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SITE-SPECIFIC GROUND MOTION PREDICTION EQUATIONS ON THE BASIS OF INSTRUMENTALLY VERIFIED SUBSOIL CLASSES OF STRONG-MOTION RECORDING SITES AND THEIR APPLICATION TO NPP SITES IN GERMANY

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ABSTRACT

A new set of Site Specific Ground Motion Prediction Equations (SGMPEs) is presented in this paper. They are based on strong-motion recordings from sites with instrumentally verified subsoil conditions in California, Turkey and at the NPP target sites. The approach follows analogy considerations by assuming that in the case of similarities in the transfer characteristics also similar ground motion recordings have to be expected. For this purpose, a cluster analysis is performed, taking H/V spectra from the NPP site measurements as search and evaluation criterion. By a scoring procedure different site measurement points MP_i (inside and outside the NPP area) can be considered. Each measurement is providing a target function (H/V spectra) which is the basis for a ranking of the best fitting strong-motion recording sites. The target function represents a statistically evaluated, several days covering time window of instrumental data where the H/V-spectra are determined in a sequence of equal time steps. The scatter due to day time and working phases is smoothed out by calculating different fractiles of the H/V spectra. Having identified the best fitting recording stations, the available data is combined within a special data group standing for the most likely subsoil class of the NPP-Site. Basic steps of the whole concept are illustrated for two NPP-Sites in Germany being classified by quite different subsoil classes. The procedure is open for sensitivity and parameter studies, and offers the advantage of a “self-growing” database and the adoption of modified single-station approach.

INTRODUCTION

As so far, ground motion prediction equations (GMPEs) for soil sites might be misleading if the selection of records is restricted to the uppermost 30 m of the subsoil (and the average shear wave velocity $v_{s,30}$) and if the whole underlying geological depth profile is ignored. Despite the fact that alongside the river Rhine in Western and South-Western Germany, the thickness of the sediments reaches several hundred meters, site-specific data and corresponding attenuation relationships are missing due to the lack of earthquakes and strong-motion records. The concept of subsoil and geology-dependent ground classes offers an alternative approach by the explicit consideration of the thickness of sedimentary layers and their effect on the site amplification as well as on the shape of site-specific spectra. Possible combinations of soil condition classes A, B, C, and geological subsoil classes R, T, S as implemented in German Building code can be taken from Schwarz *et al.* (2007, 2009).

INSTRUMENTAL INVESTIGATION OF THE STRONG MOTION RECORDING SITES

The primary database of classified strong motion recording sites refers to the outcome of a measurement campaign carried out in the spring of 2004 in California. It was done in close cooperation with the United States Geological Survey (USGS). Figure 1 shows the respective region of California and the strong-motion recording sites between the south coast of San Pablo Bay in the North (north of San Francisco) and Imperial Valley in the South where the measurements were carried out. As a whole, 300 strong-motion sites in the central and southern parts of California were investigated and classified (Lang & Schwarz, 2006). Within this comprehensive instrumental study, the recording sites are classified with respect to their ground classes considering the characteristics of the uppermost 30 m of the subsoil overlaying the geological depth profile. The initial earthquake database consists of more than 615 strong-motion records of 102 near-field events being recorded at 183 stations at time of the first data elaboration and publication of ground motion prediction equations by Schwarz *et al.* (2007).

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 records was developed. This allows the classification of a site of interest into site-specific subsoil classes of the German seismic code DIN 4149: 2005 simply by the shape of spectral H/V-ratio on micro-tremor data recorded at the site (Lang, 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 (see Fig. 2).

For the purpose of a code–related application, as a whole, six (respectively seven) site-specific ground classes are distinguished (Schwarz *et al*., 2007; Kaufmann *et al.*, 2011). The commonly used subsoil class “soft soil” (C) is replaced and differentiated by three classes (C-R, C-T, C-S), where C-R stands for soft soil above rock (with high amplification factor in a small plateau range), C-S for layers with more than 100 m thickness, and C-T for a transition range. Example sites with corresponding and quite distinguished H/V spectral noise ratios support the validity of the developed classification scheme and the applicability of the general approach to other site classification concepts (Schwarz *et al.*, 2009).

