations (Brüstle *et al*., 1999) will help to build a new database for the study of ground motion attenuation.

The strongest event in the past 100 years, in the Northern Rhine Area (NRA), the Roermond earthquake of April 13, 1992 (M_L 6.0, Reamer and Hinzen, 2004; M_W 5.4, Camelbeeck *et al*., 1994) was not recorded unclipped at any distances closer than 40 km (Ahorner, 1993). The first earthquake to cause damage in the German part of the LRE since the Roermond earthquake occurred on July 22, 2002 at 5:45 UTC (M_L 4.9). The epicenter was close to the city of Alsdorf, ca. 14 km northeast of Aachen and 54 km east of Cologne (Fig. 1) with a depth of 15.8 km. It was felt in the LRE and in large parts of the surrounding areas of Germany, Belgium, the

© 2005 – OGS

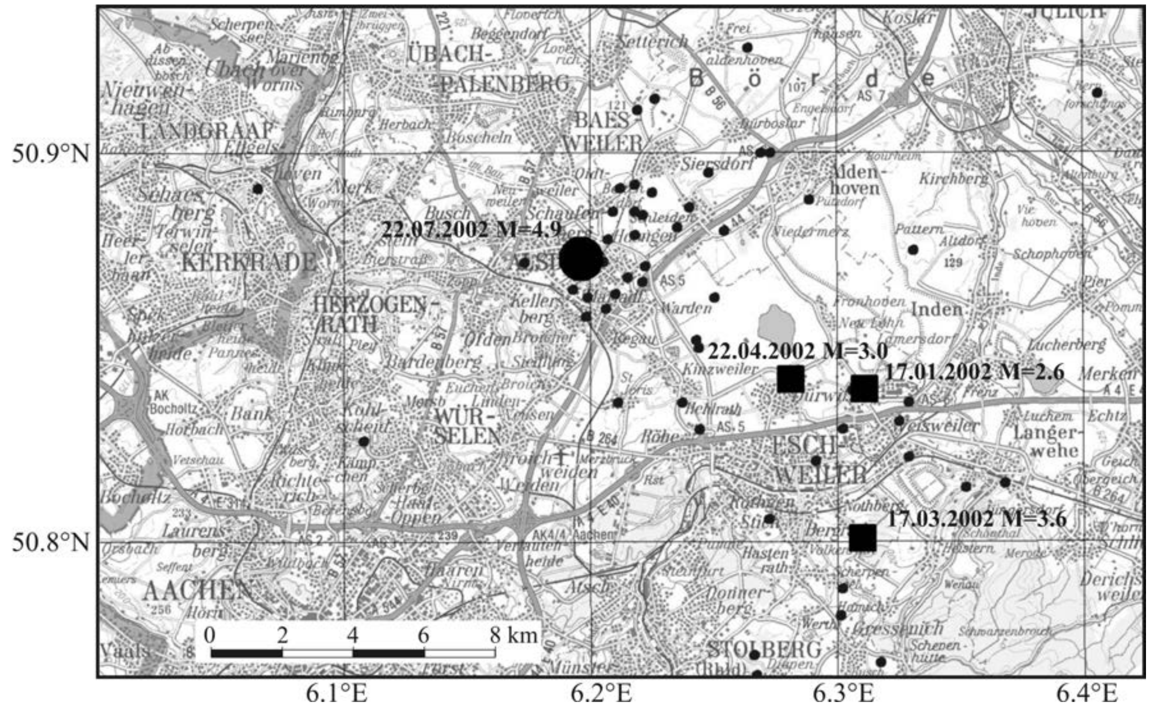

Fig. 1 - Map showing the epicenter of the July 22, 2002 Alsdorf earthquake in the Roer Valley Graben (large circle) and the location of smaller events recorded in 2002. The squares show earthquakes with magnitudes above 2.5, which were felt while the circles indicate the locations of smaller, mostly unfelt events.

Netherlands, Luxembourg and France. It caused some damage in the mesoseismal zone of degree VI (MSK). A macroseismic map is shown in Fig. 2.

Only a few months before the Alsdorf earthquake, 11 stations in the Rhenish brown coal mining district had been upgraded to digital recording with 24 Bit AD converters or had been newly installed (Fig. 3). A short period station ROD had been set up 6 days before the Alsdorf earthquake at an epicentral distance of 29 km. In this paper, data from recordings on soft rock at epicentral distances between 14.5 and 54 km are presented. These records will be addressed in the following as “semi”-strong ground motions. The term strong ground motions has different definitions; i.e., Cramer (1996) used it for “motion of sufficient strength to affect people and their environment”. The United States Geological Survey (USGS, 2004) defines it as “ground motion of sufficient amplitude and duration to be potentially damaging to a building or other structure”. As the stations are in an area of intensity V with no clear damage reported, according to the latter definition, we adopt the term “semi”. The data set is complemented by records from hard rock stations with epicentral distance of up to 176 km. The classification into hard and soft rock stations follows the German building code DIN4149 (2005). Ground motion parameters, peak ground motion velocity (PGV), peak ground motion acceleration (PGA), Arias intensity (I_A), and duration of the strong ground movement are determined, and the decrease of these parameters with distance is discussed. Response spectra are calculated for 13 soft rock sites between a 21 and 35 km epicentral distance, shape and amplitude are compared with published attenuation models and the German building code.

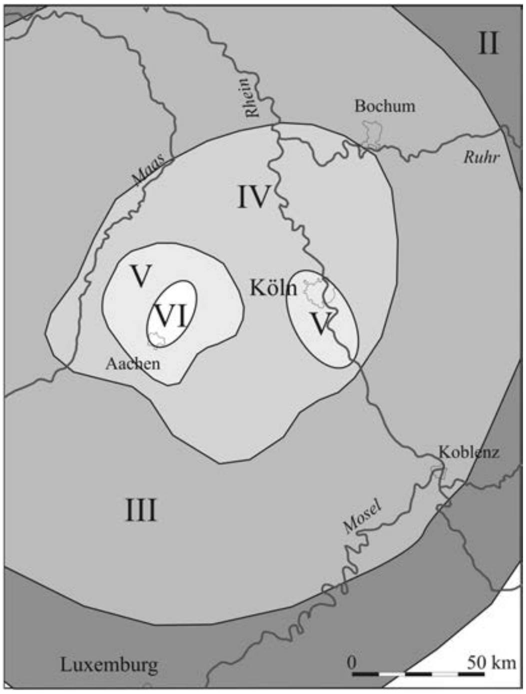

Fig. 2 - Macroseismic map of the July 22, 2002 Alsdorf earthquake (after Hinzen and Weber, 2004).

