PREDICTION OF SOIL FACTORS BY A NON-PARAMETRIC APPROACH

I.Peruš, & P.Fajfar
Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova 2, Slovenia

SUMMARY:
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. A non-parametric empirical approach, called the CAE (Conditional Average Estimator) method has been used. Soil factors (*SF*s) for peak ground acceleration and spectral accelerations were predicted by using combined PEER and European database of recorded ground motions. Comparisons were made with *SF*s used in codes (Eurocode 8 and ASCE 7-10), with *SF*s proposed by Huang-Whittaker-Luco, with *SF*s obtained from four NGA GMPEs, and the European Akkar-Bommer model. The study reveals that: (1) *SF*s depend strongly on the ground motion intensity. They depend also on the magnitude of the earthquake. (2) Existing models yield very different results for *SF*s. (3) *SF*s predicted in this study are, for higher intensities of ground motion, generally smaller than the existing ones.

Keywords: soil factor, ground motion, NGA models, seismic codes, CAE method

1. 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 in terms of the shear velocity at the upper 30m of the soil profile, V_{s30}.

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. Seed and Idriss, 1982, Darragh and Shakal, 1991, Borcherdt, 1994, Choi and Stewart, 2005, Walling et al., 2008, Zhao et al., 2009). Soil factors are provided in codes and standards (e.g. NEHRP Provisions, 2003, ASCE/SEI 7-10, 2010 and Eurocode 8, 2005), and nonlinear soil influence is included in some GMPEs (e.g. NGA, see Earthquake Spectra, 2008). Huang et al. (2010) 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. The differences depend on the used database, reference ground motion, the procedure used to infer the resultant soil factors, and site classification method. The latter is thought to be the most significant contributor to the uncertainty in the various estimates (Borcherdt, 2002). Recently, the importance of soil factors and their proper use in PSHA was discussed by Goulet and Stewart (2009). They proposed a simple modification of usual hybrid procedure to reduce the bias.

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 (Perus et al., 2006, Perus and Fajfar, 2010), 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 ASCE 7-10 and Eurocode 8, as well as with the results obtained by an European GMPE (AB – Akkar and Bommer, 2010) and NGA GMPEs (AS – Abrahamson and Silva, 2008, BA – Boore and Atkinson, 2008, CB – Campbell and Bozorgnia, 2008 and CY – Chiou and Youngs, 2008). A comparison is made also with the HWL - Huang et al. (2010) proposal.

2. THE DATABASE

The PF-L database used in the presented study was reconstructed based on the recent data available in the literature and/or through the help and kind co-operation of the original authors. Thus, the PF-L database (Perus and Fajfar, 2010) includes all records (3550 records representing both main and after-shocks) which are included in five PEER-NGA databases (Earthquake Spectra, 2008, PEER NGA, 2010) and in the European database (Akkar and Bommer, 2010). This database is used in this study primarily for comparison with the NGA models and with proposed soil factors of the HWL model, and for consistency with work by Perus and Fajfar (2010). For illustration, parts of the PF-L database (R_{jb} ≤ 50 km) are shown in Fig. 1. Both “soil” data (180m/s ≤ V_{s30} ≤ 360m/s and data characterized as “soft soil” in the European database) and “rock” data (V_{s30} ≥ 760m/s and data characterized as “rock” in the European database) are presented. The area of circles is related to the value of the spectral acceleration at T=0.2s (Fig. 1). Fig. 1 indicates that the amount of “rock” data is much smaller than the amount of “soil” data and that there are very little “rock” data for magnitudes larger than 7 and smaller than 5. Fig. 2 shows that majority of data corresponds to weak ground motions.

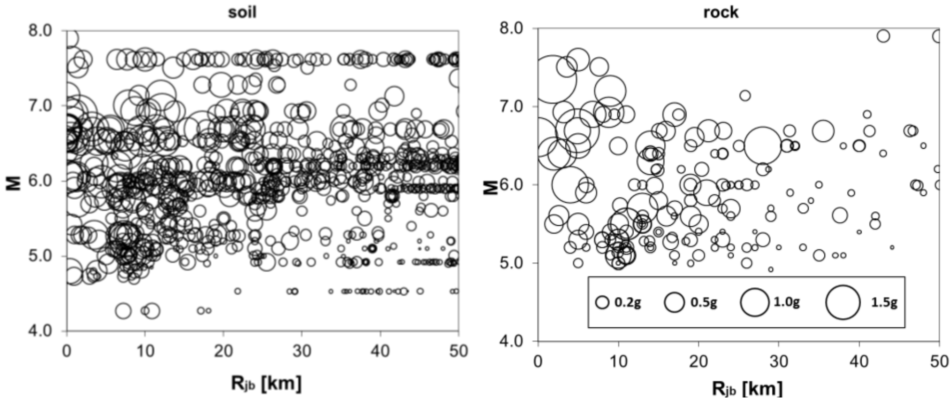


Figure 1. Data distribution for the combined PF-L database (European and NGA databases), used in the study. Shown are data for soil (1596 recordings) and rock sites (235 recordings) for distances R_{jb} < 50km. The area of circles corresponds to S_a(T=0.2s)