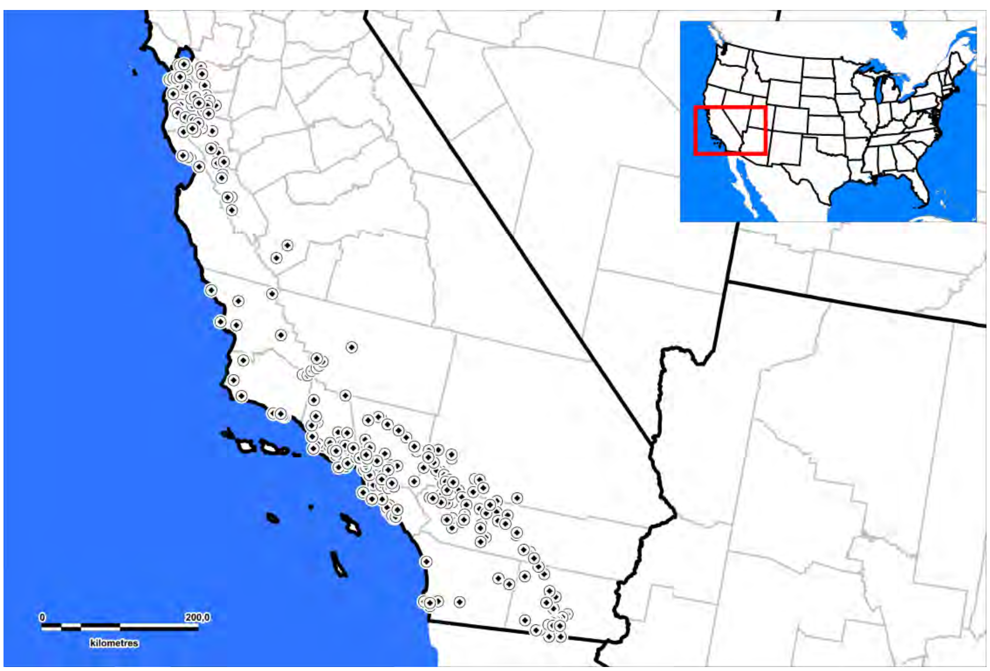
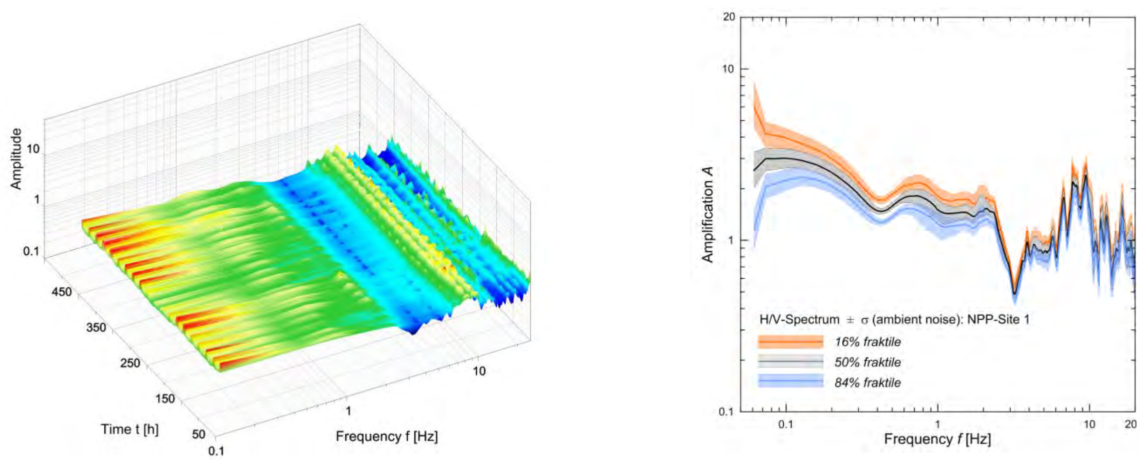


Figure 1. Map of central and southern California with instrumentally observed strong-motion sites.

