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EMPIRICAL GROUND-MOTION RELATIONS FOR CALIFORNIAN STRONG-MOTION DATA BASED ON INSTRUMENTAL SUBSOIL CLASSIFICATION

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ABSTRACT

One of the world's largest strong-motion networks, consisting of more than 1,200 accelerographs either installed at the free-field or inside of buildings, is contained within the borders of the state of California. In contrast to the large amount of high-quality strong-motion data from this network, an elaborated classification of the station's subsoil conditions into groups that might share similar site amplifications is not available for most of the stations. Based on microtremor recordings at nearly 300 strong-motion sites and the application of the spectral H/V-technique, a subsoil classification of these sites could be developed regarding not only the stiffness of the uppermost 30 m, but also the total thickness of sedimentary soil layers above geological bedrock. Thereby, the classification concept of the German seismic code provision DIN 4149:2005 is applied, distinguishing between six respectively seven site-specific subsoil classes. This serves as the basis for the elaboration of site-dependent empirical ground-motion relationships for horizontal spectral accelerations S_a and peak ground acceleration *PGA* by the use of a one- and two-stage regression analysis. Recapitulating it can be stated, that both peak ground accelerations and spectral accelerations show significant lower values for deep sediment sites (H > 100 m) than for sites with shallow (H < 25 m) or intermediate thick (25 m < H < 100 m) sedimentary soil layers. The results of these investigations, which cover the effects of deep sediment sites may be used to specify the description of seismic action for German or North American earthquake regions. Furthermore, results can be used in order to perform a more refined probabilistic seismic hazard assessment.

Introduction

For Central Europe only a small number of strong-motion records is available. Even though the last damaging earthquake on April 13, 1992 near Roermond (The Netherlands) was recorded by several stations, their epicentral distances were larger than 50 km (Schwarz and Ahorner, 1995). Nevertheless, macroseismic observations from historical events give a clear indication of site effects leading to the renewal of the idea to introduce intensity correction factors. The variety of subsoil conditions in the seismic zones of Germany provides the background for a refined classification scheme of subsoil conditions considering near-surface shear-wave velocities v_s as well as the total sedimentary thickness (Schwarz *et al.,* 1999). To prove the recommended elastic design spectra first studies are directed to the K-Net

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database and soft soil conditions (Schwarz *et al.*, 2004). As it can be shown for the particularly affected soft soil conditions, the amplification of ground motion is strongly dependent on the total depth of sedimentary soil layers.

The temporary strong-motion network of German TaskForce for Earthquakes which was installed immediately after the 1999 Kocaeli and Duezce (Turkey) earthquakes provides a unique database of aftershocks for which the efficiency of a subsoil- and geology-dependent classification scheme could be tested. In a series of parameter studies concerning the future directions in strong-motion instrumentation (Schwarz *et al.,* 2005) it was emphasized that starting from the whole (site-independent) database and the differentiation or sampling of data, precedence has to be given to the sub-classification of site conditions. In general, this procedure leads to a serious reduction of data remaining within the individual groups. Thus, derived results based on the entire dataset might be dominated by groups with a larger number of records. These comprehensive investigations lead to the conclusion that the derived ground motions models (i.e., spectral attenuation coefficients) are also affected by the type of regression used. The separate consideration of data from a single subsoil class can lead to a more or less different attenuation equation if all data groups are considered while introducing for each subsoil class one additional coefficient. By combining these aspects, the paper has to be regarded as an attempt to clarify methodological aspects as well as practical demands. Thereby, the studies profit from a recently elaborated classification scheme of subsoil conditions which is mainly based on instrumental site investigations (Lang and Schwarz, 2006).

Classification of Recording Sites

In order to allow a consistent site classification even of those Californian strong-motion sites where detailed information on the geological subsoil conditions is missing, a hybrid procedure based on analytical investigations of model soil profiles and instrumental measurements based on noise recordings was developed. This allowing the classification of a site of interest into site-specific subsoil classes of the German seismic code DIN 4149: 2005 (NABau, 2005) simply by the shape of spectral H/V-ratio on microtremor data recorded at the site (Lang, 2004; Lang *et al.*, 2004; Lang and Schwarz, 2006). In this respect, the main decisive factor is the location of its predominant peak in the spectral domain being characterized by a distinct and well-defined hump.

Table 1. Possible combinations of site classes according to the German seismic code DIN 4149: 2005.

Soil condition class: / **Geological subsoil class:**		R: areas pred. characterized by rocks	T: transition zones between R and S	S: sediment basins
		$H_{tot} < 25$ m	$25 < H_{tot} < 100$ m	$H_{tot} > 100$ m
A: firm to medium-firm soil	$v_{s,25}$ [1] > 800	A-R	-	-
B: loose soil (gravel to coarse sands, marls)	350 < $v_{s,25}$ [1] < 800	B-R	B-T	(B-S) [2]
C: fine-grained soil (fine sands, loesses)	150 < $v_{s,25}$ [1] < 350	C-R	C-T	C-S

[1] Average shear-wave velocity of the uppermost 25 m of subsoil materials [*m/sec*].
[2] As proposed by Schwarz *et al.* (1999). Combination B-S is not considered in DIN 4149: 2005.