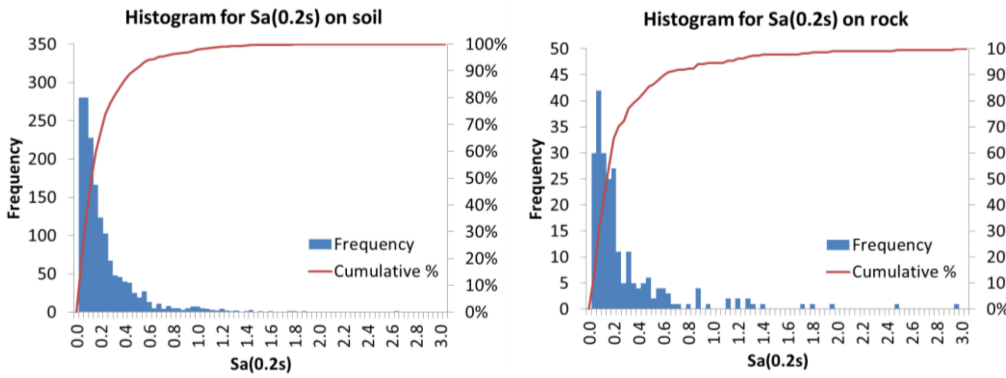


Figure 2. Histograms for S_a(T=0.2s) from PF-L database for soil and rock sites

3. THE ESTIMATION OF THE SOIL FACTOR

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 by Perus et al. (2006). Perus and Fajfar (2010) used the CAE method 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). Four different soil classes, represented by four discrete values of parameter *S*, were defined in the PF-L database (see Perus and Fajfar, 2010). However, in this study only two different soil classes were analyzed, namely “soil” and “rock”. The first (unknown, i.e. *PGA* and S_a) 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 variable.

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 (Perus and Fajfar, 2010) can be written as:

$$\ln P\hat{G}A = \sum_{n=1}^{N} A_n \cdot \ln PGA_n \quad , \quad a_n = \frac{1}{4\pi^2 \; w_R w_M w_S} \exp\left[-\frac{(M-M_n)^2}{2w_M^2} - \frac{(R-R_n)^2}{2w_R^2} - \frac{(S-S_n)^2}{2w_S^2} \right] \tag{3.1}$$

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. 3.1 *PGA* is replaced by spectral acceleration $S_a(T)$.

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 proposed by Perus and Fajfar (2010) (w_M=0.4, $w_{R=0}$=3 km and $w_{R=50}$=8 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. 3.1) is the estimated probability density function ρ 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 ρ 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 (Perus et al., 2006, Perus and Fajfar, 2010).

The soil factor *SF* = *SF*(*M*, R_{jb}, *S*) 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. 3.1). In both cases the magnitude *M* and the distance from the fault, R_{jb}, are the same.

$$SF = \frac{P\hat{G}A_{soil}}{P\hat{G}A_{rock}} \tag{3.2}$$

In the case of spectral values, $P\hat{G}A$ in Eq. 3.2 is replaced by spectral acceleration $\hat{S}_a$. Note that the upper mark in labels $P\hat{G}A$ and $\hat{S}_a$ which indicates the estimation/prediction, will be omitted in the following text and figures.

In this study, in the first stage, Eq. 3.1 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 $0 \text{ km} \leq R_{jb} \leq 50$ km. The *SFs* were determined from these results according to Eq. 3.2.

In this way, a new, smaller database was formed, which includes data on *PGA* and $S_a(T)$ for soil and rock sites for the same event (equal *M*) and at the same distance (equal R_{jb}), and corresponding *SFs* (determined according to Eq. 3.2). The new database was further reduced by eliminating data corresponding to weak ground motions without engineering significance. Only data corresponding to recordings with predicted $S_a(T=0.2\text{s})$ greater than or equal to 0.2 g remained in the reduced database. Moreover, all less accurate predictions characterized by $\rho < 0.3$ were eliminated. The final reduced database, which was used in the second stage of analyses, comprised 226 recordings.