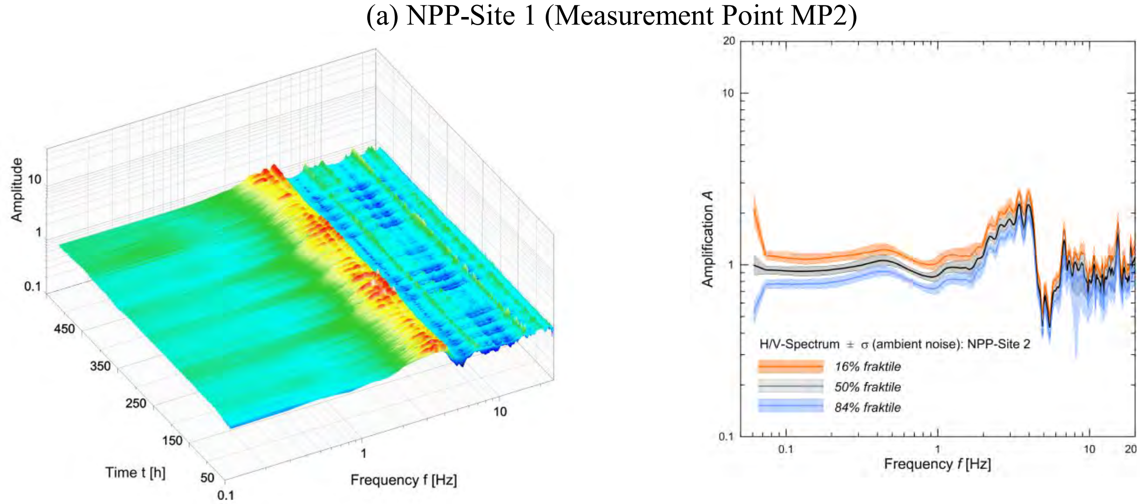
INSTRUMENTAL SITE CLASSIFICATION OF THE TARGET SITES

During a series of different measurement campaigns, instrumental micro-tremor recordings were conducted at different locations (Measurement Points MP_i) around both target NPP-Sites, providing the basis for the site classification and the calibration of the depth profile. A large set of H/V spectral noise ratios continuously determined in one-hour segments over several days covering a time window of measurements indicate the quite stable transfer characteristics of the NPP-Sites under consideration. The scatter due to day time and working phases is smoothed out by calculating different fractiles of the H/V spectra. Sets of individual H/V-spectra over the time allow a statistical investigation being expressed by the Median, 16% and 84% - fractiles (see Figure 2). The Median curves are used as search criterion (Figure 3).

Results of this instrumental site classification clearly indicating a (C-S) soft soil site, underlain by very thick layers of sediments reaching several hundreds of meters for NPP-Site 1 and a rock type site assignment for NPP-Site 2 (Lang, 2004; Schwarz, *et al.*, 2009). Within the initial phase of test measurements and the on-going permanent recording phase, a remarkable number of small (near field) and stronger (far distant) earthquakes could be recorded contributing to site-related datasets DS3-NPP-1 and DS4-NPP-2 (see Table 2).



(a) NPP-Site 1 (Measurement Point MP2)



(b) NPP-Site 2 (Measurement Point MP7)

Figure 2. Monitoring of the H/V spectral noise ratios at NPP target sites and their statistical evaluation.

CLUSTER ANALYSIS AND SELECTION OF REFERENCE SITES

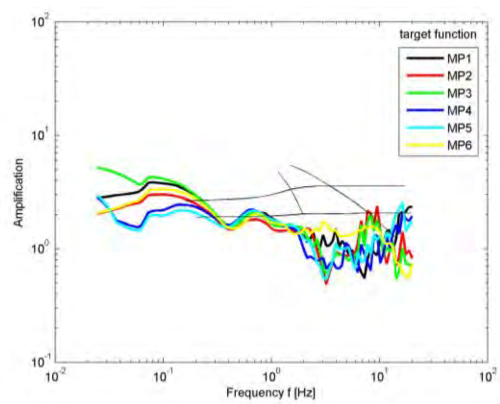
The whole procedure can be described by the following steps:

(1) Target functions in the form of the Median H/V-spectra (see Figure 2) are determined as an outcome from instrumental NPP site investigations. Reference functions are available from the measurements at the strong motion recording sites.

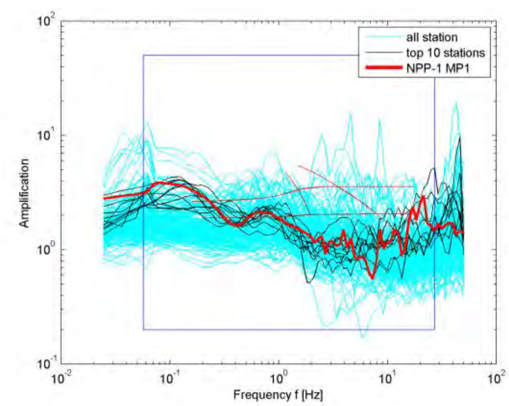
(2) By analogy considerations between the different target functions (from measurement points MP_i of NPP site) and the H/V function of the reference sites (light blue curves in Figure 3), the most appropriate ones (black lines) are identified using error minimization routines within a frequency range being variable in selection (see frames in Figure 3).

(3) The instrumentally determined H/V-spectra from the strong motion stations serve as reference to identify a set of the 10 best matching spectra in comparison to the NPP target site H/V-spectra. Information about the depth profile and site classification is checked with respect to its consistency concerning the basic data from the target site to avoid any contradiction within the target site classification. (Generalizing the experience from several applications, such inconsistencies were not observed yet, indicating the quality of the preliminary data elaboration). Finally for each target function (from one MP), a list of the top 10 reference (strong motion recording) sites is taken into a scoring list.

