PREDICTION OF SITE-SPECIFIC GROUND-MOTION PARAMETERS BY A NON-PARAMETRIC APPROACH

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ABSTRACT

A non-parametric empirical approach, called the CAE (Conditional Average Estimator) method has been used for prediction of the ground-motion parameters on soil and rock sites and of soil factors representing the (de)amplification of peak ground and spectral accelerations on soil sites. Using a combined PEER and European database, the soil factors were predicted as a function of the intensity of ground motion, as well as as a function of the magnitude. The results were compared with the results obtained by NGA and European GMPEs and with the soil factors used in different codes. The results of the study reveal that the soil factor decreases with increasing ground motion intensity in terms of accelerations and also with decreasing magnitude of the earthquake. Existing models yield very different results for soil factors. They seem to be mostly conservative. The problem of soil influence is still far from being solved.

INTRODUCTION

Seismic ground motion at a specific site depends on the local site characteristics. In the case of usual structures, the so-called soil factors, representing the ratio between relevant ground motion parameters (typically accelerations) at a soil and a rock site, are used for determining design ground motion parameters. In the case of important structures, like nuclear power plants, ground motion prediction equations (GMPEs) are used for the prediction of the ground motion parameters. GMPEs include soil characteristics, which are typically defined as the shear velocity at the upper 30m of the soil profile, \( V_{30} \).

The problem addressed in this paper is the estimation of the (de)amplification of ground motion at soil sites (compared to rock sites) as a function of the intensity of ground motion. Research has already been performed on this topic (e.g. [1], [2], [3], [4], [5], [6]). Soil factors are provided in codes (e.g. NEHRP Provisions [7], ASCE-7 [8] and Eurocode 8 [9]), and nonlinear soil influence is included in some GMPEs (e.g. NGA, see Earthquake Spectra [10], 2008). Huang et al. [11] proposed a family of site class coefficients which were calculated based on the NGA GMPEs. The problem is, however, that very different results are obtained with different proposals.

In our research, the prediction of ground-motion parameters on rock and soil sites was made by a non-parametric empirical approach, called the CAE (Conditional Average Estimator) method ([12], [13]), which does not take into account any a priori information about the phenomenon. In the paper, the CAE method is briefly summarized. The input and output parameters and the database used in the study are explained. Using a combined PEER and European database, the soil factors are predicted as a function of the intensity of ground motion. The results are compared with the soil factors used in NEHRP/ASCE-7 and Eurocode 8, as well as with the results obtained by an European GMPE (AB – Akkar and Bommer [14]) and NGA GMPEs (AS – Abrahamson and Silva [15], BA – Boore and Atkinson [16], CB – Campbell and Bozorgnia [17] and CY – Chiou and Youngs [18]). A comparison is made also with the HWL - Huang et al. [11] proposal.

COMPUTATIONAL PROCEDURE

The CAE method and input/output variables

The CAE (Conditional Average Estimator) method, used in our study, is an empirical approach for the estimation of an unknown quantity as a function of known input parameters. It is based on a special type of multi-dimensional non-parametric regression and represents a type of probabilistic neural network. A more detailed description of the method is given in [12]. In [13], the CAE method was used for ground motion prediction. The same approach was used also in this study. Using the CAE method, peak ground acceleration \( PGA \) and spectral accelerations \( S_a \) at different periods \( T \), were predicted for selected data of the earthquake (moment magnitude \( M \)) and of the local site (distance measure \( R \), which represents the Joyner-Boore distance \( R_{jb} \) in km, and the soil class \( S \), characterized by the average shear-wave velocity in the top 30 m). In general, four discrete values of parameter \( S \), representing four different soil classes, which are included in the database, were used. However, in this study only
two different soil classes were analyzed, namely “soil” and “rock”. Class “soil” ($S=0.33$) includes data recorded on soils with $180\text{m/s} \leq V_{s30} \leq 360\text{m/s}$ and data characterized as “soft soil” in the European database, whereas class “rock” ($S=1.0$) corresponds to $V_{s30} \geq 760\text{m/s}$ and data characterized as “rock” in the European database. The class “soft soil” ($S=0.0$) which includes data recorded on soils with $V_{s30} < 180\text{m/s}$ and data characterized as “very soft soil” in the European database, and class “stiff soil” ($S=0.67$) which corresponds to $360\text{m/s} < V_{s30} \leq 760\text{m/s}$ and data characterized as “stiff soil” in the European database, were not analyzed in this study. The first (unknown, i.e. $PGA$ and $S_0$) and the second (known, i.e. $M$, $R_{jb}$ and $S$) set of variables are called the output and input variables, respectively. It was assumed that the fault type does not influence the soil amplification factor, therefore it was not used as an input parameter. For analysis, an appropriate database is needed, which provides empirical data of a sufficient number of recordings which include both input and corresponding output variables.