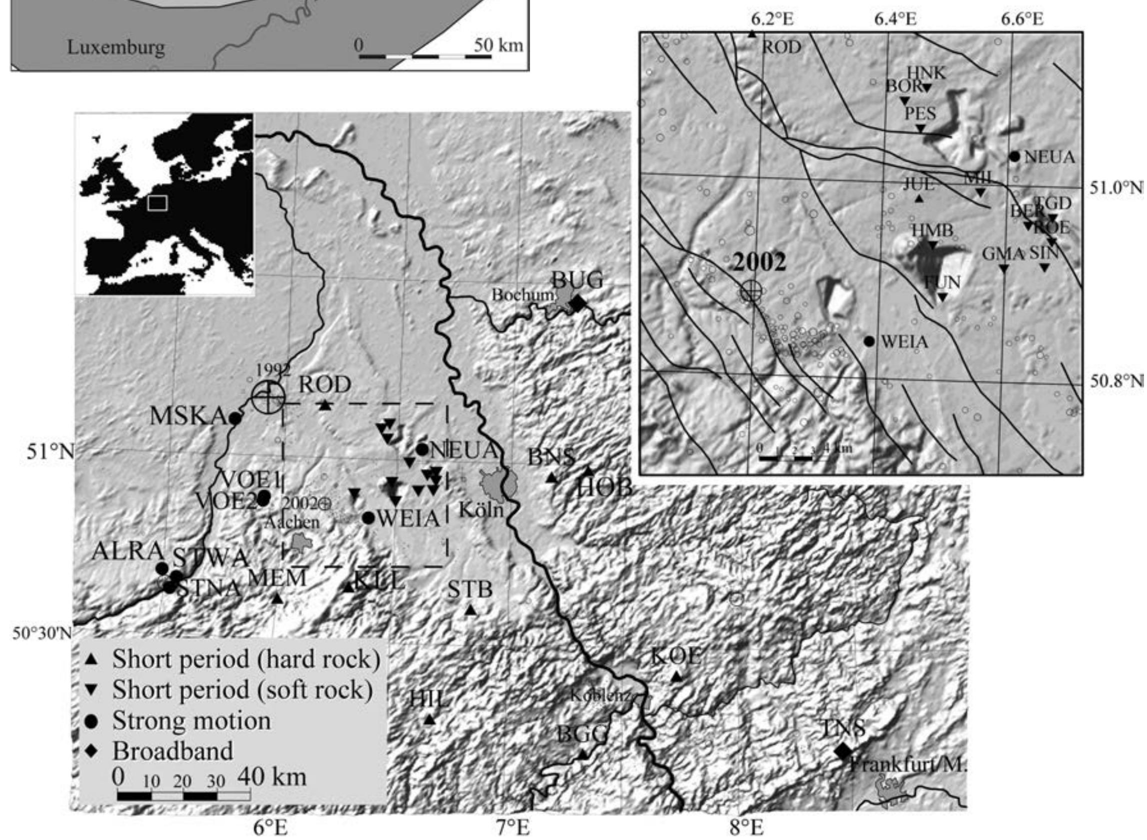

Fig. 3 - Location of stations in the northern Rhine area, which were used in this study (Table 1). The white rectangle in the upper left inset shows the location of the main map. The circles give locations of instrumentally recorded earthquakes between 1975 and 2002 (Reamer and Hinzen, 2004). The crossed circles indicate the epicenters of the 2002 Alsdorf and 1992 Roermond earthquakes. The inset in the upper right zooms into the dashed rectangle in the main map and shows the stations on soft rock in the LRE. Lines here show the surface traces of Quaternary faults. The gray-shaded terrain map is based on SRTM data, NASA.

2. Database

Fig. 1, shows the epicenters of earthquakes recorded by the Bensberg seismic network (BENS) in 2002 in the surrounding area of Alsdorf (details of the network and equipment can be found under www.erdbebenstation.de). In early 2002, a raised microseismic activity was observed in the Weisweiler area, ca. 8 km southeast of the epicenter of the Alsdorf earthquake. From January to April 2002, three earthquakes with local magnitudes above 2.5 were observed. Later in 2002, the activity shifted north and culminated in the M_L 4.9 event on July 22, 2002 (Fig. 3).

Digital seismograms from 14 stations of the BENS network located on soft rock, in a distance range from 14.5 to 35.1 km, are used (Fig. 3). A seismogram example, from one of the closest stations (HMB) at a 21.2 km distance, is shown in Fig. 4. Maximum accelerations from 4 strong motion stations in Belgium, operated by ORB (Royal Belgian Observatory) at distances of up to 54.4 km and published acceleration data (Dost *et al.*, 2004) of two stations in the Netherlands operated by KNMI (Royal Dutch Meteorological Institute) at a distance of ca. 18 km have been included. In addition to these soft rock stations, data from hard rock stations of the BENS and GRSN (German Regional Seismic Network) networks are used to extend the distance range to 176 km. Table 1, shows the type of instruments, distances and station codes for all stations used in this study.

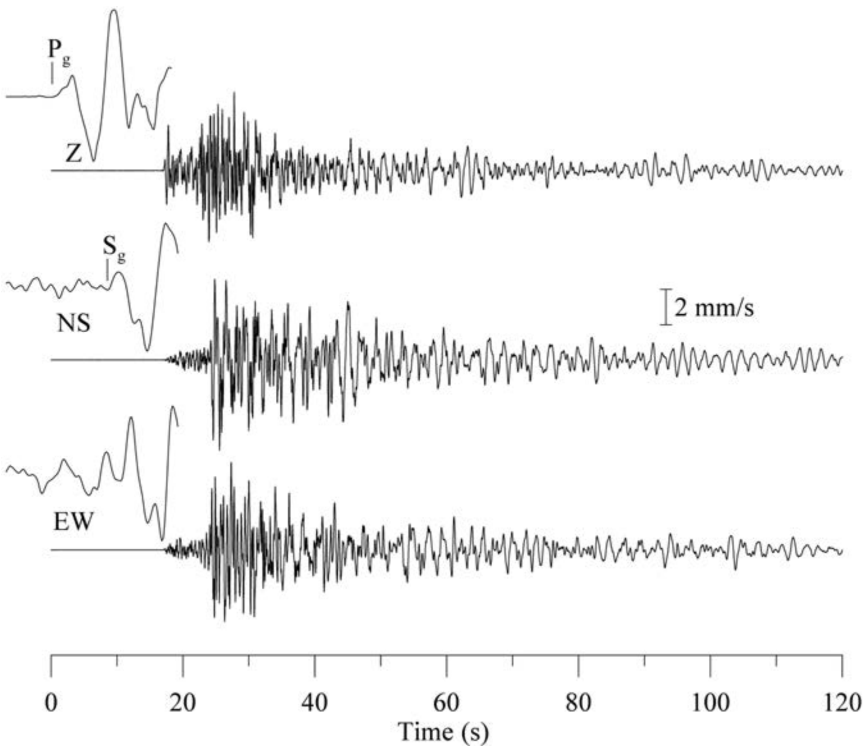

Fig. 4 - Seismogram example recorded at station HMB at an epicentral distance of 21.2 km. From top to bottom the traces show the ground velocity of the vertical (Z), north-south (NS), and east-west (EW) component, respectively. Start time of the plot is 05:45:00.0 (UTC). The insets at the beginning of the traces show an enlargement of the arrival of the direct P-wave (Pg) and the direct S-wave (Sg) in time windows of 10 seconds on the vertical and horizontal components, respectively. The bar indicates the amplitude scale for the main seismograms.

Table 1 - Station list, measured PGA, PGV, I_A and strong motion duration. Sample rates of short period (SP) stations with geophones of 1.0-1.25 Hz eigenfrequency, strong motion stations (SM) with accelerometers, and broad-band stations (BB) with STS2 Seismometers was 125 Hz, 200 Hz, and 80 Hz, respectively. BENS network, Cologne University; stations BUG and TNS are part of the GRSN, German Regional Seismic Network; KNMI, Royal Dutch Metheorological Institute; ORB, Roayl Belgium Observatory.