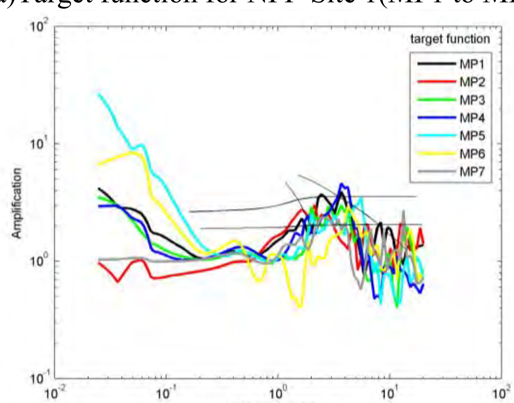
(4) Steps (2) and (3) are repeated for the different target functions (derived from the MP_i being distributed over the NPP area, Figure 3). The location of the Measurement Points (MP_i) can be taken as a selection criterion depending on the design object (structure / component) and its location within the NPP.



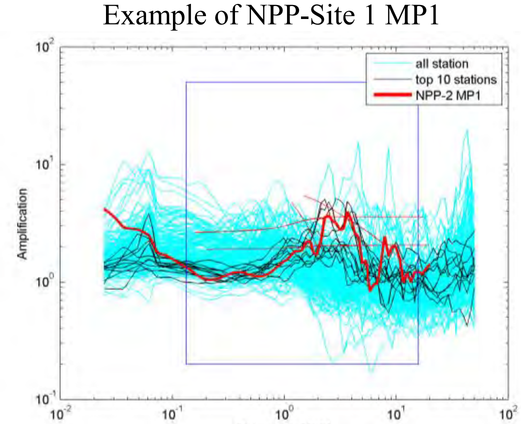
(a)Target function for NPP-Site 1(MP1 to MP6)



Example of NPP-Site 1 MP1



(b) Target function for NPP-Site 2 (MP1 to MP7)



Example of NPP-Site 2 MP1

Figure 3. Target H/V-spectra derived from NPP-Site measurements, and examples for their use as selection criterion regarding the set of reference functions derived from strong-motion recording sites.

Table 1. Number of records in dependence of the Measurement Points considered.

NPP-Site	MP_i	No. of reference stations	No. of records	**NPP-Site**	MP_i	No. of reference stations s	No. of records
1	1-2	14	40	**2**	1-6	28	99
	1-5	26	82		1-5, 7	29	101
	all	30	95		all	37	126

(5) Having identified the reference sites, best fitting the transfer characteristics at the target site (NPP), a simple scoring list is provided, leading to a ranking of all identified reference sites. Strong motion records from these reference sites are combined within a site class that is most appropriate for the ground motion prediction (see Table 1 and Figures 4 to 7).

DATA COMBINATION AND COMPOSITION

The whole procedure can be characterized as a modified „single-station“ approach while only records from classified stations with comparable subsoil profiles (under the assumption of similar site amplification effects) are finally used for the elaboration of Site-Specific Ground Motion Prediction Equations (SGMPEs). The key and linking element of the presented procedure is the instrumental subsoil classification, making the different datasets unique and site-specifically applicable.

The amount of data might vary depending on the selection of Measurement Points being considered within the scoring procedure of steps (3) and (4). The number of reference stations (strong motion recording sites) and the number of available waveforms can be taken from Table 1. Three different data compositions will be considered for both NPP target sites (see Figure 6). The basic Dataset DS1 [CAL] herein applied, is illustrated by the magnitude-distance parameters of all records in Figure 4. Different symbols indicate those records that were selected on the basis of the variant “all MP_i”, where the largest number of records will govern the prediction equations. As it can be concluded from the distribution in Figure 4, the whole procedure leads to a site-specific data composition.

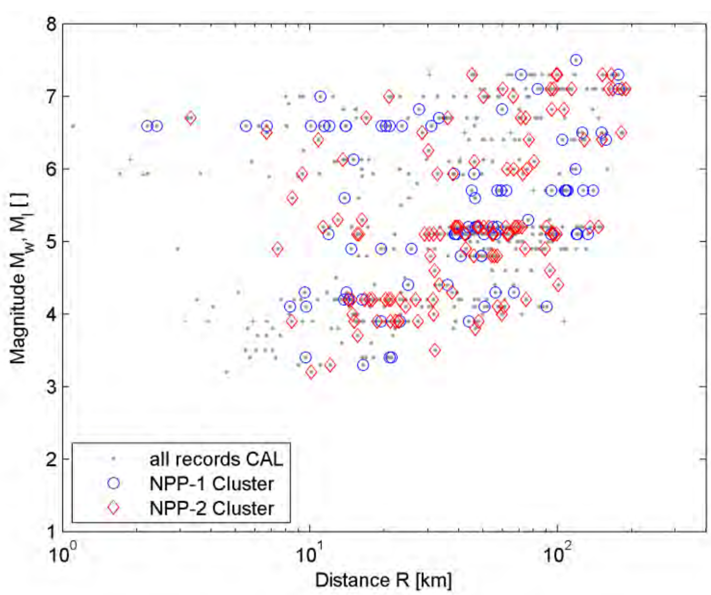


Figure 4. Database for NPP sites selected from Californian strong motion reference sites. Concerning the composition of datasets and Level of Data Acquisition (LODA) see also Table 2.