The basic equations of the CAE method [13] can be written as:

$$
\ln P\hat{G}_A = \sum_{n=1}^{N} A_n \ln PGA_n, \quad A_n = \frac{1}{\sum_{i=1}^{N} a_i} a_n = \frac{1}{4\pi^2 w_r w_M w_S} \exp \left[ -\frac{(M-M_e)^2}{2w_M^2} - \frac{(R-R_e)^2}{2w_R^2} - \frac{(S-S_e)^2}{2w_S^2} \right]
$$

where $\ln P\hat{G}_A$ is the estimated $\ln PGA$. $\ln PGA_n$ is $\ln PGA$ of the $n$-th recording in the database, $M_n$, $R_n$ and $S_n$ are the input parameters of the $n$-th recording in the database, $M$, $R$ and $S$ are the input parameters under consideration, and $w_{M}, w_{R}$ and $w_{S}$ are the smoothing parameters for $M$, $R$ and $S$, respectively. In the case of the estimation of spectral values, in Eq. (1) $PGA$ is replaced by spectral acceleration $S_a(T)$. Note that the upper mark in labels $P\hat{G}_A$, which indicates the estimation, will be omitted in the following text.

The choice of smoothing parameters is an important step in the CAE method, which influences the results of the prediction. Although some guidelines can be used, this choice is, for the time being, still subjective. In this study the same values for the smoothing parameters for magnitude and distance were used as in [13] ($w_M=0.4$, $w_R=0.1$, $w_S=3\text{ km}$ and $w_R=8\text{ km}$). For the smoothing parameter for soil class, $w_S = 0.1$ was chosen. Such a small value practically eliminates the influence of the recordings obtained on soils, which belong to a class different than the investigated one.

An intermediate result in the computational process (Eq. (1)) is the estimated probability density function $\rho$ of known input variables. It helps to detect the possible less accurate predictions due to the data distribution in the database and due to local extrapolation outside the data range. The higher the $\rho$ value is, the more registrations (relatively to the total number of registrations in database) with input parameters (e.g. $M$ and $R_{jb}$) similar to the input parameters of the sample registration under consideration exist in the database. When studying the influence of magnitude on the soil factor (see Section Results), predictions characterized by a low $\rho$ value were eliminated.

The database and limitations

The PF-L database [13] includes all records (3550 records representing both main and after-shocks) which are included in five PEER-NGA databases ([10], [19]) and in the European database [14]. For illustration, parts of the PF-L database ($R_{jb} \leq 50 \text{ km}$) are shown in Fig. 1. Both “soil” data ($180\text{m/s} \leq V_{s30} \leq 360\text{m/s}$) and “rock” data ($V_{s30} \geq 760\text{m/s}$) are presented. Bubble size relates to the value of the peak ground acceleration. Considering the scarcity of “rock” data for magnitudes smaller than 5 and larger than 7, only input parameters within $5 \leq M \leq 7$ and $0 \text{ km} \leq R_{jb} \leq 50 \text{ km}$ were taken into account for the determination of soil factors, although all available data were considered in analyses (Eq. (1)). Another feature of the database is a relatively small number of recordings with larger ground accelerations. (Note that for 45% recordings on soil and for 42% recordings on rock $PGA$ was smaller than $0.05\text{g}$.) Because very small accelerations have no engineering significance, only PGAs greater than or equal to $0.05 \text{ g}$ are taken into account. For spectral accelerations, the lower limits of $0.1 \text{ g}$ and $0.05 \text{ g}$ were considered for $S_a$ at $T=0.2\text{s}$ and $T=1.0\text{s}$, respectively.
Fig. 1: Data distribution for the combined PF-L database (European and NGA databases), used in the presented study. Shown are data for rock (235 recordings) and soil sites (1596 recordings) for distances $R_{jb} < 50$km. Bubbles’ area corresponds to PGA