Station code	Distance	PGA			PGV			I_A			$T_{5\%-95\%}$		
	R	Z	N	E	Z	N	E	Z	N	E	Z	N	E
	km	cm/s^2	cm/s^2	cm/s^2	mm/s	mm/s	mm/s	m/s	m/s	m/s	s	s	s
WEIA	14.5	26.50	18.80	21.10	5.91	8.73	20.04	5.18E-02	3.74E-02	4.71E-02	16.8	28.9	27.7
VOE1	18.5		52.00	23.00		34.40	15.50						
VOE2	18.7		33.00	28.00		24.00	16.70						
HMB	21.2	19.90	15.44	19.02	5.24	6.20	4.51	3.47E-02	2.86E-02	3.14E-02	13.2	17.0	16.1
FUN	21.7	15.45	21.10	20.41	3.27	10.36	5.09	1.62E-02	2.64E-02	2.01E-02	12.7	10.4	10.1
PES	26.5	7.80	6.58	6.21	3.37	4.20	3.85	1.02E-02	8.97E-03	7.56E-03	21.6	34.1	39.1
BOR	27.6	16.11	7.41	6.79	4.02	5.63	4.70	1.47E-02	9.90E-03	1.02E-02	20.4	32.6	33.5
MIL	28.2	8.11	15.51	11.93	2.03	4.13	3.17	1.09E-02	2.50E-02	1.92E-02	19.8	14.4	19.0
GMA	28.7	6.64	8.56	6.98	2.62	4.41	3.06	4.79E-03	6.28E-03	5.01E-03	22.8	21.5	25.0
ROD	28.9	10.76	15.83	18.64	3.46	10.71	10.75	1.59E-02	2.37E-02	2.32E-02	22.6	19.6	22.9
HNK	30.3	4.21	9.01	**	2.00	4.40	**	3.13E-03	1.10E-02	**	28.4	30.4	**
BER	32.2	4.04	4.34	7.25	2.37	2.89	3.51	4.38E-03	4.15E-03	6.55E-03	22.7	34.8	30.1
SIN	33.3	4.90	3.70	5.18	1.72	1.86	2.23	3.94E-03	3.61E-03	5.31E-03	25.1	31.6	26.4
NEUA	34.1	11.00	21.00	12.60	***	***	***	***	***	***	***	***	***
ROE	34.4	5.92	4.12	5.09	1.99	2.37	2.60	4.68E-03	3.52E-03	3.88E-03	22.2	32.4	31.6
TGD	35.1	8.31	7.56	9.19	3.06	3.30	3.78	8.50E-03	1.05E-02	1.45E-02	21.7	28.9	25.2
MSKA	36.7	3.90	5.80	6.40	***	***	***	***	***	***	***	***	***
STWA	50.9	3.70	8.40	10.00	***	***	***	***	***	***	***	***	***
ALRA	53.8	3.70	8.50	11.30	***	***	***	***	***	***	***	***	***
STNA	54.4	4.30	7.40	6.20	***	***	***	***	***	***	***	***	***
MEM	32.0	1.37	1.27	1.45	0.98	1.02	0.67	2.67E-04	2.47E-04	2.04E-04	20.50	22.80	21.50
STB	55.9	0.98	2.11	2.06	0.18	0.38	0.37	1.48E-04	3.52E-04	4.32E-04	23.1	18.5	15.9
HIL	74.4	0.62	0.61	0.99	0.20	0.39	0.39	6.97E-05	9.36E-05	1.01E-04	30.0	23.7	25.0
HOB	80.9	1.30	*	*	0.50	*	*	2.76E-04	*	*	23.0	*	*
BUG	97.4	2.34	2.18	2.38	0.89	1.17	1.57	2.45E-04	3.66E-04	4.04E-04	17.1	16.5	8.0
BGG	111.0	0.84	1.71	2.83	0.35	0.53	0.64	5.43E-05	2.54E-04	5.97E-04	27.0	17.9	10.9
KOE	120.0	0.39	0.48	0.48	0.16	0.14	0.14	2.12E-05	2.95E-05	2.94E-05	31.7	18.1	18.0
TNS	176.0	0.16	0.25	0.31	0.09	0.15	0.14	7.23E-06	1.35E-05	1.57E-05	47.8	40.6	33.5

* trace clipped
** electric noise
*** record incomplete

Station operated by:
1) Cologne University
2) Dost et al. (2004) (componentes are radial and transverse)
3) Royal Observatory Belgium
4) Ruhr-University Bochum
5) University Frankfurt

3. PGA, PGV and I_A

Initially, seismograms from all stations were band-limited to 0.1–50 Hz, with the exception of those with sampling rates less than 100 Hz as indicated in Table 1. Within these pass-bands, the instrument response was returned, and ground velocity and ground acceleration seismograms were calculated for the short period and broadband stations, and the strong motion stations, respectively. The velocity seismograms were differentiated, in a second step, to get ground acceleration data and the accelerograms were integrated to calculate ground motion velocity. From these seismograms PGVs and PGAs were determined for each component (vertical, north-south and east-west). Processing of the waveform data was made with the SEISAN software package (Havskov and Ottemøller, 1999), Degtra A4 by Mario Ordaz, Institute of Engineering, UNAM, and routes of BENS network.

The decay of the PGAs with epicentral distance, *R*, is shown in Fig. 5. Observations at distances of up to 50 km are mostly from soft rock stations (open symbols) and solely on hard

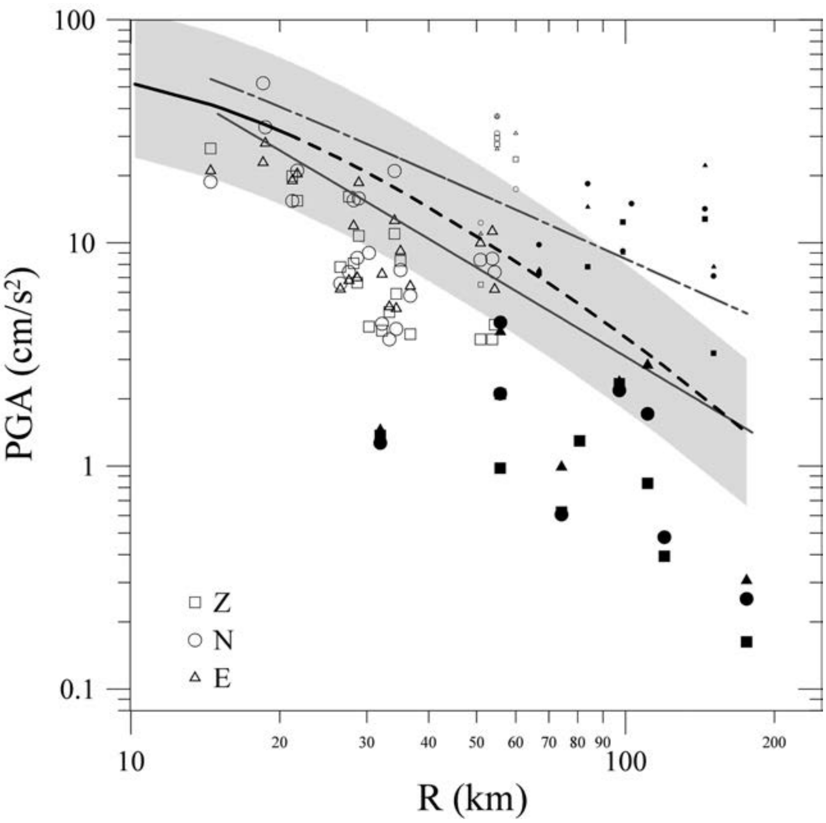

Fig. 5 - PGA of the vertical and horizontal components of records from the July 22, 2002 Alsdorf earthquake. Open and closed symbols indicate soft-rock and hard-rock sites, respectively. The small black symbols show measured PGAs from the 1992 M_L 6.0 (Reamer and Hinzen, 2004) Roermond earthquake (Ahorner, 1993). The heavy continuous line shows an empirical relation from Dost *et al*. (2004) derived for the Netherlands, the dashed line extrapolates the relation to larger distances. The gray band indicates ± 1 standard deviation of this relation. The continuous and broken gray lines give the values from the empirical relations of Campbell (1989) and Sabetta and Pugliese (1987), respectively.