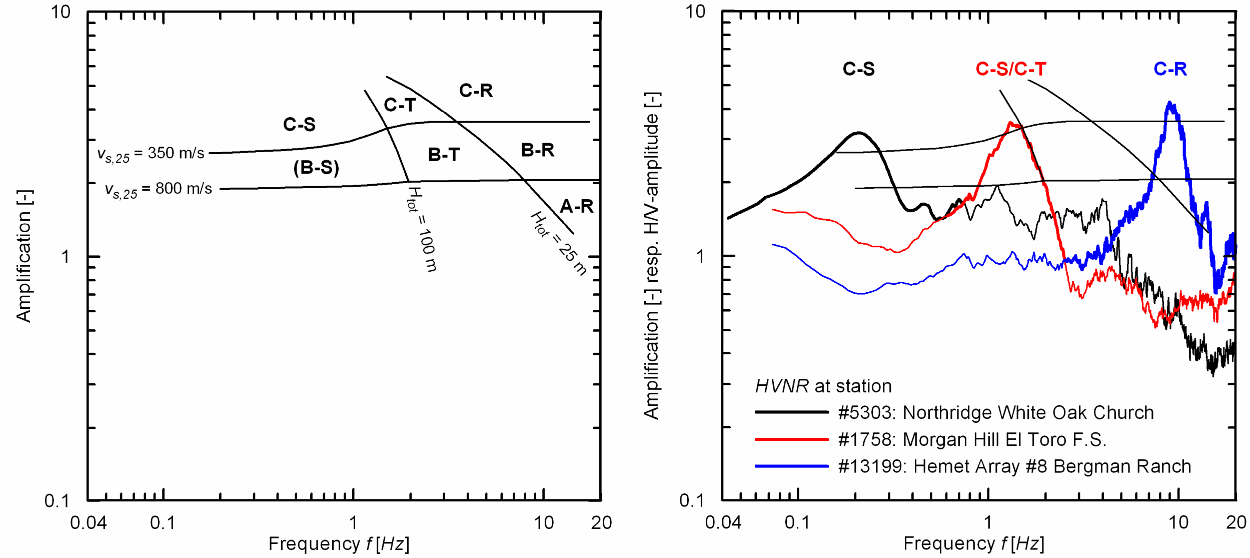

Figure 1. (a) Qualitative ranges of possible peak locations of one-dimensional transfer functions for site classes of DIN 4149: 2005 (b) overlain with spectral H/V-ratios on microtremors recorded at selected Californian strong motion sites showing soft soil conditions but different sediment thicknesses.

As Table 1 illustrates, site classes of the German seismic code DIN 4149: 2005 are discretized by a certain range of average shear-wave velocity $v_{s,25}$ and total thickness of sediments above geological bedrock H_{tot}. Consequently, a variety of model profiles can be generated for each site class meeting its respective boundary conditions. Their transfer functions, in addition, mark the range of possible peak locations in the frequency-amplification domain, where the classification of a site can be realized by its predominant peak of spectral H/V-ratio (Fig. 1). In order to demonstrate the differences between the site classes in terms of seismic loads to be assessed, elastic design spectra of DIN 4149: 2005 are given in Fig. 2. The comparison between these spectra and those of Eurocode 8 for Southern Alps (Type 1) seismic regions (CEN, 2002) clearly indicates a more sophisticated site classification within DIN 4149: 2005 additionally taking into account the effects of sedimentary thickness H_{tot}.

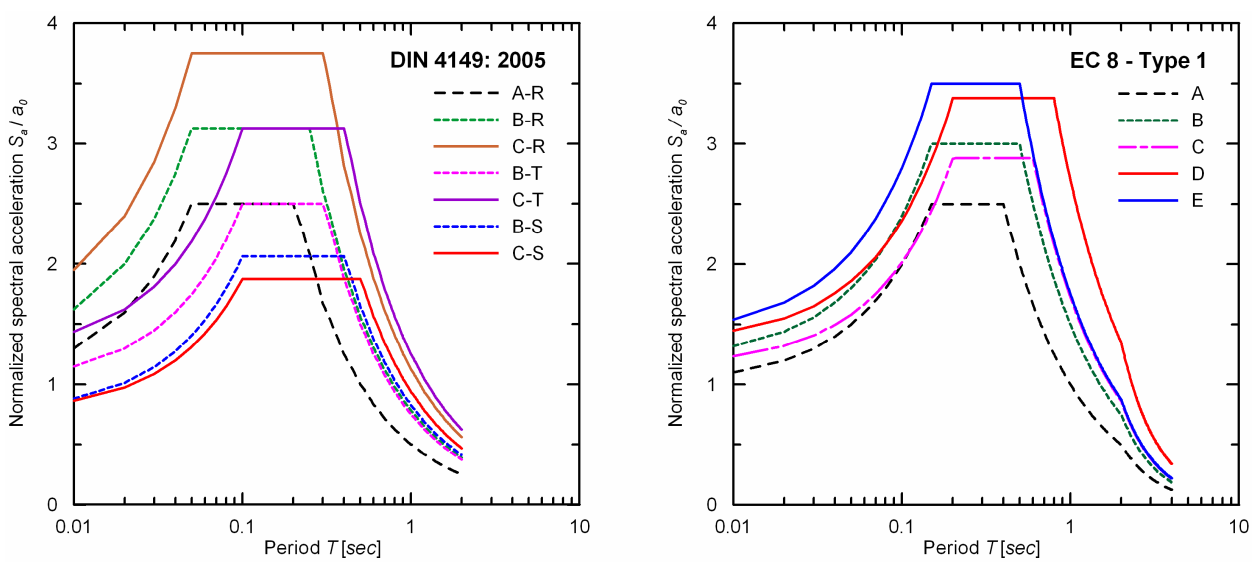

Figure 2. Normalized elastic design spectra (damping ξ = 5%) for site classes of the earthquake code provisions (a) DIN 4149:2005 (NABau, 2005) and (b) Eurocode 8 – Type 1 (CEN, 2002).