DATA ELABORATION AND REGRESSION TYPES

Ground Motion Prediction Equation: Generally, two types of regression analyses are elaborated, differing in the applied regression model and in the size of the dataset to rest upon (see Figures 4 and 5).

Regression type I: The dataset is restricted to records in the site classes for which the ground motion prediction is worked out. Since this type of regression is based exactly on that type of data (narrowed dataset) for which a prediction is elaborated, no site coefficients are incorporated. The general form of the regression is given by Equation 1:

$$\log(y) = C_1 + C_2 M + C_3 \log(r) + \sigma P \quad (1)$$

Regression type II: Irrespective of the selected 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. Based on pure rock-type soil conditions, coefficients are determined. Since not all of DIN 4149: 2005 site classes are well-represented by a certain number of records, a regression analysis for some of these site classes (e.g. C-T) may not be representative and is omitted (Schwarz *et al.*, 2007).

The regression model to be used is given by Equation 2. A ground motion prediction for a specific site class (i-j; i-soil class, j-geological class) is performed by setting the respective “Switch” variable $S_{i\text{-}j}$ to 1 while all others are set to 0, thus solely using the respective coefficient C_k. Consequently, a calibration of the results for the particular site classes is ensured by Equation 2:

$$\log(y) = C_1 + C_2 M + C_3 \log(r) + C_4 S_{(B\text{-}R)} + C_5 S_{(C\text{-}R)} + C_6 S_{(B\text{-}T)} + C_7 S_{(C\text{-}T)} + C_8 S_{(C\text{-}S)} + \sigma P \quad (2)$$

with y the ground motion parameter in g (PGA or S_a), M the magnitude (M_w), r a function of the distance measure ($r = \sqrt{(R^2 + h^2)}$), while R is the distance (either epicentral r_{repi} or Joyner-Boore distance r_{JB}), h the source depth and P the uncertainty term in the GMPE.

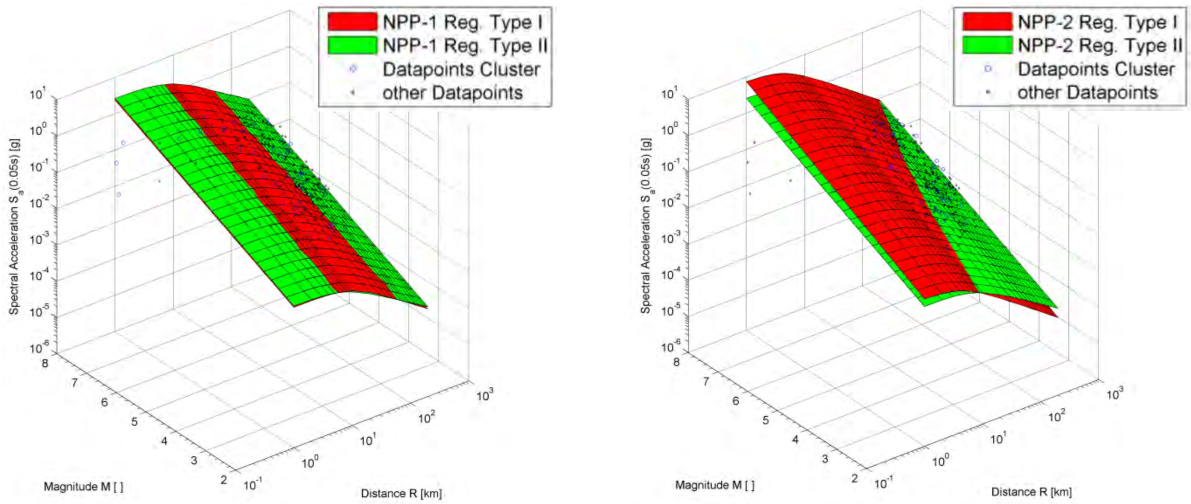
Site-Specific Ground Motion Prediction Equation for NPP sites: In case of the proposed cluster analysis of ground motion records, the prediction Equations 2 have to be replaced by the SGMPE for this regression type. The site class coefficients (C_4 to C_8) and corresponding “Switch”-variables $S_{i\text{-}j}$ have to be extended by the site-specific class for the NPP site. For Equation 1 (Regression type I) no modification is needed, because it is solely based on the site-specific class for the NPP site.