rock at distances beyond 50 km. The amplitudes scatter in a band, which varies by ca. a factor of 6 from the lowest to the highest values. The average ratio between the vertical PGA and the maximum of the two horizontal PGAs is 0.76±0.40. At 6 out of 26 stations the vertical PGA is even larger than the larger of the two horizontal PGA components. Dost *et al*. (2004) recently determined an empirical scaling law for the Netherlands based on acceleration data recorded at distances of around 2-4 km and 23 km from induced and natural events with stations on stiff soil for $1 < M_L < 5$. The relation gives amplitudes of the mean of the two horizontal peak accelerations A_h in m/s^2, depending on hypocentral distance, r:

$$\log(A_n) = -1.41 + 0.57M_L - 0.00139r - 1.33\log(r). \quad (1)$$

The dashed line in Fig. 5 extrapolates this scaling relation for M_L 4.9 to the distance range of our observations. For the soft rock stations, at distances of up to 50 km, this scaling relation provides a very good upper bound for the horizontal ground movements. As expected, this scaling

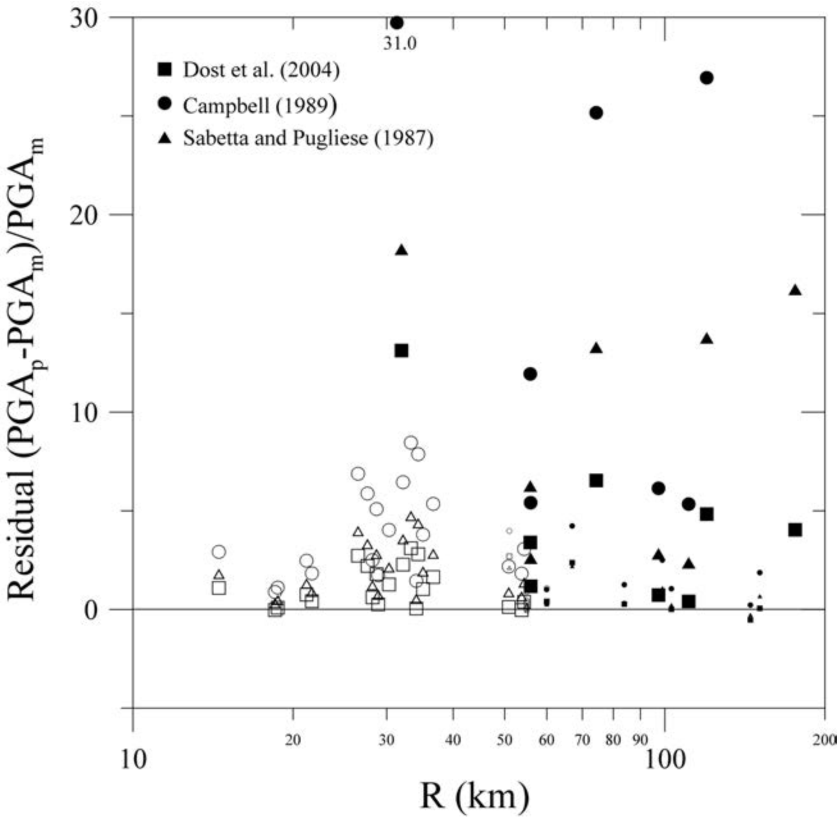

Fig. 6 - Normalized residuals of measured and predicted values for the PGA. The measured values are the mean of the two horizontal components from Table 1. The predictions calculated with three empirical relations (see legend) assuming M_L 4.9. Open and closed symbols indicate soft-and hard-rock sites, respectively. The small black symbols show residuals of PGAs from the 1992 M_L 6.0 Roermond earthquake calculated from values given by Ahorner (1993).

law overestimates the peak acceleration at the hard rock sites. For comparison, data from the 1992 Roermond earthquake (Ahorner, 1993), which was one order of magnitude stronger than the Alsdorf earthquake, are shown in Fig. 5.

In Fig. 6, the measured PGAs are compared to predictions from three empirical scaling relations, Dost *et al*. (2004), Campbell (1989):

$$\ln(A_n) = -2.501 + 0.623M_L - 1.0\ln(R + 7.28) \tag{2}$$

and Sabetta and Pugliese (1987):

$$\log(A_n) = -1.562 + 0.306M - \log\sqrt{R^2 + 5.8^2} + 0.169S. \tag{3}$$

Eqs. (2) and (3) give the ground motion in units of g (1g = 981 cm/s^2) and in Eq. (3) the factor S = 0 for deep soil and $M = M_L$ for magnitudes less than 5.5. The plot shows the normalized residuals of the predicted PGA_p and the measured values PGA_m. All three relations, predict systematically higher PGAs than observed. The best approximation is with the scaling relation from Dost *et al*. (2004). Here, the average, normalized residual for soft rock measurements is 1.1±1.0. The average normalized residuals for the Sabetta and Pugliese (1987) and for the Campbell (1989) relations are 1.9±1.4 and 3.8±2.3, respectively. For the few data points from the stronger (M_L=6) Roermond earthquake (small black symbols), the residuals are smaller, even if the hard rock values are taken into consideration. The average residuals for the Dost *et al*. (2004), Sabetta and Pugliese (1987) and for the Campbell (1989) relations are 0.6±1.0, 0.6±0.8, and 1.7±1.3, respectively. The maximum of the two horizontal PGAs in the Alsdorf data set, is on average 10% larger than the average of the two values, which is close to the 12% observed by Sabetta and Pugliese (1987).

Similarly to Eq. (1), Dost *et al*. (2004) calibrated the attenuation of PGVs for the Netherlands:

$$\log(V_h) = -1.53 + 0.74M_L - 0.00139r - 1.33\log(r) \tag{4}$$

where V_h, the mean of the two horizontal peak velocities, is measured in cm/s. The PGVs, as shown in Fig. 7, are overestimated by the relation from Dost *et al*. (2004) for most stations, 21 out of 29 PGVs of horizontal components are below the -1 sigma range of that relation.