Database

The entire earthquake database herein applied consists of 615 strong-motion records of around 100 near-field events being recorded at 183 stations in the central and southern parts of California. For further analysis only the stronger component of both horizontal ones will be utilized. As it was already addressed, a subsoil classification of the recording sites was conducted on the basis of instrumental microtremor measurements (Lang and Schwarz, 2006) allowing a subdivision of the entire dataset into site-specific subsoil classes of the German seismic code DIN 4149: 2005. As it becomes obvious from Fig. 3 showing the magnitude-distance relationship of applied earthquake events depending on DIN 4149: 2005 site classes, site class C-S holds the majority of earthquake records, while site classes B-R and C-T show only a few records. Fig. 4 breaks down the applied database into specified types of magnitudes and computable types of distances. Basically, moment magnitudes M_w and local magnitudes M_L were available, while a transition between both types of magnitudes happens around magnitude 5-6. For nearly all events larger than magnitude 6 only moment magnitudes M_w were available. In general, moment magnitudes M_w are used for regression analysis; in case of lacking information local magnitudes M_L are taken (assuming $M_w = M_L$). For larger magnitude events where information about the spatial dimension of the rupture area was available, the Joyner-Boore-distance r_{JB} (Joyner and Boore, 1981) is calculated, while epicentral distances r_e are assigned to the smaller magnitude records.

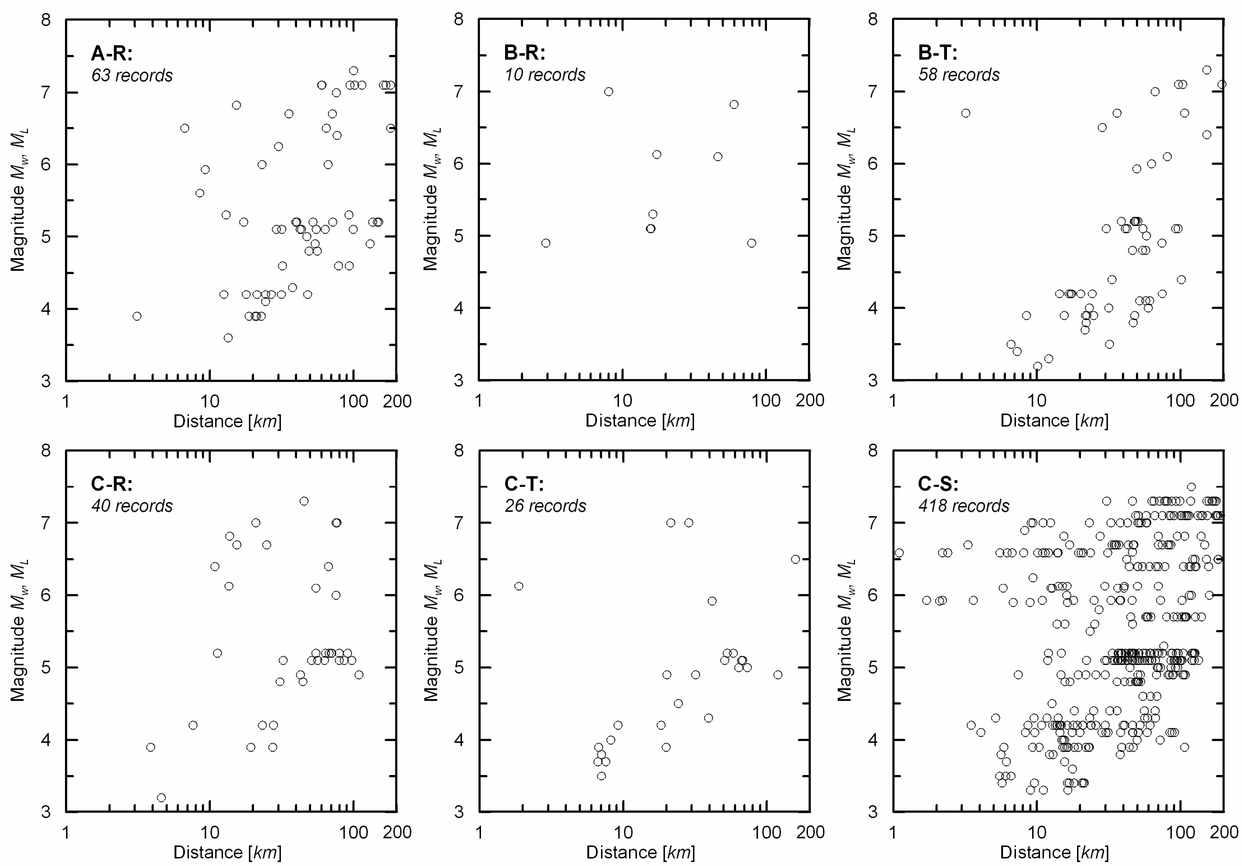

Figure 3. Composition of applied earthquake recordings depending on site classes of DIN 4149: 2005.