The modifications in Equation 3 are related to NPP-Site 1 where Equation 2 has to be extended by the coefficient C_9 and the corresponding cluster variable $S_{(NPP\text{-}Site,Cluster)}$:

$$\log(y) = C_1 + C_2 M + C_3 \log(r) + C_4 S_{(B\text{-}R)} + C_5 S_{(C\text{-}R)} + C_6 S_{(B\text{-}T)} + C_7 S_{(C\text{-}T)} + C_8 S_{(C\text{-}S)} + C_9 S_{(NPP\text{-}Site,Cluster)} + \sigma P \quad (3)$$

It has to be noticed that recordings contained in the site-specific class have to be removed from their original class. It could happen that all recordings from a certain class move to the site-specific class. In this case the coefficient and “Switch”-variable for that class have to be removed from Equation 3.

Figure 5 illustrates the surface of SGMPE for the period of T = 0.05s within the “magnitude-distance space” of spectral accelerations for both regression types. The dots represent the database within the NPP-Site classes 1 and 2. The SGMPEs have to ensure the closest distance to the data by error minimization procedures. The approach uses a linear magnitude term within the regression types. This seems to be a reliable simplification concerning the reached approximation of the data by the surface created by the SGPME’s for the different periods, which finally describe the spectrum shape and amplitude level.



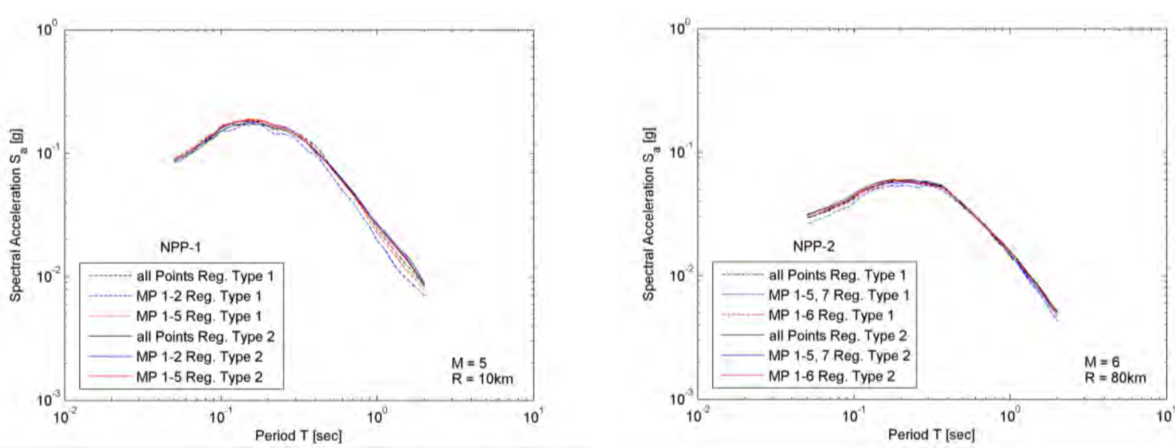
(a) NPP-Site 1 (b) NPP-Site 2

Figure 5. Composition of the NPP-Site specific database (dots) and the corresponding SGMPE (Eq. 1 and 3) visualized as the surface of spectral accelerations within "magnitude-distance space" (see also Figure 4) calculated for period $T = 0.05$s and 5% damping.

SGMPEs can be elaborated for different definitions of the horizontal ground motion. According to German design practice (KTA 2201.1), the definition of a horizontal resultant is preferred. Results in Figure 4 follow the vector sum approach of SDOF-responses proposed by Schwarz and Ahorner (1995).