In the second stage, the reduced database was used for analysing the predicted *SF*s and to present them in different formats. Two different types of analyses were used:

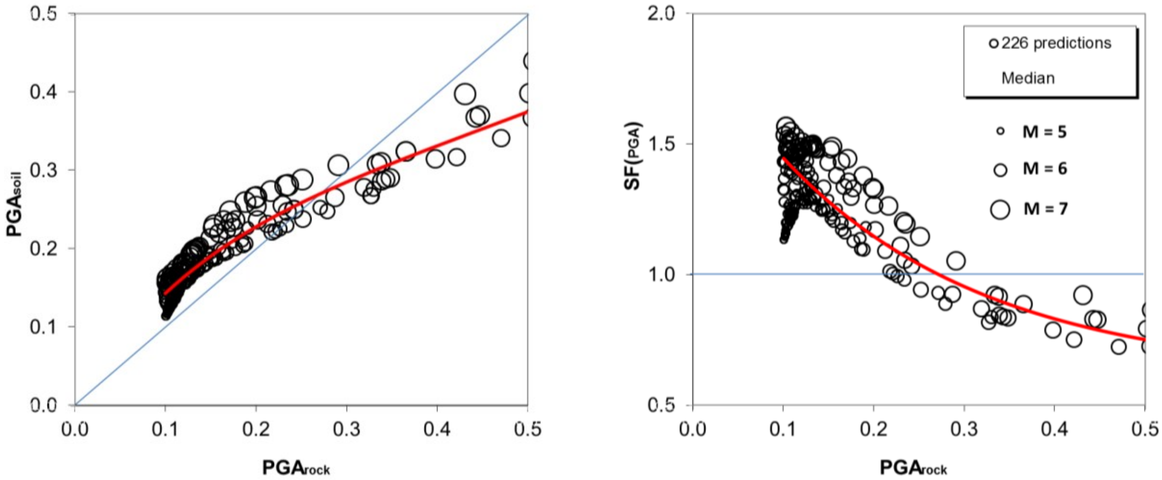
- A standard statistical regression analysis was performed in order to obtain *SF*s as a smooth function of *PGA*, $S_a(0.2\text{s})$ and $S_a(1\text{s})$ on reference rock site. The results are presented in Fig. 5.
- *SFs* were calculated by using the CAE method for selected discrete values of PGA_{rock} and *M*. In this way, *SFs* can be determined at a constant magnitude, *M*, for increasing values of PGA_{rock}. This approach was used for the determination of spectral soil factors shown in Figs. 4a and 6.

4. RESULTS

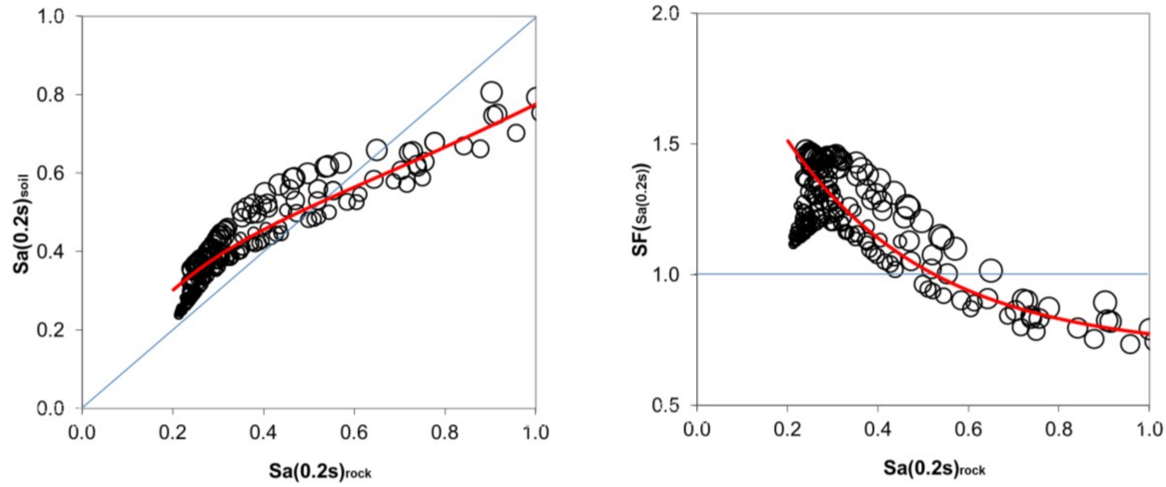
Selected results of the study are presented in Figs. 3. Fig. 3a shows the relation between PGA_{soil} and PGA_{rock}, and soil factors as a function of PGA_{rock}. It can be clearly seen that the soil factor depends on the intensity of ground motion. With some exception at low *PGAs*, soil factors decrease 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 those 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. 3b). In the case of spectral accelerations at T=1s (Fig. 3c) the soil factors are larger. They also decrease with increasing ground motion intensity. However, a de-amplification at soil sites does not occur. The continuous curves representing mean results are also shown in Figs. 3. They were obtained using nonlinear regression by applying the general form for the soil factor: $SF = a \cdot \exp(b \cdot PGA_{rock}) + c$, whereas PGA_{soil} in the left hand diagram (Fig. 3) was obtained as $PGA_{soil} = SF \cdot PGA_{rock}$. For spectral accelerations, S_a, PGA_{rock} and PGA_{soil} were replaced with $S_{a,rock}$ and $S_{a,soil}$, respectively.