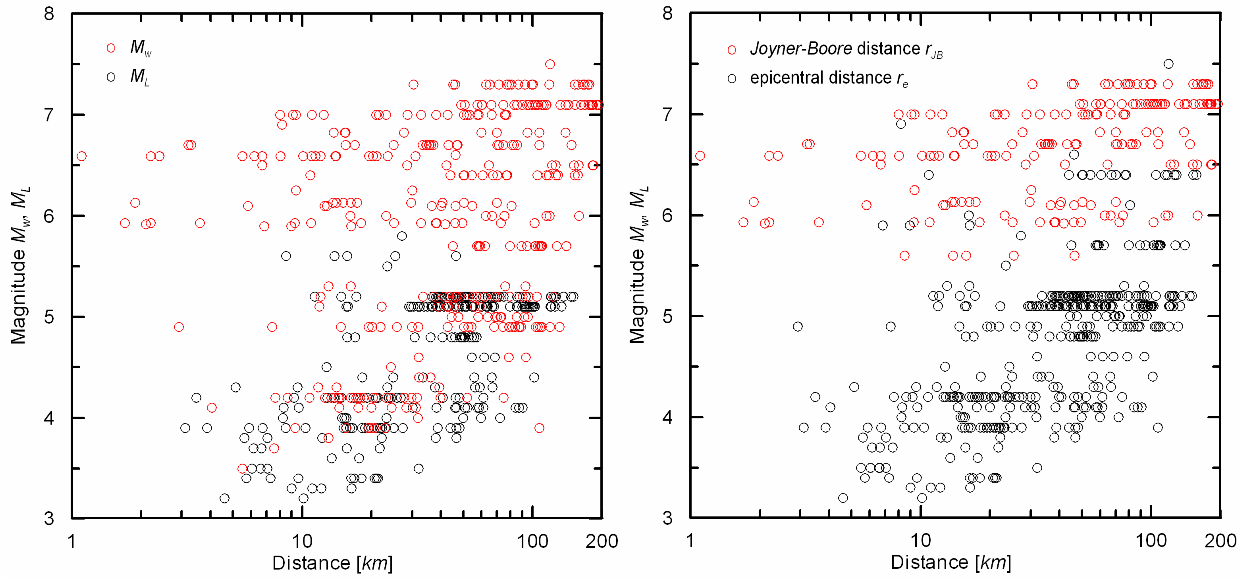

Figure 4. Spreading of the applied earthquake records in terms of (a) type of magnitude M and (b) type of distance d.

In order to emphasize the influence of near-surface geology and total thickness of sedimentary materials on the results of ground-motion prediction equations, different concepts of soil classification will be regarded. Table 2 gives an overview of these analyzed datasets being composed of those records classified into the six different site classes of DIN 4149: 2005. While Regression type I is restricted to one single data group, Type II distinguishes between the six site classes of DIN 4149: 2005. In addition, different compositions of the DIN 4149 site classes according to conventional (e.g., Ambraseys *et al.*, 1996) or other site-specific classification concepts (e.g., disregarding the influence of shallow soft or stiff soil layers above bedrock) are generated in Type I* to illustrate the variation of results and influence of classification limits.

Generally, three different types of regression analyses are elaborated differing in the applied regression model (equation (1) and (2)) and in the size of the dataset to rest upon (see Table 2).

Regression type I:
A regression analysis is conducted for the entire dataset regardless of site class or soil conditions. Consequently derived prediction curves will not be related to a particular site class but rather to “all soils”. The general form of the regression is given by equation (2).

Regression type I*:
The dataset is restricted to records on those site classes for which the ground motion prediction is worked out. Since not all of the DIN 4149: 2005 site classes are well-represented by a certain number of records (see Fig. 3), a regression analysis for some of these site classes (e.g., B-R, C-T) may not be representative and consequently is omitted. The general form of the regression is given by equation (2).

Regression type II:
Irrespective of the DIN 4149: 2005 site class for which the ground motion prediction is to be elaborated, the regression analysis is based on the entire dataset covering all events recorded at all types of subsoil. The respective regression is represented by equation (1). Based on pure rock-type soil conditions, coefficients are determined for the respective site class according to the classification concept of DIN 4149: 2005. A ground motion prediction for a specific site class *i-j* is performed by setting/adjusting the respective “Dummy” variable $S_{i\text{-}j} = 1$ while all others to 0, thus solely determining the respective coefficient C_k. Consequently, a calibration of the results for the particular site classes is ensured.

Table 2. Number of records and their distribution into site classes depending on different levels of categorization.

Type	Soil Classification	No. of records for the resp. DIN 4149 site classes						Dataset	No. of records [2]
		A-R	B-R	B-T	C-R	C-T	C-S		
		63	10	58	40	26	418		
I	no							all soils	615
I*	data combinations							rock 1 [3]	63
								rock 2	73
								rock 3	113
								stiff 1	58
								stiff 2 [3]	68
								soft 1	418
								soft 2	444
								soft 3 [3]	484
II	site-specific [1] (DIN 4149: 2005)	●						A-R	615
			●					B-R	
				●				B-T	
					●			C-R	
						●		C-T	
							●	C-S	

Annotations:
[1] Points (●) indicate the DIN 4149: 2005 site class for which the regression analysis is performed.
[2] Number of records onto which the regression analysis rests upon (gray-shaded areas).
[3] Representing the conventional site classes (rock, stiff soil, soft soil) as defined by Ambraseys *et al.* (1996).

Ground Motion Prediction Equation for the Horizontal Component

Regression model

In order to predict ground motion parameters (horizontal *PGA* and spectral acceleration) the same regression model is used as proposed by Ambraseys *et al.* (1996). Merely a refinement is introduced by substituting the conventional site classes (rock, stiff soil, soft soil) for the site-specific subsoil classes of DIN 4149: 2005 (see Table 1). To assess the different site class coefficients C_k a single-stage regression analysis with "Dummy" variables $S_{i\text{-}j}$ is applied (Regression type II). The general form of the regression model is represented by equation (1):

$$\log(y) = C_1 + C_2 M + C_3 \log(r) + C_4 S_{B\text{-}R} + C_5 S_{C\text{-}R} + C_6 S_{B\text{-}T} + C_7 S_{C\text{-}T} + C_8 S_{C\text{-}S} + \sigma P \quad (1)$$

in which y is the ground motion parameter in g (PGA or S_a), M the magnitude (M_w), r a function of the distance measure ($r = \sqrt{(d^2 + h_0^2)}$, while d is the distance (either epicentral r_e or fault distance r_{JB}) and h_0 a coefficient to be determined by iteration), and P the uncertainty in the prediction.