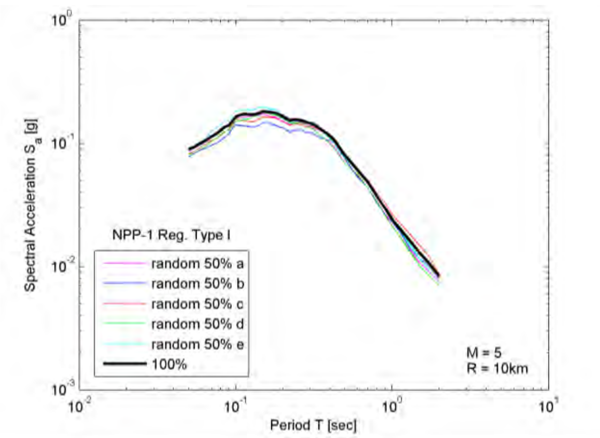
SENSITIVITY STUDIES

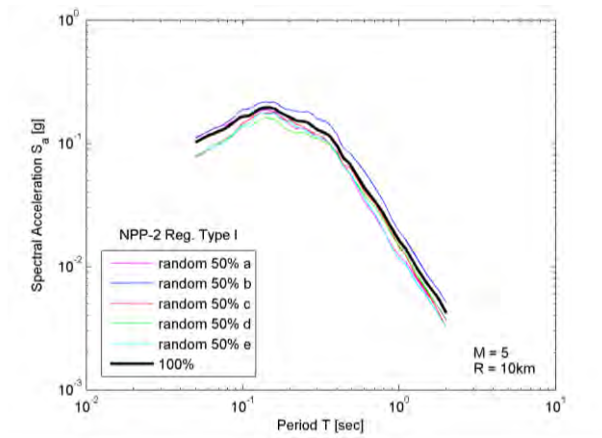
It has to be emphasized that the number and composition of strong motion records used for elaborating the SGMPEs might vary depending on the selection criteria applied to the Measurement Points and therefore, to the number and quality of target functions (see the Median curves in Figures 2 and 3). For illustration, SGMPEs are determined for the cases given by Table 1 using regression Equations 1 and 3. As an outcome of this simple modification of the whole selection process, six SGMPEs for each NPP-Site are available leading to similar spectra for two magnitude-distance combinations, representing probable near and more distant design events (Figure 6).



(a) NPP-Site 1: $M_W = 5.0$; $R = 10$ km (b) NPP-Site 2: $M_W = 6.0$; $R = 80$ km

Figure 6. Results of sensitivity studies including the effect of selected site measurement points (MP_i) on the SGMPE and corresponding spectra for different hazards-related magnitude-distance pairs.





(a) NPP-Site 1:Random 50 (b) NPP-Site 2:Random 50

Figure 7. Comparison of a set of spectra derived from randomly generated SGMPEs referring to a certain percentage (here 50%) of the instrumentally, by cluster analysis identified database „NPP-1" and "NPP-2" (Random *p*: *p* = % of data considered). The „100%" curves are representing the basic model.

The scatter of the predicted spectra in Figure 6 is rather small and represents an element of uncertainty concerning the data selection. A further sophistication is reached by a methodology taking profit from the inherent advantages of a well-elaborated database. By defining a variable *p* between 50% and 100%, some subsets of the whole dataset are randomly selected by a simulation tool with this percentage. Trials "a" to "e" in Figure 7 present the spectra predicted by SGMPEs relying on these randomly selected subsets. This test enables a quality check of the whole NPP site database. The scatter remains in small limits even in the case where only 50% of the complete dataset is allowed to come into consideration. These variants of SGMPEs offer interesting alternatives for visualizing and factorizing the uncertainties in the ground motion models. They are self-representative and also suited for Probabilistic Safety Analysis and similar simulation procedures.

LEVELS OF DATA ACQUISITION (LODA) AND SITE-RELATED DATABASE

Datasets with a different level of ground motion amplitude can be combined if they are similar with respect to the H/V spectral ratio (see Table 2). At the moment, instrumentally classified datasets are also available for strong motion recording sites in Greece, Italy and at other NPP sites. The proposed concept might be considered as practical implication of a single-station approach if the quality of H/V spectra is used to identify the recording sites best fitting the depth profile of the reference site. It is an advantage of the whole approach that the database (the number of classified records) is permanently growing due to the events recorded from Californian (and other investigated) stations leading to different levels of data availability, subsequently considered as **L**evels **o**f **D**ata **A**cquisition (LODA).

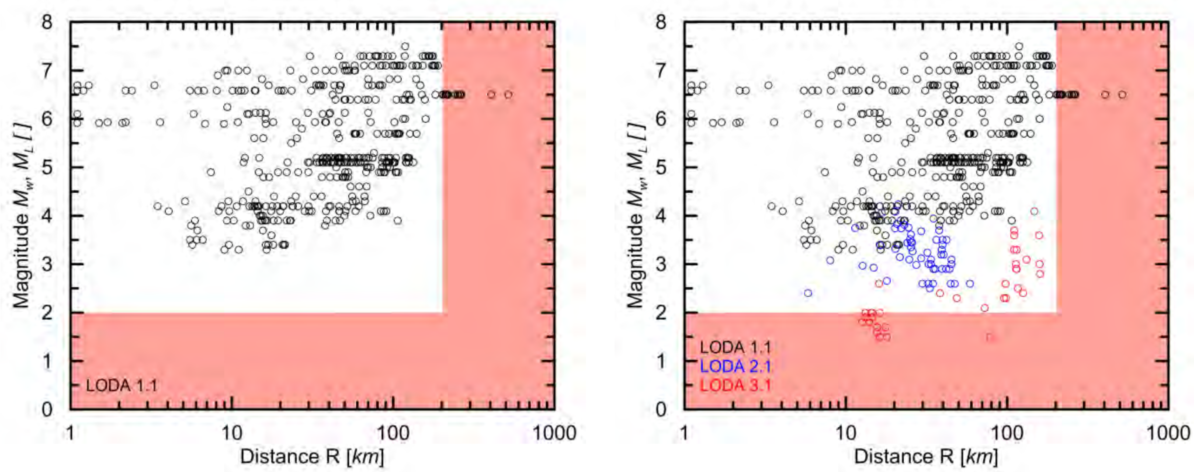
Dataset DS1 [CAL] herein applied consists of 615 strong motion records of around 100 near-field events recorded at 183 stations at the time of the first data elaboration and publication of ground motion prediction equations (by Schwarz *et al.*, 2007). Over several years of data up-dating, different Levels of Data Acquisition (LODA) related to the SGMPEs could be developed and compared with respect to the predicted spectral amplitudes. In a series of parameter studies, the effect of data composition, dataset combination and dataset enlargement (LODA) on predicted spectral accelerations for discrete magnitude-distance-combinations will be checked. Besides the realistic description of site-specific ground motion it can be studied to which extent the procedure contributes to a reduction in the uncertainty of ground motion.