Results in Fig. 3 suggest that the soil factor generally increases with increasing magnitude. This influence was presented and discussed more in detail by Perus and Fajfar (2011). The results by Perus and Fajfar (2011), presented at constant magnitudes, clearly showed that, for the same ground motion intensity (in terms of *PGA* or S_a at a rock site), the soil factor increases with the magnitude.

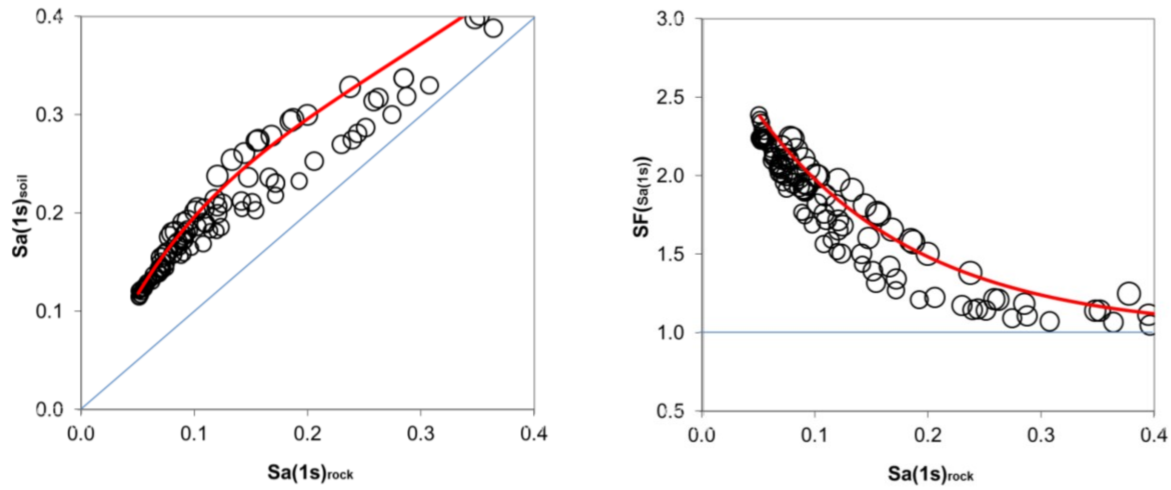
In Fig. 4 the predicted acceleration spectra for rock and soil, and spectral soil factors for constant PGA_{rock} are presented for a M6.5 strike-slip earthquake scenario from Perus and Fajfar (2010). (Note that the procedure for obtaining soil factors presented in Fig. 4 – and those in Fig. 6 – was different from the procedure used for obtaining Figs. 3 and 5, as explained in Chapter 3.) The CAE soil factors are similar to those obtained by CB NGA model at short periods. However, very large differences can be observed at T=1 s. A substantial decrease of the soil factor with increasing ground motion intensity is clearly visible in the whole period range.



(a) PGA



(b) $S_a(T=0.2s)$



(c) $S_a(T=1s)$

Figure 3. 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 circles corresponds to the magnitude