**Soil factor**

The soil factor $SF = SF(M, R_{jb}, S_{soil}, S_{rock})$ in terms of PGA is defined as the ratio between the estimated PGA at a soil site $PGA_{soil}$ and at a rock site $PGA_{rock}$. Both estimates are obtained by the CAE method (Eq. (1)). In both cases the magnitude $M$ and the distance from the fault $R_{jb}$ are the same.

$$SF = \frac{PGA_{soil}}{PGA_{rock}}$$

(2)

In the case of spectral values, in Eq. (2) $PGA$ is replaced by spectral acceleration $S_a(T)$.

In the study, the estimates of $PGA$ (or $S_a(T)$) and the corresponding soil factors were determined for different values of the input variables $M$ and $R_{jb}$. These values were selected in two different ways. In the first variant, Eq. (1) was used for the prediction of $PGA$ (or $S_a(T)$) for $M$ and $R_{jb}$ corresponding to all recordings on “soil” and “rock” sites in the PF-L database within $5 \leq M \leq 7$ and $0 \text{ km} \leq R_{jb} \leq 50 \text{ km}$. In the second variant, $PGA$ (or $S_a(T)$) for both soil types were calculated for discrete values of $M$ and $R_{jb}$ within the same range as above (usually at constant magnitudes, $M$, for the increasing distances from the fault, $R_{jb}$). As noted previously, only the results for $PGA \geq 0.05g$, $S_a(0.2s) \geq 0.1g$, and $S_a(1s) \geq 0.05g$ are considered.

**RESULTS**

Selected results of the study are presented in Figs. 2 and 3. Fig. 2a shows the relation between $PGA_{soil}$ and $PGA_{rock}$ as a function of $PGA_{rock}$. Predictions were made for input variables $M$ and $R_{jb}$ corresponding to recordings measured on rock and on soil sites in the PF-L database (first variant). It can be clearly seen that soil factor depends on the intensity of ground motion. With some exception at the low $PGAs$, the soil factor decreases with increasing $PGA$. At soil sites, site amplification occurs for $PGA$ lower than about 0.3g. For larger $PGA$, the accelerations at soil sites are smaller than at the rock sites. Qualitatively, these features have been well known (see references in Introduction). Qualitatively similar relations were obtained for spectral accelerations at $T=0.2s$ (Fig. 2b). In the case of spectral accelerations at $T=1s$ (Fig. 2c) the soil factor is larger. It also decreases with increasing ground motion intensity. However, a de-amplification at soil sites does not occur. In addition to the discrete results of estimates, the continuous curves representing median results are also shown in Figs. 2. They were obtained by using CAE approach. Any other statistical technique could have been also used.

Results in Fig. 2 suggest that the soil factor generally increases with increasing magnitude. In order to quantify this influence, relations $PGA_{soil} - PGA_{rock}$ and soil factors were predicted for discrete values of magnitudes ($5 - 7$, step 0.5) and distances ($0 - 50$km, step 1km) (the second variant described in section Soil factor). Shown are results for $\rho > 0.3$ (see section The CAE method and input/output variables) and $PGA_{min} \geq 0.05g$, $S_{a,min}(T=0.2s) \geq$...
0.1g, and $S_{a,min}(T=1s) \geq 0.05g$). Results presented in Fig. 3 clearly show that, at the same ground motion intensity at a rock site, the soil factor increases with the magnitude.