The regression model to be used for Regression types I and I* is given by equation (2). Since both types of regression are based exactly on that type of data (narrowed dataset) for which a prediction is elaborated, no site coefficients are incorporated:

$$\log(y) = C_1 + C_2 M + C_3 \log(r) + \sigma P \quad (2)$$

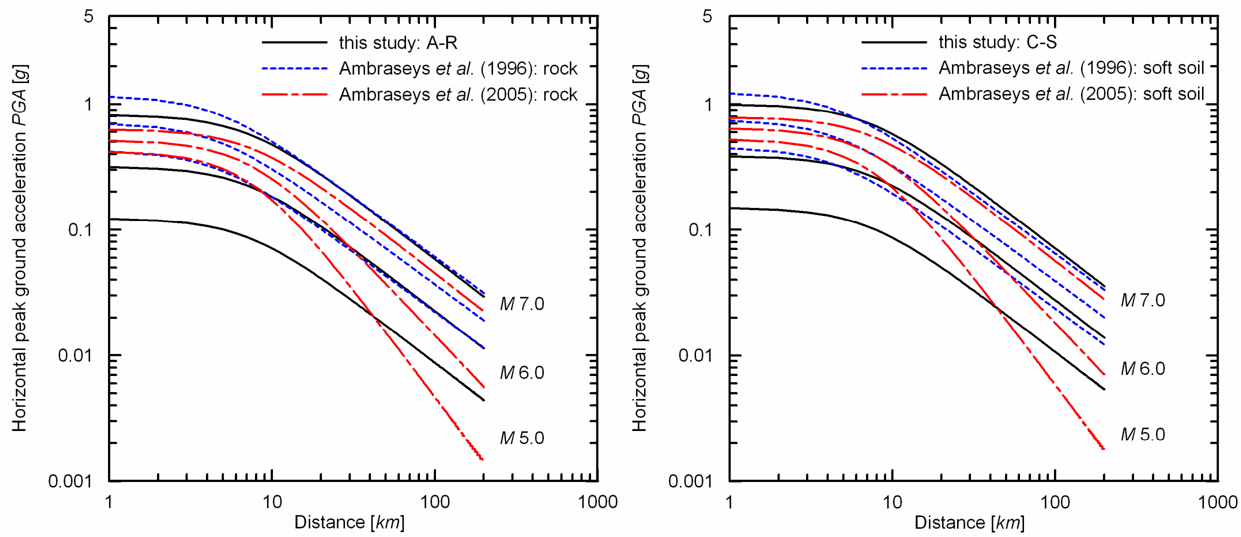

Figure 5. Comparison of attenuation curves for horizontal peak ground acceleration by Ambraseys *et al.* (1996), Ambraseys *et al.* (2005) with this study (Type II, entire dataset).

Horizontal peak ground acceleration

Adopting the "site-specific" regression analysis to the entire dataset and thus deriving site coefficients C_k for horizontal peak ground acceleration *PGA*, equation (1) transforms into:

$$\begin{aligned} \log(y) = &- 2.4088 + 0.4368\,M - 0.9602\,\log(d^2 + 6.6^2)^{0.5} \\ &+ 0.1789\,S_{B\text{-}R} + 0.1321\,S_{C\text{-}R} - 0.0083\,S_{B\text{-}T} + 0.0677\,S_{C\text{-}T} + 0.0892\,S_{C\text{-}S} + 0.27\,P \end{aligned} \tag{3}$$

To receive an impression about the level of *PGA* values derived by equation (3), Fig. 5 correlates the attenuation curves of this study with the results of the ground motion prediction models published by Ambraseys *et al.* (1996) and Ambraseys *et al.* (2005). For reliability reasons, attenuation curves are only derived for those DIN 4149: 2005 site classes having a certain number of records and showing an even dataset.

Horizontal spectral acceleration

As shown in Fig. 3, site class C-S has the highest number of available records. A separate regression analysis only would be substantiated for site classes C-S and A-R, and with restrictions for site class B-T. Due to methodical reasons all data groups are used for the regression and have to be analyzed. Based on predicted spectral accelerations for discrete magnitude-distance-combinations $M_i - d_j$ the influence of covered data on the results is checked. The following magnitude-distance-combinations are investigated:

- magnitude M_1 5.0 and distance d_1 = 10 km, d_2 = 25 km, d_3 = 50 km
- magnitude M_2 7.0 and distance d_4 = 100 km.

With regard to the composition of the dataset (see Fig. 3 and Fig. 4), it can be stated:

- Combination $M_1 - d_1$ (near-field event), which can be regarded as being significant for structural design in Central European earthquake regions is located (except for site class A-R) at the "inner" data border, for which no events are available.
- Combinations $M_1 - d_2$ and $M_1 - d_3$ are located right within the center of the dataset, i.e. a representative coverage within the analyzed data groups is ensured.
- Combination $M_2 - d_4$ (high-magnitude far-field event) which is solely significant for the main earthquake areas worldwide, lies at the "outer" border of the dataset, which is (except for site class C-T) sufficiently covered by available records.