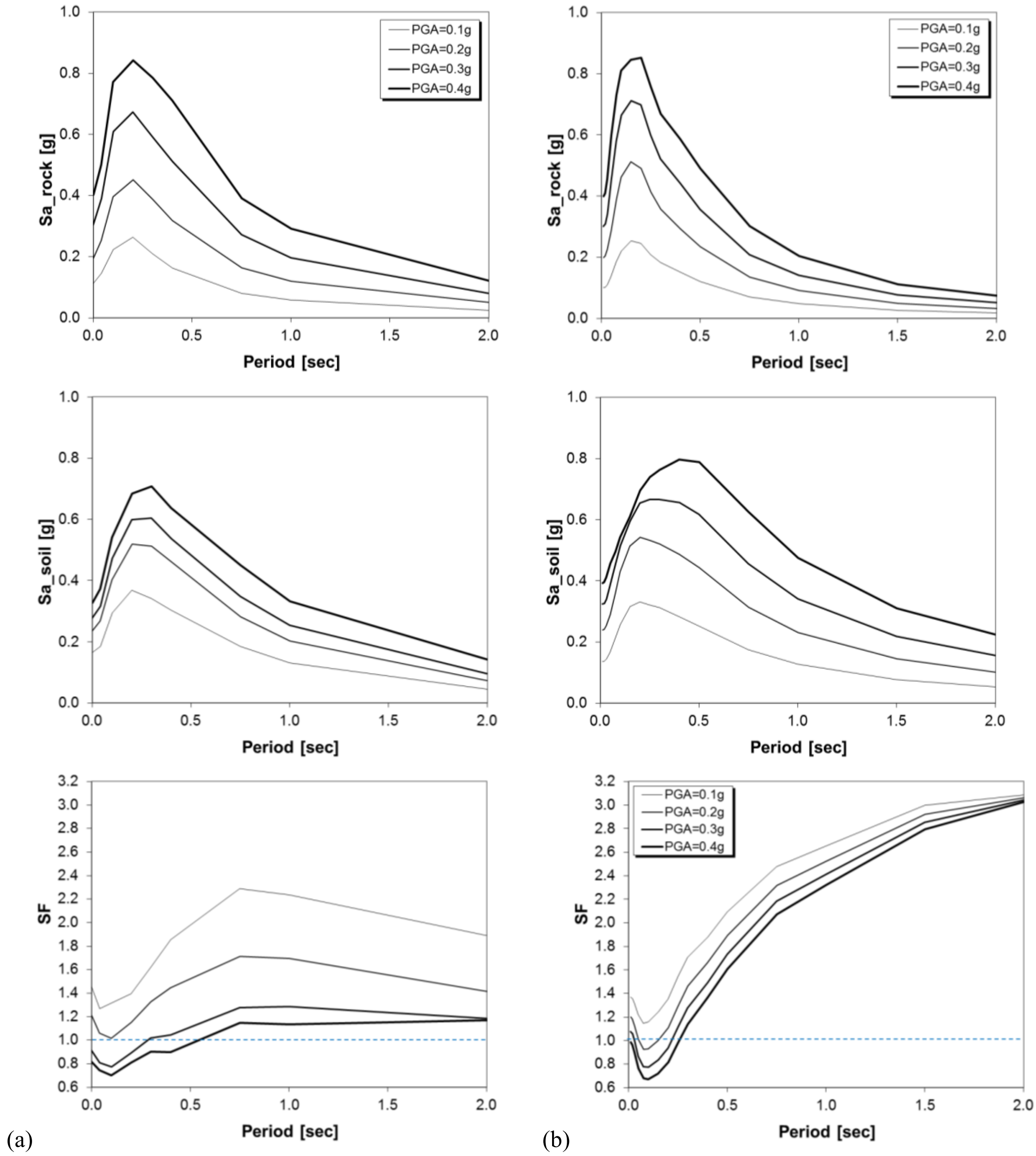
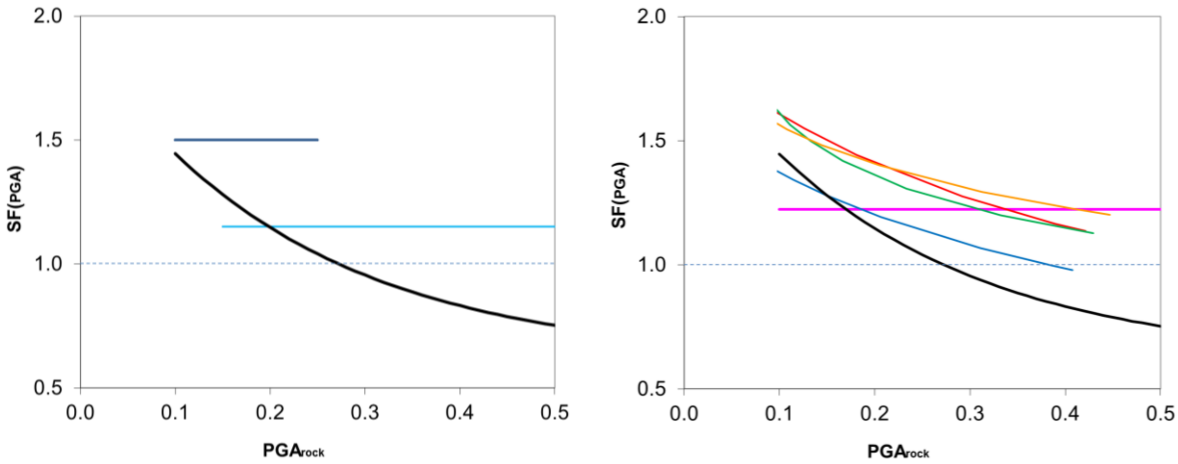