In addition to the peak values from accelerations and velocities, the I_A and the duration of strong ground movements were calculated. The latter were measured between the times when 5% and 95% of the total trace energy arrived ($T_{5\%-95\%}$). These quantities are listed in Table 1, and I_A is plotted versus the epicentral distance, R, in Fig. 8. Campbell and Duke (1974) determined an empirical relation between I_A and the distance for earthquakes from California, mainly based on records of the 1971 San Fernando earthquake (Cramer, 1996):

$$I_A = 313 \cdot e^{M_S(0.33M_S - 1.47)} r^{-3.79} S \tag{5}$$

where I_A is measured in m/s, r is the distance from the center of the energy release for which the hypocentral distance was used. Factor S depends on the subsoil. The dashed and dash-dotted lines in Fig. 8 show the predictions for soft-rock ($S=0.65r^{0.74}$) and hard-rock ($S=0.57r^{0.46}$) sites

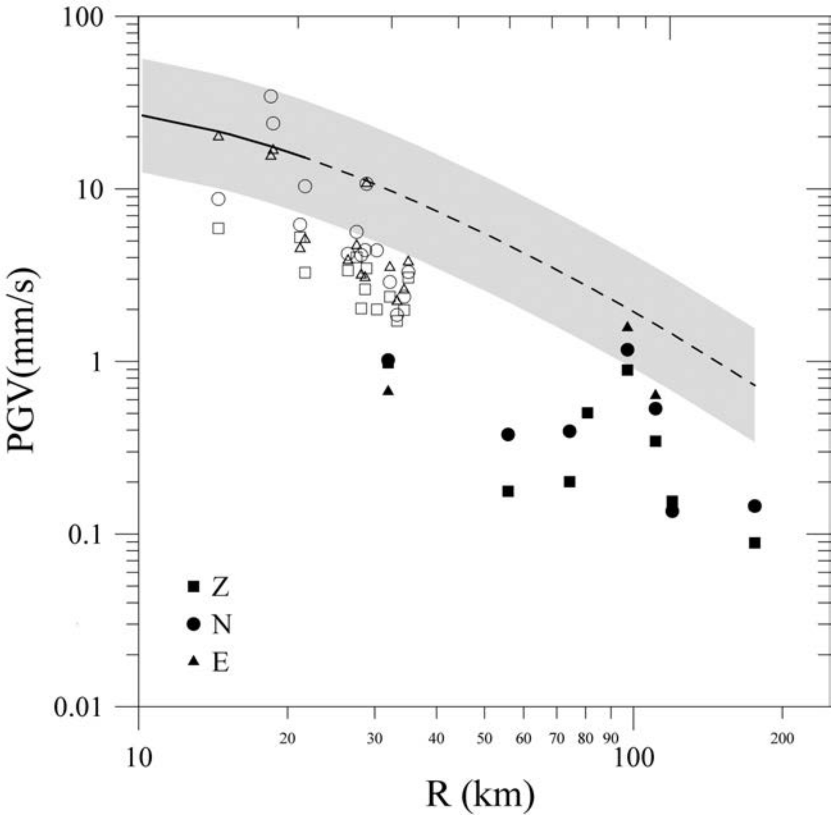

Fig. 7 - PGV of the vertical and horizontal components of records from the July 22, 2002 Alsdorf earthquake at epicentral distances from 14.5 to 176 km. Open and closed symbols indicate soft-rock and hard-rock sites, respectively. The waveforms were band limited to 0.1-50 Hz. The line shows an empirical relation from Dost *et al*. (2004) derived for the Netherlands, the dashed line extrapolates the relation to larger distances. The gray band indicates ± 1 standard deviation of this relation.

assuming that the surface wave magnitude is equal to the local magnitude. In both cases, the empirical relations are a fair representation for the observed data. However, if the lower moment magnitude is used in Eq. (5), the empirical relation underestimates the observed values. The diagram in Fig. 9 indicates a strong correlation between the PGAs and the I_As. Least squares fits calculated separately for soft- and hard-rock sites show coefficients of determination of 0.88 and 0.89, respectively. Parameters of the fits are given in Fig. 9.

The durations of the strong ground motions, $T_{5\%\text{-}95\%}$, are mostly between 10 and 40 s. A clear correlation with distance is not observed, for either soft- or for hard-rock sites (Fig. 10). This also applies to the $T_{5\%\text{-}95\%}$ detracted by the S-P travel time, that are also shown in Fig. 10. For comparison, a duration model calibrated for the northern Rhine area, on the basis of 257 seismograms of earthquakes with magnitudes between 2.9 and 4.4 (Hinzen, 2004), is shown. This model gives a fair estimate of the duration at hard-rock sites, at distances of over 50 km. However, the reverberation of the soft rock extends the duration by a factor 2 to 3 compared to the model.

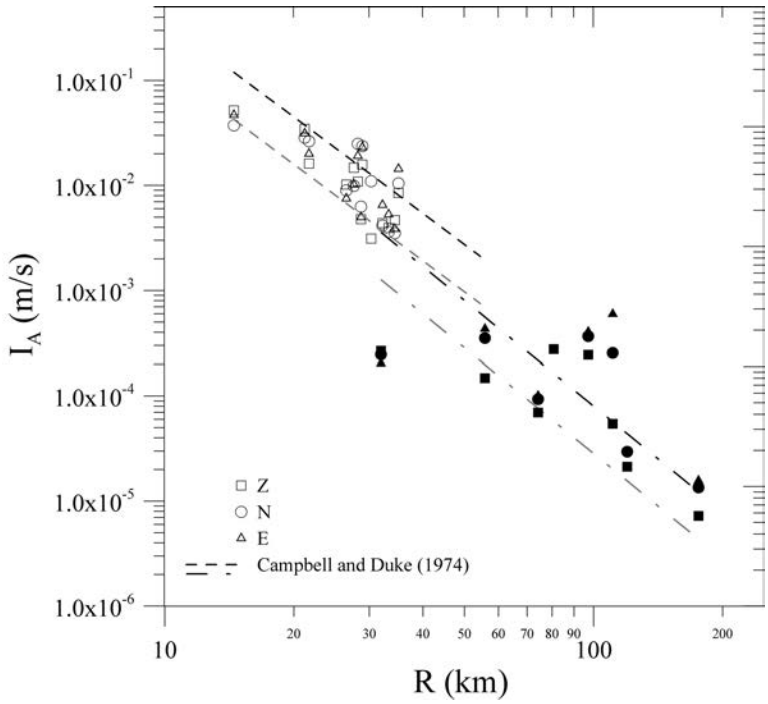

Fig. 8 - I_A from records of the July 22, 2002 Alsdorf earthquake plotted versus epicentral distance. Open and closed symbols indicate soft-rock and hard-rock sites, respectively. The dashed and dash-dotted lines show values from an empirical relation (Campbell and Duke, 1974) for soft- and hard-rock, respectively. The black and gray lines show the predicted values for the local and moment magnitude of 4.9 and 4.3, respectively.

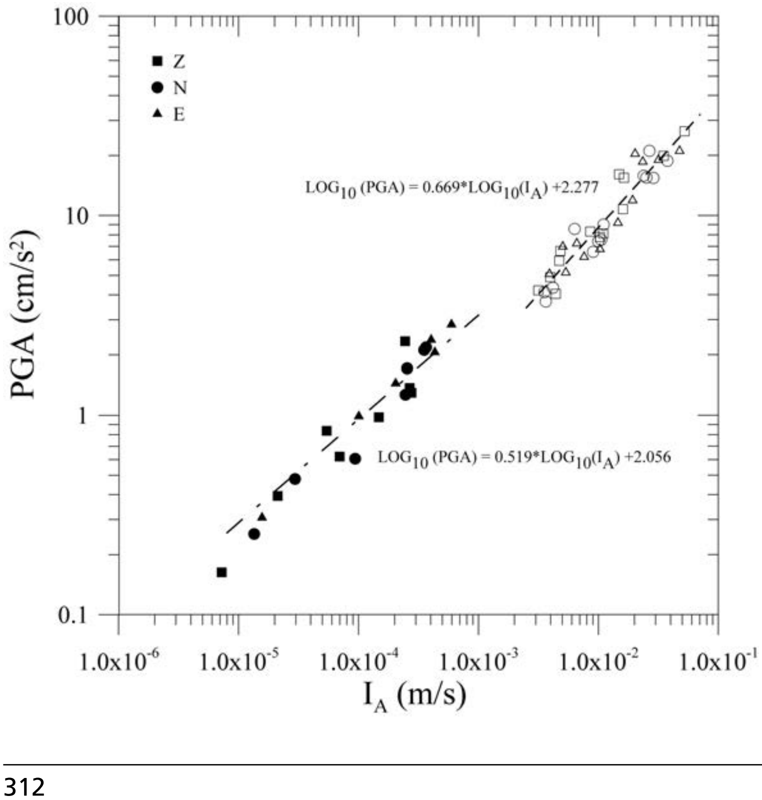

Fig. 9 - PGA plotted versus I_A. Open and closed symbols indicate soft-rock and hard-rock stations, respectively. The dashed and dash-dotted lines are least squares fits to the soft- and hard-rock measurements, respectively.
Coefficients of determination are 0.899 and 0.883, respectively.