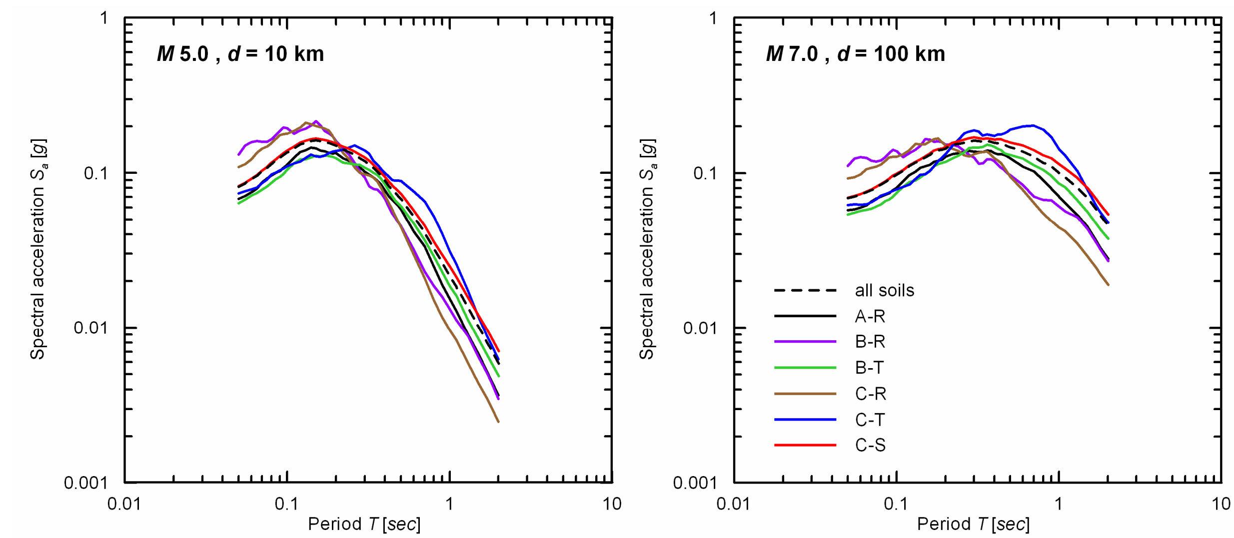

Figure 6. Comparison of predicted spectral acceleration for Type I dataset ("all soils") with Type II datasets (site classes of DIN 4149: 2005).

A comparison between predicted spectral accelerations using Regression type I and type II illustrates the circumstance, that site class C-S obviously holds the majority of the applied database (Fig. 6). As it can be taken from Table 2 both regression types rest upon the entire dataset. The prediction curves of Regression type I which can be regarded as site-independent ("all soils") clearly reflect the similarities to spectral curves for site class C-S derived with Regression type II. In order to enlarge the database and to consider conventional classification principles of subsoil conditions which are related to the average shear-wave velocity of the upper 25 or 30 m ($v_{s,25}$ or $v_{s,30}$) additional data groups are analyzed being composed out of the site-specific subsoil classes according to DIN 4149: 2005 (see Table 2). Since the classification of sites being characterized by thin layers over geological bedrock in particular can be done on different ways and the related effects are sometimes considered by a separate subsoil class (e.g., class E in Eurocode 8; Fig. 2), additional data combinations are generated (Type I* in Table 2). Fig. 7 illustrates the influence of a stepwise enlargement of the different datasets on the predicted spectral accelerations (Type I*) and compares them with the results of Regression type II. Generally the following can be observed:

- The differences in predicted spectral accelerations between the same site classes but resting upon different datasets (e.g., A-R and rock 1, B-T and stiff 1, C-S and soft 1) strongly depend on the number of records available for the respective site class.
- The influence of a dataset enlargement by additional records can be neglected since their amount is too small in contrast to the "starting" dataset. The differences for stiff soil conditions (between stiff 1 and stiff 2) may result from the small number of available records.
- In case of the comparisons for stiff and soft soil conditions, the decrease of spectral amplifications below 0.2 sec between the different datasets can somehow be regarded as reflecting deamplification effects occurring with increasing soil thicknesses.

To examine the effects coming from the size of the dataset the regression is based on, Fig. 8 correlates the predicted spectral accelerations for those pairs of site classes which are identical but being based on different regression types (Type I* and II). At the present state of elaboration (and considering the available dataset), the study supports the conclusion that both Regression types (I, II) lead to similar results for subsoil classes C-S and A-R. Even with increasing (epicentral or fault) distance *d* results of both regression types remain stable and only show slight variations. In contrast, the deviations between the results for site classes B-T and stiff 1 decrease with distance, which can be mainly attributed to the better coverage of available data at larger distances and the results' representativeness for the respective magnitudes and distances (see Fig. 3).