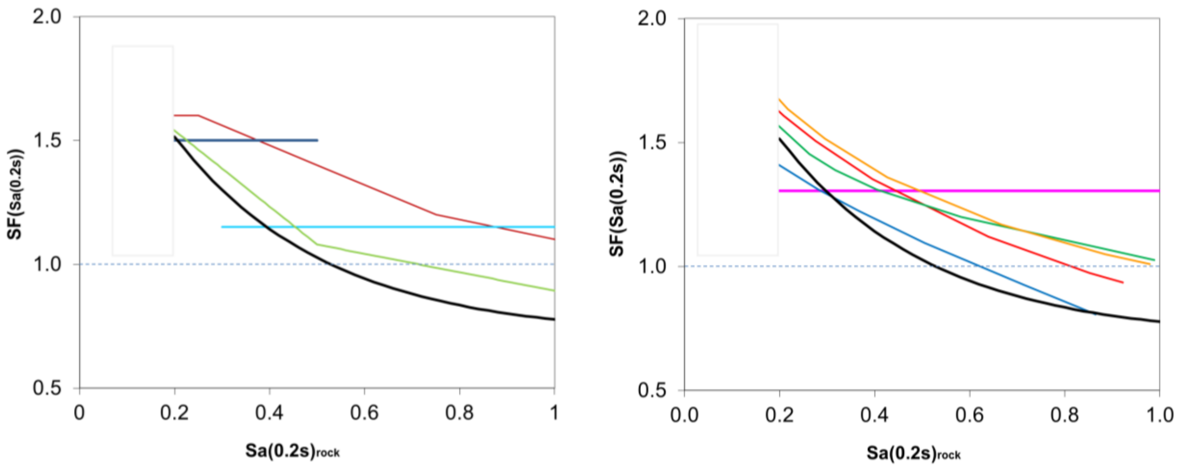
Figure 4. Spectra for rock and soil, and corresponding spectral soil factors for constant PGA_{rock} for a *M*6.5 event (strike-slip earthquake scenario from Perus and Fajfar (2010)) by (a) the CAE method and (b) CB NGA model

5. COMPARISON WITH SELECTED PROPOSALS

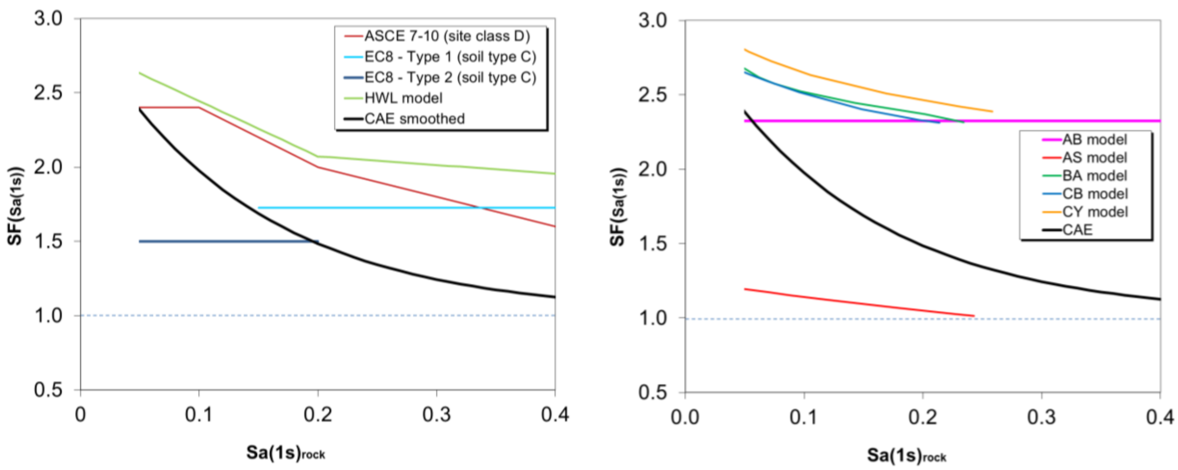
In this section, the soil factors (*SF*s) for *PGA* and spectral accelerations S_a at T=0.2 and 1 second obtained by CAE in this study were compared with some existing proposals. Comparisons were made with *SF*s from codes and standards (ASCE 7-10, 2010 and Eurocode 8 (EC8), 2005) and with *SF*s proposed by Huang-Whittaker-Luco (HWL, 2010), as well as with *SF*s obtained from four NGA GMPEs (Abrahamson and Silva, 2008, Boore and Atkinson, 2008, Campbell and Bozorgnia, 2008, Chiou and Youngs, 2008) and the European AB model (Akkar and Bommer, 2010). Note that the HWL model is based on the average *SF*s values from three NGA models (AB, CB and CY) for many different earthquake scenarios.