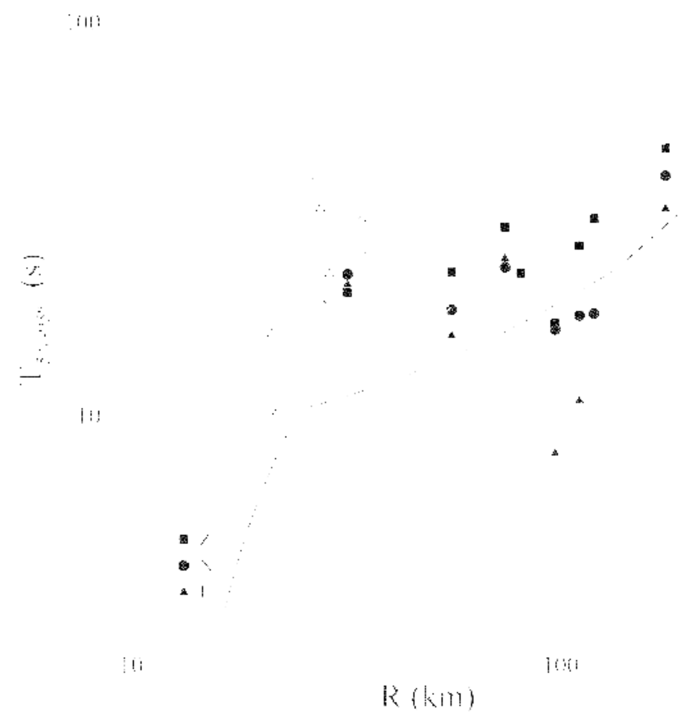

Fig. 10 - Duration of the strong ground motion in relation to the epicentral distance. Open and closed symbols indicate soft- and hard-rock sites, respectively. The dash-dotted line shows a duration model calibrated for the northern Rhine area (Hinzen, 2004).
The smaller gray symbols show the $T_{5\%-95\%}$ detracted by the S-P times.

4. Response spectra

Elastic acceleration response spectra were calculated from the records of the stations in the distance range from 21.2 to 35.1 km (Fig. 3), that have uniform sensors and data acquisition (Table 1). The spectra were determined for 5% of the critical damping and 400 discrete frequency values in the frequency range between 0.167 Hz and 50 Hz. A total of 13 response spectra for the vertical component and 25 response spectra for the horizontal component are shown in Fig. 11. Maximum response amplitudes attain values of almost 1 m/s^2 for some horizontal components. The geometric mean of these vertical and horizontal response spectra with the corresponding ± 1 mean absolute deviation (MAD) range is shown in Fig. 12. Below a corner frequency of ca. 3 Hz, both the response spectra for the vertical and horizontal components show a low frequency falloff roughly proportional to f^2. The plateau above frequencies of 3 Hz shows almost equal amplitudes for both components. The maximum mean acceleration response amplitudes are 0.213 m/s^2 at 8.0 Hz and 0.205 m/s^2 at 7.1 Hz for the vertical and horizontal component, respectively. In addition, the geometric mean of the same response spectra was calculated after the spectra had all been corrected to the median distance of 28.8 km assuming a $1/r$ geometrical spreading (dashed lines). The mean of the distance-scaled spectra follows the non-scaled mean very closely for both the vertical and horizontal component. This would not be the case if there were strong attenuation in this distance range.

The thin lines in Fig. 12, show the shape of the response spectra from the proposed new German building standard DIN4149 (2005). The code spectra represent a site on soft soil in a sedimentary basin. The norm spectra are scaled at 50 Hz to the amplitudes of the mean observed response accelerations. For both components the scaled standard spectra underestimate the

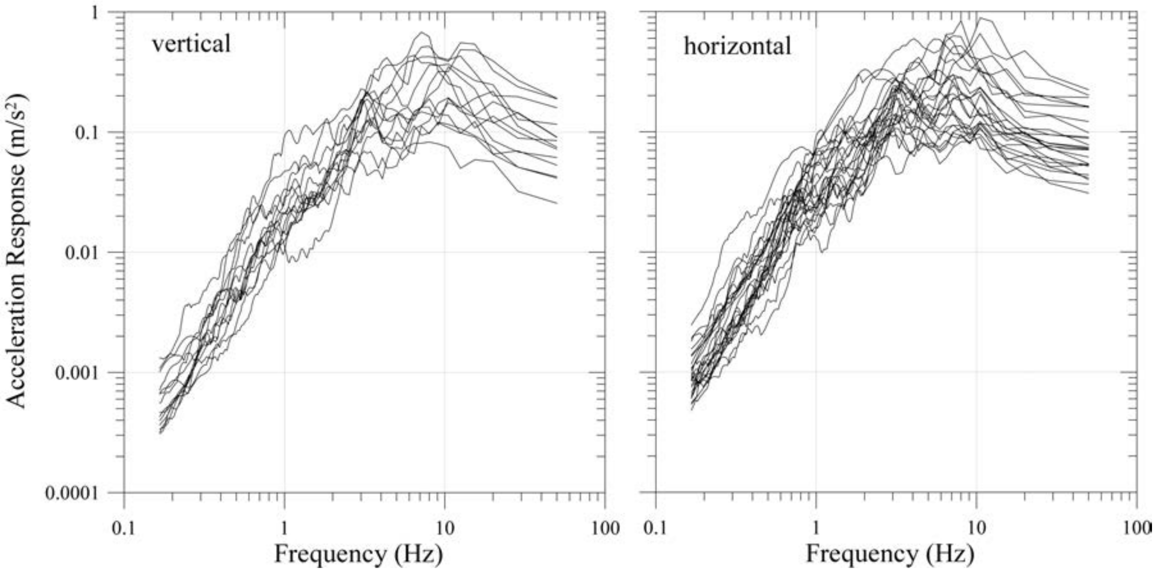

Fig. 11 - Elastic acceleration response spectra for 5% of the critical damping of 13 vertical (left) and 25 horizontal (right) ground motions recorded at soft-rock sites during the July 22, 2002. Alsdorf earthquake.