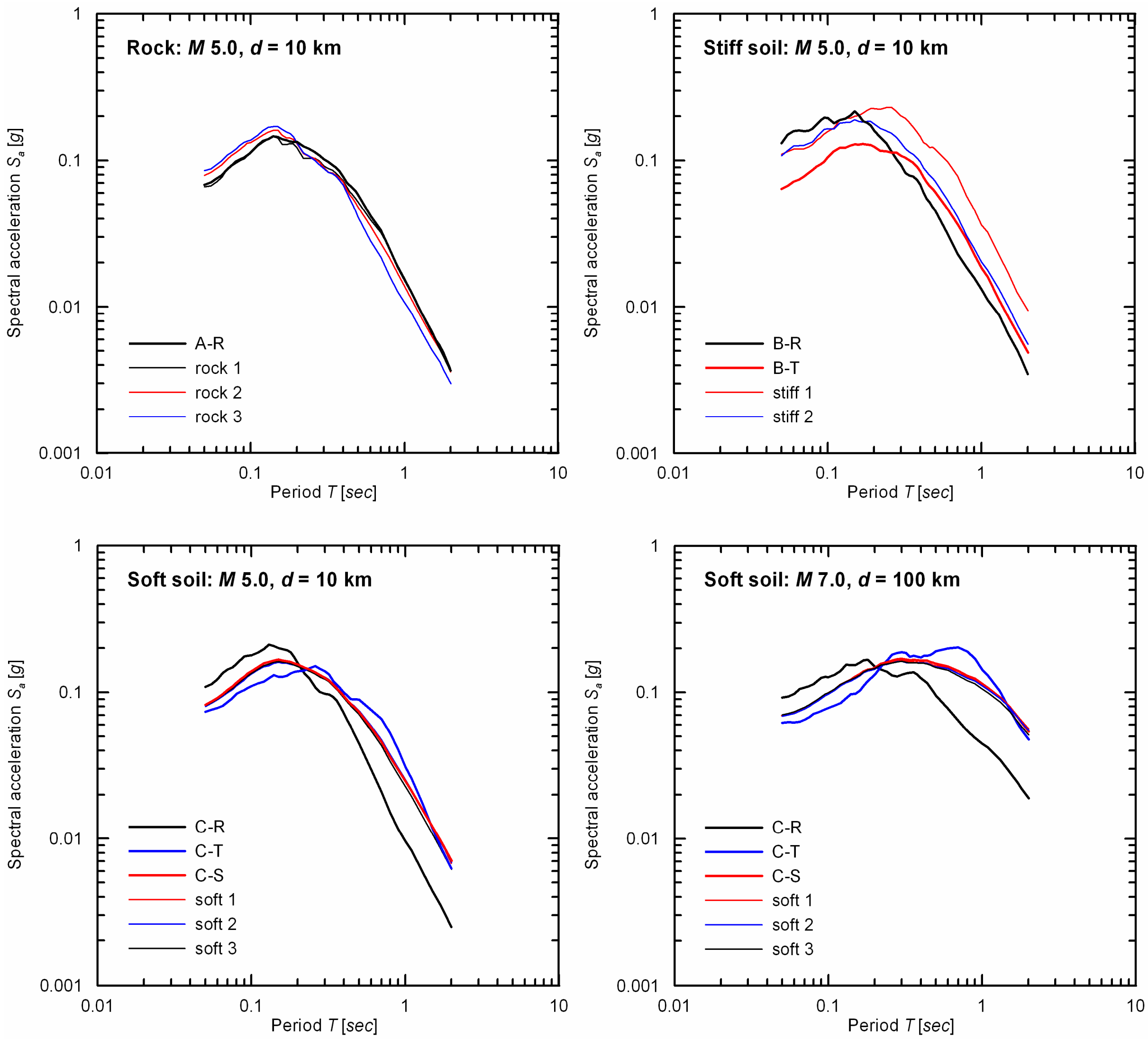

Figure 7. Comparison of predicted spectral acceleration for Type I* with Type II datasets in order to illustrate the influence of record number the regression rests upon. (Note: Spectra for soft 1, soft 2 and soft 3 are fully hidden by the respective C-S spectra.)

The respective coefficients for the prediction of spectral accelerations according to equation (2) for site classes rock 1 and soft 1 are given in the Appendix (Table A1 resp. Table A2).

Conclusions

With regard to the herein presented state of elaboration of empirical site-specific ground motion prediction equation based on Californian strong-motion data, the following aspects can be concluded:

- The adopted classification procedure of the recording sites using the experimental H/V-method on microtremors allows for a homogeneous categorization even of those sites where no subsoil information is available and thus increases availability and applicability of strong ground-motion data.
- Results show, that the total depth of sedimentary soil layers has influence on the spectral ground-motion characteristics. The classification concept of DIN 4149: 2005 and the proposed elastic design spectra (see Fig. 2) reflect a plausible coordination between the single site classes and in the present case establish the basis for a differentiation or combination of comparable data groups.