(a) PGA



(b) $S_a(T=0.2\text{s})$



(c) $S_a(T=1\text{s})$

Figure 5. Comparison of SFs for *PGA* (a) and spectral accelerations at T=0.2s (b) and T=1s (c) (NGA models: V_{s30_rock}=1100m/s, M=6.5, HWL model: V_{s30_rock}=1130m/s)

For EC8, *SF*s 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 is, according to EC8, appropriate for stronger earthquakes, and type 2 for weaker ones. In the case of

ASCE 7-10, *SF*s 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, *SF*s corresponding to a soil site with V_{s30} = 270m/s and a reference rock site with V_{s30} = 1130m/s (mean value of soils with V_{s30}=760 and 1500 m/s) were obtained.

*SF*s for four NGA models were calculated for the scenario used by Perus and Fajfar (2010). In that study, a vertical strike-slip fault was assumed with M=6.5 and Z_{TOP}=2 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 results are compared in Fig.5. The existing *SF*s, with the only exception of the AB European model, recognize the decrease of *SF*s with increasing ground motion intensity The EC8 soil factors for each of two spectral shapes are independent of the ground motion intensity. However, a distinction is made indirectly, because Type 1 spectrum is intended for earthquakes with larger magnitudes.

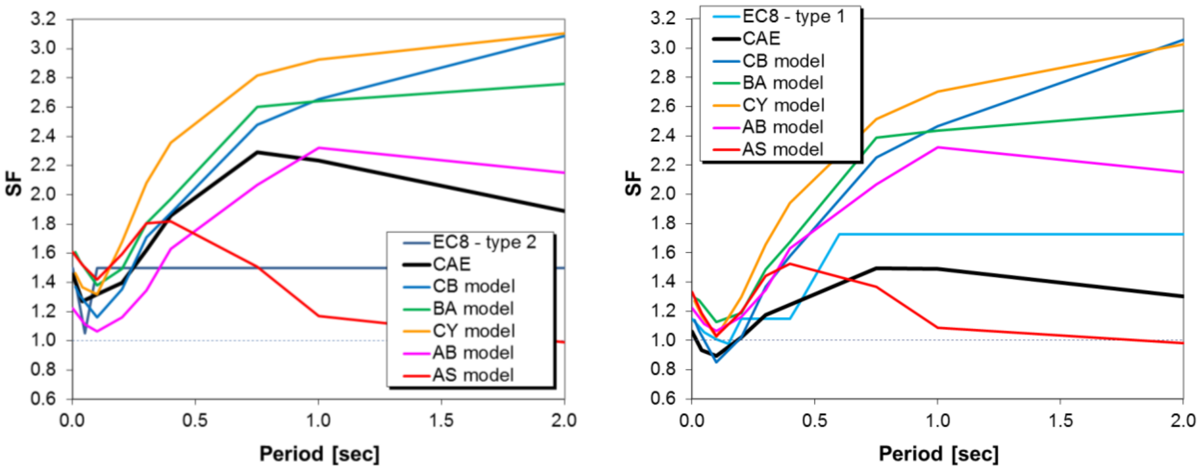


Figure 6. Comparison of spectral soil factors for two different *PGA*s. Results for the proposed CAE method and four NGA models were calculated for the *M*6.5 strike-slip earthquake scenario from Perus and Fajfar (2010)

The results shown in Fig. 5 demonstrate large differences between predictions obtained by different approaches. The CAE soil factors are generally smaller than the existing *SF*s, with some exceptions at small ground motion intensities. An exception is the AS NGA model, which yields very low values in the case of the spectral acceleration at T=1s. Interestingly, the *SF*s for CB NGA model match very well with CAE in the case of *PGA* and $S_a(T$=0.2). Note that the *SF*s for the NGA models were determined for M=6.5. However, the influence of magnitude on the soil factors determined from the NGA models is very small.

Comparison of spectral soil factors for two different values of *PGA* also reveals differences between different proposals (Fig. 6). In the short-period range, they are within reasonable limits. However, in the medium-period range, the differences increase substantially. The long-period range was not studied. Three NGA models (CB, BA and CY) provide similar spectral soil factors over the entire considered period range. Their values are at the upper limit of all results in the medium-period range. The AS NGA model provides in the short-period range similar results as the other three NGA models. However, in the medium-period range the soil factors estimated by this model present the lower limit of all results. Eurocode 8 type 2 spectrum results are at the lower end in the medium-period range at small intensities. At higher intensities the spectral soil factors according to Eurocode 8 type 1 spectrum are generally near (a little bit below) to the average values of investigated models. The soil factors obtained by the CAE method in this study are near to average results in the case of weak ground motion (PGA_{rock} = 0.1g), whereas they are smaller than all other results (with the exception of the AS NGA model in the medium-period range, and, locally, of the Eurocode 8 in the short period range) in the case of PGA_{rock} = 0.25g.