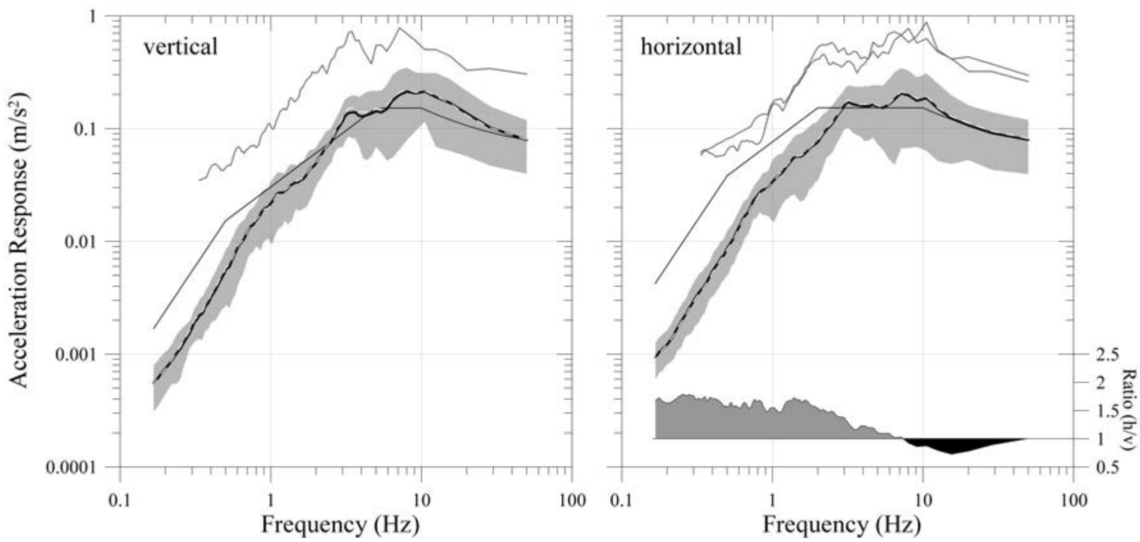

Fig. 12 - The heavy lines show the geometric mean of response spectra for 5% of the critical damping of 13 vertical (left) and 25 horizontal (right) component ground motions measured during the July 22, 2002. Alsdorf earthquake. Stations were located at epicentral distances between 21.2 and 35.1 km. The shaded area of the main plots indicates the ± one mean absolute deviation range. White dashed lines are the geometric means of the spectra after a distance correction to the median of the covered distance range of 28.9 km, assuming a $1/r$ geometrical spreading was applied. The thin straight lines are the scaled response spectra from the new German building code DIN4149 (2005) for soft-soil site in a sedimentary basin. These spectra are scaled at 50 Hz to the acceleration response of the mean measured spectra. The thick gray lines are response spectra from the 1992 M_L 6 Roermond earthquake at a 55 km distance, measured on soft rock. At the bottom of the right plot, the ratio between the observed horizontal and vertical mean acceleration response is shown.

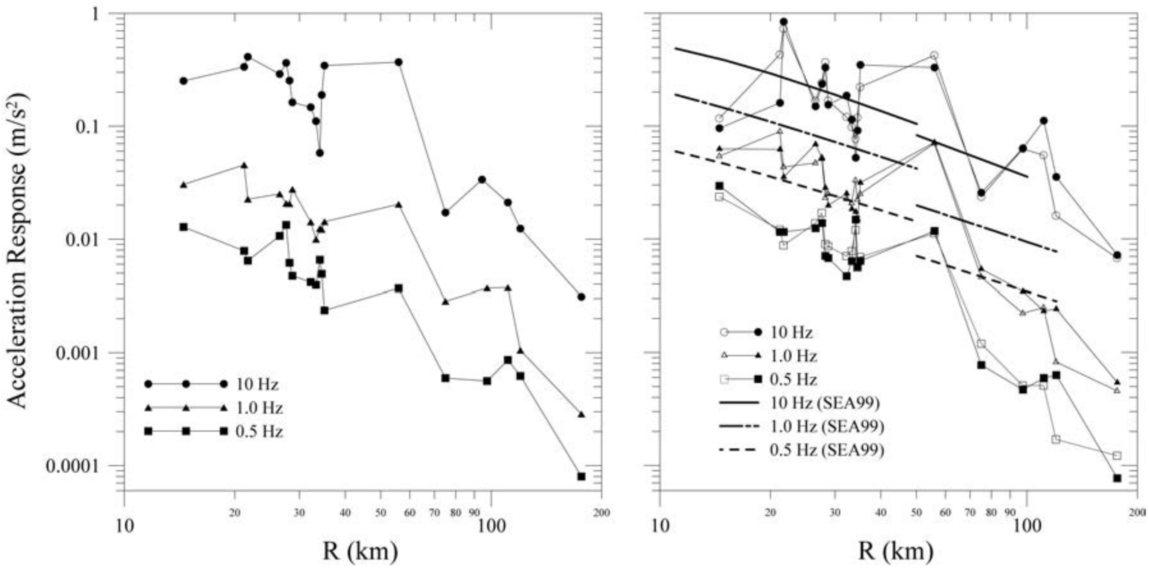

Fig. 13 - Spectral amplitudes of elastic acceleration response spectra calculated for 5% of the critical damping from records of the July 22, 2002. Alsdorf earthquake in the distance range from 14 to 176 km for 0.5, 1.0 and 10 Hz. The left diagram shows the values for the vertical component of motion and the right diagram shows the horizontal components. Here, round and square symbols indicate the north-south and east-west components, respectively. For the horizontal ground movement thick lines indicate the corresponding values from the SEA99 model (Spudich *et al*., 1999, Pankow and Pechmann, 2004). For distances < 50 km the soft rock and for distances > 50 km the hard rock model was used. All SEA99 values are calculated for M_W 4.3.

observations at high frequencies, above ca. 6 Hz in the vertical component and between ca. 6 and 15 Hz in the horizontal component. Amplitudes of the standard spectra are higher than the observations at frequencies below 2 Hz.

In Fig. 13, the amplitudes of the response spectra for three selected frequencies (0.5, 1.0, and 10 Hz) are shown with respect to the epicentral distance for the vertical and the two horizontal components. Additionally, the plot for the horizontal components shows modelled values from the SEA99 model (Spudich *et al*., 1999; Pankow and Pechmann, 2004). These model values were calculated with the assumption of a moment magnitude, M_W, of 4.3 derived from M_L 4.9 with the empirical relation for the northern Rhine area given by Reamer and Hinzen (2004). The Joyner-Boore distance (Abrahamson and Shedlock, 1997) in the SEA99 model was assumed to be equal to the epicentral distance. For an earthquake with magnitude under 5 and a corresponding source dimension on the order of 500 m, this assumption seems feasible as the smallest distance is 30 times larger than the source dimension. These calculations were done to test whether the SEA99 model, which was developed for tectonic extensional regimes, can also be utilized to forecast data from an earthquake in the LRE with a moment magnitude below the model limit of 5.0.

For the high-frequency end of the spectrum (10 Hz values), the predicted values from model SEA99 are a good fit to the observed horizontal response amplitudes. However there seems to be an increasing discrepancy with decreasing frequency. For the 0.5 Hz values, the observations are significantly smaller than the model amplitudes, at least for the soft-rock sites.

5. Discussion and conclusions

For the first time unclipped, semi-strong ground motion records from a damaging earthquake (intensity VI) in the German part of the LRE, at distances shorter than 30 km, have been analyzed. Together with data from hard-rock sites at distances greater than 50 km, a description of PGA and PGV attenuation for a M_L 4.9 earthquake, has been made. Recently published scaling relations for the Netherlands (Dost *et al*., 2004) provide a reasonable upper bound to the observed PGAs also at distances beyond the model borders of ca. 23 km. The average normalized residuals for 32 observed PGAs is 2.0. Relations based on observations by Campbell (1989) and Sabetta and Pugliese (1987) in California and Italy result in significantly larger average residuals of 7.8 and 4.1, respectively. While these relations are based on M_L, an empirical relation by Campbell (1997) based on M_W is a better estimate for the Alsdorf data set, with an average residual of 2.1. Among the empirical relations tested for this data, the Dost *et al*. relation (2004) produced the best prediction. However, most of their travel paths are located in the northern part of the Netherlands, which might explain the remaining factor of 2 difference . For M_L-based empirical relations, differences in local and regional attenuation have a double effect as they influence not only the ground movement of a certain event, but also control the amplitude correction term in the magnitude definition. Magnitude calibrations for the northern Rhine area (Reamer and Hinzen, 2004) show increasing differences in the numerical values of M_L and M_W for magnitudes above 3.