Table 2. Datasets within the instrumentally classified database and their development with respect to the reached **L**evel **o**f **D**ata **A**cquisition (LODA).

Year	Datasets within the whole instrumentally classified Database and **L**evels **o**f **D**ata **A**cquisition (LODA)							
	DS1 [CAL]		DS2 [TRK]		DS3 [NPP-1]		DS4 [NPP-2]	
	code	name	code	name	code	name	code	name
2004	LODA-1.1	CAL-2004	LODA-2.1	TRK-2004				
2006	LODA-1.2	CAL-2006						
2009					LODA-3.1	NPP1-2009		
2013	LODA-1.3	CAL-2013	LODA-2.2	TRK-2013	LODA-3.2	NPP1-2013	LODA-4.1	NPP2-2013

Table 2 illustrates the basic idea behind the approach foreseen to reach a further refinement of NPP-Site related SGMPEs including datasets from other study areas and as well as data arising from a NPP-Site related network of seismic instrumentation. Over a sufficiently long time window, this instrumentation can lead to a general enlargement of weak ground motion records from lower magnitude earthquakes. Following the original intention, the Levels of Data Acquisition (LODA) have to be distinguished with respect to the dataset number and its origin ([CAL], [TRK] etc.), the records included and the time of elaboration (version). Using this precise assignment and by combining datasets with different LODA, a set of SGMPEs be can be created which represent the quality as well as the uncertainty of the ground motion modeling for the target NPP-Site.

The scheme in Table 2 refers to the data elaboration for NPP-Sites. The general concept, the development of a database and therefore, the reached level of data acquisition (LODA) were presented by Schwarz *et al.* (2009), combing the LODA-1.2 (DS1), LODA-2.1 (DS2) and LODA 3.1 (DS3) datasets.



(a) LODA-1.1 (b) LODAs-1.1, 2.1 and 3.1

Figure. 8: Composition of a site-related database as a combination of different datasets (DS) including the option to consider different time **L**evels **o**f **D**ata **A**cquisition (LODA); databases are used for the generation of a set of Site-Specific Ground Motion Prediction Equations (SGMPEs) (starting from the initial dataset DS 1[CAL] with Californian strong-motion recordings (LODA-1.1).

Figure 8(a) explains this for NPP-Site 1, exemplary. The initial point is given with LODA 1.1 (Schwarz *et al.*, 2007) and the dataset DS1 [CAL] created in 2004. The development and the progress in the data elaboration are indicated by the multi-regional composition for LODAs-"1.2 + 2.1+ 3.1". In general, it has to be distinguished between the available data and those which will be selected as „NPP-Site" dataset and input for the SGMPEs (see Figure 4). Shaded areas in Figure 8 represent ranges of magnitude (M_W, $M_L < 2.0$) and distance parameters (r_{Epi}, r_{JB}) which should not be considered. For each „LODA-n.v" (n-number of dataset, v-variant (over the time), see Table 2) the number of records will be different. Results presented in this paper are related to "LODA-1.1", exclusively.

CONCLUSIONS

On the basis of a database composed of uniformly elaborated sub-datasets and records which are site-specific with respect to the depth profile and their site classification, different GMPEs can be derived depending on the conditions of the target site. The instrumental site classification and corresponding characterization of the recordings enables a site-dependent selection of those data which are most appropriate for the hazard level (and the deaggregation of magnitude and distance parameters) as well as for the refinement of site characterization. The dataset for the required site-specific GMPEs can be qualified by records from the target site. The advantage of the approach is quite evident: The equations can be used as input parameters for PSHA, directly. Additional uncertainties resulting from the site response analysis can be avoided. The data reflects the local amplification particularities for the depth profile and ground conditions. Results are realistic and more reliable than those from hypothetical site response studies. Next steps of the presented (still ongoing) studies are focused on the implementation to Probabilistic Seismic Hazard Assessment (including lower bound motion filter) and further site amplification considerations.

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