6. CONCLUSIONS

A non-parametric empirical approach, called the CAE (Conditional Average Estimator) method has been used for the estimation of soil factors. The results were compared with the results obtained from NGA and European GMPEs and with the soil factors used in different codes and standards.

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.
- The CAE results are, for weak ground motions, near to the average values obtained from investigated models. In the case of larger intensities they are smaller than those obtained by most existing models.

The results of this study suggest that the problem of predicting the site (de)amplification of seismic ground motion by using soil factors 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.

ACKNOWLEDGEMENT
The research presented in this paper has been supported by the Slovenian Research Agency. This support is gratefully acknowledged.

REFERENCES

Abrahamson, N.A. and Silva, W.J. (2008). Summary of the Abrahamson & Silva NGA Ground motion Relations. *Earthquake Spectra* **24:1**, 45-66.

Akkar, S. and Bommer, J.J. (2010). Empirical equations for the prediction of PGA, PGV, and spectral accelerations in Europe, the Mediterranean region, and the Middle East. *Seismological Research Letters* **81:2**, 195-206.

American Society of Civil Engineers (ASCE) (2010). Minimum design loads for buildings and other structures, ASCE/SEI 7-10, American Society of Civil Engineers, Reston, Virginia, USA.

Boore, D.M. and Atkinson, G.M. (2008). Ground motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. *Earthquake Spectra* **24:1**, 99-138.

Borcherdt, R.D. (1994). Estimates of site-dependent response spectra for design (methodology and justification). *Earthquake Spectra* **10**, 617–653.

Borcherdt, R.D. (2002). Empirical Evidence for site coefficients in building code provisions. *Earthquake Spectra* **18:2**, 189-217.

Building Seismic Safety Council (BSSC) (2003). NEHRP Recommended Provisions and Commentary for Seismic Regulations for New Buildings and Other Structures. FEMA 450CD, Washington DC, USA.

Campbell, K.W. and Bozorgnia, Y. (2008). NGA Ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s. *Earthquake Spectra* **24:1**, 139-171.

CEN, Eurocode 8 (2005). Design of structures for earthquake resistance, Part 3: Assessment and retrofitting of buildings, EN 1998-3, Brussels.

Chiou, B.S.J. and Youngs, R.R. (2008). An NGA model for the average horizontal component of peak ground motion and response spectra, *Earthquake Spectra* **24:1**,173-215.
Choi, Y. and Stewart, J.P. (2005). Nonlinear site amplification as a function of 30 m shear wave velocity. *Earthquake Spectra* **21:5**, 1-30.
Darragh, R.B. and Shakal, A.F. (1991). The site response of two rock and soil station pairs to strong and weak ground motion. *Bulletin of the Seismological Society of America* **81:5**, 1885-1899.
Earthquake Spectra (2008). Special Issue on the Next Generation Attenuation Project. **24:1**, 1-341.
Goulet, C.A. and Stewart. J.P. (2009). Pitfalls of deterministic application of nonlinear site factors in probabilistic assessment of ground motions. *Earthquake Spectra* **25:3**, 541-555.
Huang, Y., Whittaker, A.S. and Luco, N. (2010). NEHRP site amplification factors and the NGA relationships. *Earthquake Spectra* **26:2**, 583-593.
PEER NGA (2010). http://peer.berkeley.edu/products/strong_ground_motion_db.html.
Perus, I., Poljansek, K. and Fajfar, P. (2006). Flexural deformation capacity of rectangular RC columns determined by the CAE method. *Earthquake Enginering and Structural Dynamics* **35:12**, 1453-1470.
Perus, I. and Fajfar, P. (2010). Ground motion prediction by a non-parametric approach. *Earthquake Enginering and Structural Dynamics* **39:12**, 1395-1416.
Perus, I. and Fajfar, P. (2011), Prediction of site-specific ground-motion parameters by a non-parametric approach, *Transactions, SMiRT 21*, **Divison I**, paper No. 102.
Seed, B.H. and Idriss, I.M. (1982). Ground motions and soil liquefaction during earthquakes. EERI publication, 1982.
Walling, M., Silva, W. and Abrahamson, N. (2008). Nonlinear site amplification factors for constraining the NGA models. *Earthquake Spectra* **24:1**, 243-255.
Zhao, J.X., Zhang, J. and Irikura, K. (2009). Side effect of using response spectral amplification ratios for soil sites – variability and earthquake-magitude and source-distance dependent amplification ratios for soil sites. *Soil Dynamics and Earthquake Engineering* **29**, 1262-1273.