![Figure 2: Relation between predictions at soil and rock sites and the soil factor ((a) PGA; (b) $S_a(T=0.2s)$; (c) $S_a(T=1s)$). The diameter of bubbles corresponds to the magnitude.](image)
Fig. 3: Relation between predictions at soil and rock sites and the soil factor for different magnitudes ((a) PGA; (b) $S_a(T=0.2s)$; (c) $S_a(T=1s)$)
COMPARISON WITH EXISTING PROPOSALS

In this section, the soil factors (SFs) obtained by CAE were compared with existing solutions for PGA and spectral accelerations at $T=0.2$ and 1 second. Comparisons were made with SFs from codes (NEHRP [7] / ASCE-7 [8] and Eurocode 8 [9]) and with SFs proposed by Huang-Whittaker-Luco [11] (HWL), as well as with SFs obtained from four NGA GMPEs ([15], [16], [17], [18]) and the European AB model [14]. Note that the HWL model is based on the average SFs values from three NGA models for many different earthquake scenarios.

For Eurocode 8, SFs were determined as the ratio between spectral values for sites C ($360m/s > V_{s30} > 180m/s$) and A ($V_{s30} > 800m/s$, reference rock site), for two different spectral shapes (Type 1 and Type 2). In the case of NEHRP / ASCE-7, SFs were determined as the ratio between spectral accelerations for sites D ($360m/s > V_{s30} > 180m/s$) and B ($1500 > V_{s30} > 760m/s$, reference rock site). The HWL model uses the soil with $V_{s30} = 760m/s$ as the reference site and provides soil factors for soils with shear-velocities of 1500, 360, 180 and 150 m/s. By a linear interpolation, SFs corresponding to a soil site with $V_{s30} = 270m/s$ and a reference rock site with $V_{s30} = 1130m/s$ were obtained. These SFs were used for comparison in this section.

SFs for four NGA models were calculated for the scenario used by Perus and Fajfar [13]. In this study, only vertical strike-slip fault was used for $M=7$ and $Z_{TOP}=1$ km. The median values $Z_{1,0}=0.034$ km and $Z_{1,0}=0.024$ km, recommended by the original authors for a case where the soil/sediment depth was not known, were used for the AS and CY models, respectively. The CB model includes $Z_{2.5}$, which represents the depth to $V_S=2.5$ km/s. A value of $Z_{2.5}=0.64$ km, recommended by the original authors, was used. In the case of the European AB model, the soil site is defined by $V_{s30} \leq 360m/s$ and the reference rock site by $V_{s30} \geq 760m/s$.

The existing SFs recognize the decrease of SFs with increasing ground motion intensity. The only exception is the AB European model. The EC8 soil factors for each of two spectral shapes are independent on the ground motion intensity. However, a distinction is made indirectly, because Type 1 spectrum is intended for earthquakes with larger magnitude.

Comparisons shown in Fig. 4 demonstrate large differences between results obtained by different approaches. The CAE predictions for SFs are represented by smoothed median curves plotted in Figs. 2 and 3. The CAE soil factors are generally smaller than the existing SFs. Some exceptions represent the European models, i.e. EC8 type 1 (for $S_a(T=1)$ also Type 2) and AB model, in the case of small ground motion intensity. The NEHRP / ASCE-7, the HWL and the NGA results provide higher SFs, with the exception of the AS NGA model, which yields very low values in the case of the spectral acceleration at $T=1$. Interestingly, the SFs for CB NGA model match very well with CAE in the case of PGA and $S_a(T=0.2)$. Note that the SFs for the NGA models were determined for $M=7$. However, the influence of magnitude on the soil factors determined from the NGA models is very small.

CONCLUSIONS

The main conclusions of the study are as follows:

- The soil factor depends strongly on the ground motion intensity. It decreases with increasing intensity in terms of peak ground and spectral accelerations.
- The soil factor depends also on the magnitude of the earthquake. It increases with increasing magnitude.
- Existing models yield very different results for soil factors.
- Existing models seem to predict mostly conservative soil factors.

The results suggest that the problem of predicting the site (de)amplification of seismic ground motion is far from being solved and that additional research is needed. The rapidly increasing databases of recorded ground motions will facilitate the development of more reliable ground motion predictions.
Fig. 4: Comparison of SFs for PGA (a) and spectral accelerations at $T=0.2\text{s}$ (b) and $T=1\text{s}$ (c)
(NGA models: $V_{s30,\text{rock}}=1100\text{m/s}$, HWL model: $V_{s30,\text{rock}}=1130\text{m/s}$)
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