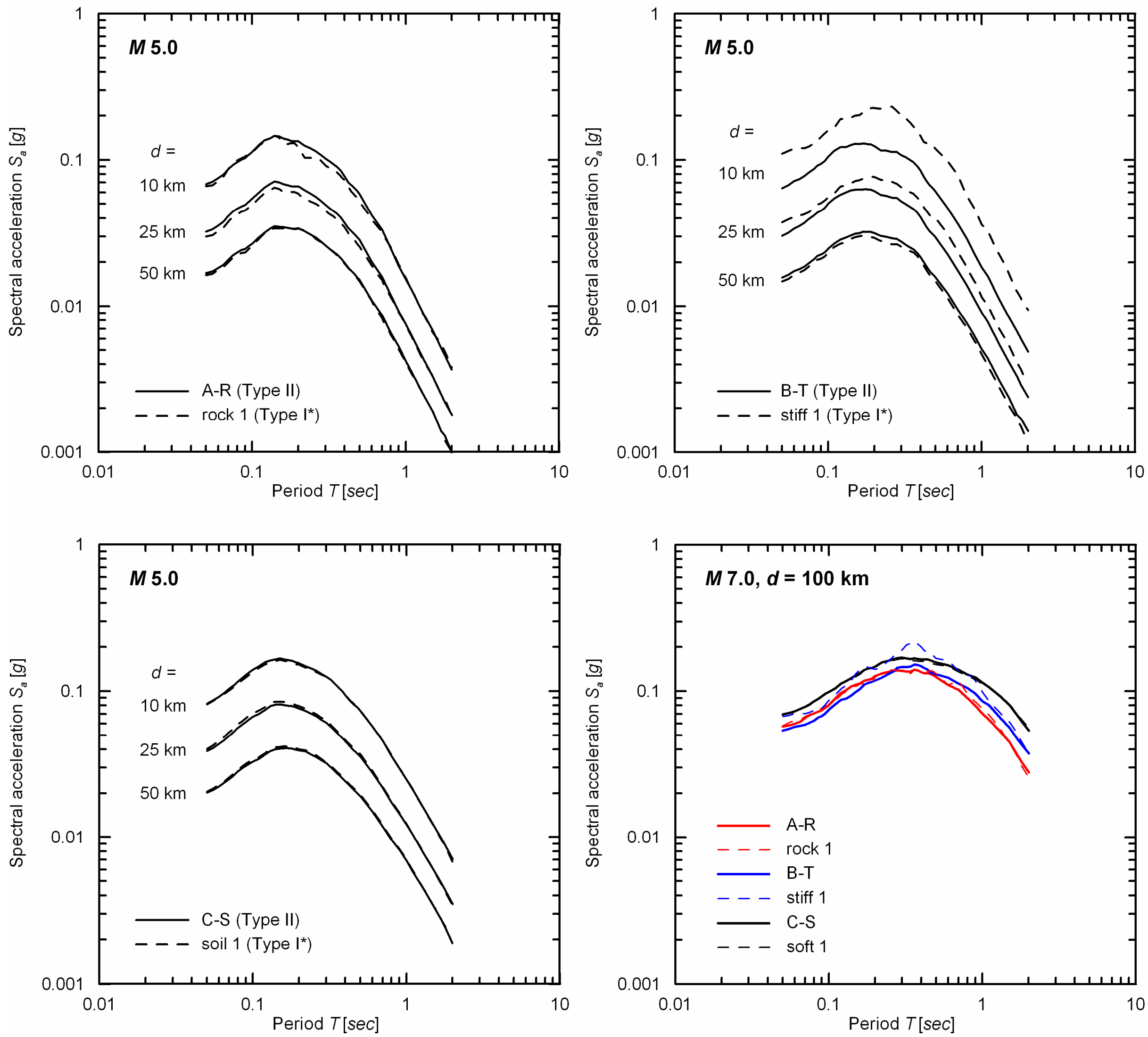

Figure 8. Comparison of predicted spectral acceleration for Type I* with Type II datasets in dependence on distance *d*.

- A peculiarity of the derived results insists in the fact, that those for data group C-S only reveal deamplifying effects to a certain extent. In the code provision DIN 4149: 2005, for site class C-S a soil factor $S < 1.0$ is established, which means that ground acceleration values on this soft soil site class are lower than on rock (A-R). That this circumstance can not be fully verified by the herein investigated Californian recordings may be attributed to the geological differences between German and Californian earthquake regions.
- In order to extent the database for those site classes where only a small number of records is available, additional earthquake data from Turkey and Greece have to be implemented in ongoing studies. Especially the supplementation of the dataset with smaller magnitude records will be of utmost importance such that a more homogeneous database is composed.

Acknowledgments

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Appendix

Table A1. Regression coefficients for Regression type I* (equation (2)) and site class “rock 1”.

T [*sec*]	C_1	C_2	C_3	h_0	σ
0.05	-2.3350	0.4084	-0.8790	2.11	0.2523
0.10	-1.9508	0.3882	-0.9295	2.53	0.2679
0.20	-2.1324	0.4042	-0.8000	1.35	0.2907
0.30	-2.6417	0.4788	-0.7863	1.62	0.3040
0.40	-2.9973	0.5369	-0.8211	1.67	0.3265
0.50	-3.4605	0.5929	-0.7851	1.35	0.3321
0.60	-3.7125	0.6235	-0.8044	1.99	0.3295
0.70	-4.1427	0.7082	-0.8708	3.38	0.3237
0.80	-4.3119	0.7188	-0.8692	2.70	0.3255
0.90	-4.5495	0.7393	-0.8488	2.63	0.3319
1.00	-4.7573	0.7654	-0.8584	3.23	0.3304
1.50	-5.3869	0.8042	-0.7990	2.76	0.2967
2.00	-5.7209	0.8305	-0.8409	2.62	0.2974

Table A2. Regression coefficients for Regression type I* (equation (2)) and site class “soft 1”.

T [*sec*]	C_1	C_2	C_3	h_0	σ
0.05	-2.0064	0.4178	-1.0375	9.11	0.2851
0.10	-1.4161	0.4117	-1.2335	13.43	0.3033
0.20	-1.7528	0.4411	-1.0817	11.21	0.2941
0.30	-2.2835	0.5026	-1.0060	8.80	0.2925
0.40	-2.7167	0.5497	-0.9635	7.45	0.2773
0.50	-2.9920	0.5904	-0.9786	8.48	0.2759
0.60	-3.3887	0.6313	-0.9300	6.86	0.2711
0.70	-3.6864	0.6582	-0.8948	5.32	0.2756
0.80	-3.9673	0.6857	-0.8657	4.61	0.2748
0.90	-4.1998	0.7056	-0.8280	4.02	0.2765
1.00	-4.3804	0.7280	-0.8330	4.27	0.2800
1.50	-5.1316	0.8147	-0.8296	4.55	0.3036
2.00	-5.5928	0.8544	-0.8174	4.07	0.3113

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