The PGVs are mostly overestimated. The average normalized residual for the empirical relation from Dost *et al*. (2004) is 2.5 for the entire data set and goes down to 1.5 if only soft rock-sites are considered. Of additional importance, the bulk soft-rock stations, in the LRE, cover a small azimuthal range of ca. 60° for this event, and the body waves penetrate the upper focal sphere without exception and thereby cover only a small fraction of the radiation pattern.

I_As and PGAs correlate well for large distance ranges for soft and hard rock sites while the strong motion durations do not show a significant correlation with the observational distance.

Response spectral amplitudes of the vertical component are smaller than those from the horizontal components at frequencies below 2 Hz by an average factor of ca. 1.7 (Fig. 12). The ratio between the horizontal and vertical acceleration response decreases, at frequencies between 2 Hz and 7 Hz, and the amplitudes of the mean vertical response spectrum are larger than those of the horizontal components at frequencies above 7 Hz. The horizontal acceleration response is ca. 70% of the vertical at 15 Hz.

Scaled standard spectra of the new German building code (DIN4149) show larger amplitudes than the geometric mean of the observed acceleration response spectra at frequencies below ca. 2-3 Hz. At higher frequencies, the observed values tend to be higher than the scaled standard spectra. Tradeoffs in shape can at least be partially interpreted by the fact that the shape of the norm spectra was determined for a significantly larger earthquake with a recurrence interval of 475 years whereas an event of the Alsdorf size is expected in the NRA roughly every 20 years. The acceleration response spectra of the stronger M_L 6.0 Roermond earthquake of 1992, which was recorded at a soft-rock station at a 55 km distance (Fig. 12) shows a clear shift of the plateau towards lower frequencies at least in the horizontal components.

The observations of semi-strong ground motion confirm, once again, that models for regions with moderate-to-low sesimicity are harder to establish than for high seismicity regions, because of the thinner database. It will be interesting to continue studies like this, when data from stronger events in the northern Rhine area become available. However, additional measurements of events of comparable or even smaller size, will help to answer important questions of scaling effects of empirical attenuation models.

The semi-strong motion seismograms from the low-gain short-period stations for mining surveillance, that constitute the principle data for this study, show the importance of records from soft-rock sites for the determination of locally calibrated empirical scaling relations for ground-motion parameters. Additional strong-motion stations and observations of earthquakes with magnitudes larger than the Alsdorf event one are necessary to build up reliable magnitude-dependent scaling laws for PSHA and DSHA.

Acknowledgements. The author thanks M. van Camp of ORB for the strong-motion data from the Belgian network. The GRSN waveform data were provided through the SZGRF, Erlangen. F. Scherbaum gave several helpful comments, which improved the manuscript. Specific comments and suggestions from P.L. Bragato and an anonymous reviewer were of great help and are highly appreciated. Special thanks goes to S.K. Reamer for many discussions. The approval from RWE Power AG to use their data is highly acknowledged.

REFERENCES

Abrahamson N.A. and Shedlock K.M.; 1997: *Overview*. Seismol. Res. Lett., **68**, 9-23.

Ahorner L.; 1993: *Gemessene Bodenbeschleunigungen beim Roermonder Erdbeben am 13. April 1992*. Bauingenieur, **68**, 201-205.

Brüstle W., Granet M. and Achauer U.; 1999: *Starkbebenmessnetz am Oberrhein*. D-A-CH Mitteilungsblatt, **18**, 10-15.

Camelbeeck T., van Eck T., Pelzing R., Ahorner L., Loohuis J., Haah H.W., Hoang-Trong P. and Hollnack D.; 1994: *The 1992 Roermond earthquake, the Netherlands, and its aftershocks*. Geol. Mijnbouw, **73**, 181-197.

Campbell K.W.; 1989: *The dependence of peak horizontal acceleration on magnitude, distance, and site effects for small-magnitude earthquakes in California and eastern North America*. Bull. Seis. Soc. Am., **79**, 1311-1339.

Campbell K.W. and Duke C.M.; 1974: *Bedrock intensity, attenuation, and site factors from San Fernando earthquake records*. Bull. Seism. Soc. Am., **64**, 173-185.

Cramer S.L.; 1996: *Geotechnical earthquake engineering*. Prentice Hall, New Jersey, 653 pp.

DIN4149; 2005: *Bauten in deutschen Erdbebengebieten Lastannahmen, Bemessung und Ausführung üblicher Hochbauten*. DIN Deutsches Institut für Normung e.V.

Dost B., van Eck T. and Haak H.; 2004: *Scaling of peak ground acceleration and peak ground velocity recorded in the Netherlands*. Boll. Geof. Teor. Appl., **45**, 153-168.

Havskov J. and Ottemøller L.; 1999: *SEISAN earthquake analysis software*. Seismological Research Letters, **70**, 532-534.

Hinzen K.-G.; 2004: *The use of engineering seismological models to interpret archaeoseismological findings in Tolbiacum, Germany, a case study.* Bull. Seismol. Soc. Am., **95**, 521-539.

Hinzen K.-G. and Weber B.; 2004: *Niederrheinische Bucht*. In: Henger M. (ed), Erdbeben in der Bundesrepublik Deutschland 2002, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, **75**, 713-725.

Hosser D.; 1987: *Realistische seismische Lastannahmen für Bauwerke. – Ergebnisse einer interdisziplinären Forschungsarbei*t. Bauingenieur, **62**, 567-574.

Pankow K.L. and Pechmann J.C.; 2004: *The SEA99 ground-motion predictive relations for extensional tectonic regimes: revisions and a new peak ground velocity relation.* Bull. Seism. Soc. Am., **94**, 341-348.

Reamer S.K. and Hinzen K.-G.; 2004: *An earthquake catalog for the northern Rhine area, Central Europe (1975-2002)*. Seismological Research Letters, **75**, 713-725.

Scherbaum F., Bommer J.J., Bungum H., Cotton F. and Abrahamson A.; 2004: c*omposite ground-motion models and logic trees: methodology, sensitivities and uncertainties.* Bull. Seism. Soc. Am. (accepted).

Sabetta F. and Pugliese A.; 1987: *Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records*. Bull. Seism. Soc. Am., **77**, 1491-1513.

Spudich P., Joyner W.B., Lindh A.G., Boore D.M., Margaris B.M. and Fletcher J.B.; 1999: *SEA99: A revised ground motion prediction relation for use in extensional tectonic regimes*. Bull. Seism. Soc. Am., **89**, 1156-1170.

USGS; 2004: http://earthquake.usgs.gov/image_glossary/strongmotion.html.

Corresponding author: Klaus-G. Hinzen
Division of Earthquake Geology, University of Cologne
Vinzenz-Pallotti-Str. 26, D-51429 Bergisch Gladbach, Germany
phone: +49 2204985211; fax: +49 2204 985220; e-mail: hinzen@uni-koeln.de