Multi-Variable Relations for Soil Effects on Elastic Response Spectra

GEORGE D. BOUCKOVALAS
Professor N.T.U.A.

ACHILLEAS G. PAPADIMITRIOU
Dr Civil Engineer N.T.U.A.

Abstract
A set of simple relations is proposed for the evaluation of soil effects on normalized elastic response spectra (5% damping), which are complementary to the relations for the fundamental soil period and the peak seismic acceleration and velocity presented in a companion paper. Namely, the soil surface-to-bedrock outcrop ratio of the normalized spectral accelerations is related to five (5) basic site and excitation parameters: the fundamental vibration periods of the soil $T_s$ and the bedrock $T_b$, the predominant excitation period $T_e$, the peak seismic acceleration at outcropping bedrock $a_{max}^b$, and the number of equivalent harmonic cycles $n$. As for the peak seismic acceleration and velocity, the effect of each parameter was estimated from a multivariable regression analysis of relevant data from more than 700 one-dimensional equivalent-linear seismic ground response analyses, for natural sites and seismic excitation conditions. The proposed relations are verified against the aforementioned database, but mainly through a detailed comparison with independent numerical predictions and actual strong motion recordings from seven (7) well documented case studies: a) two sites in the San Fernando valley during the Northridge earthquake and b) five different seismic events recorded by the SMART-1 accelerometer array in Taiwan.

1. INTRODUCTION

The companion paper [3] presents a set of relations for the approximate estimation of soil effects on the non-linear site period and the peak seismic acceleration and velocity. This paper presents similar relations for the 5% damped normalized spectral accelerations. The proposed relations in both papers comprise an integrated framework describing all aspects of seismic site response of engineering interest.

The general form of the relations draws upon 1-D wave propagation theory for a uniform site with harmonic base excitation [3]. In this way, the prediction of soil effects becomes more refined, suitable for practical applications when the more accurate site-specific numerical predictions are not justified or cannot easily be implemented (e.g. GIS-aided seismic microzonation studies [7]). A similar compilation of actual seismological data, although more rigorous, is not presently possible, as only a small part of the available recordings is accompanied by adequate information regarding the engineering characteristics of the site and the seismic excitation.

The data and the general methodology used herein are the same as in [3]. Specifically, the proposed relations are based on data from over 700 numerical analyses, for actual seismic excitations and natural soil conditions, performed with the equivalent linear method ([8], [6]). In this way, the values of all parameters varied within a wide range, making a multivariable regression analysis of the data reliable. The relative error of the proposed relations is estimated on the basis of the numerical analyses in the database, but their validity is mainly verified against actual recordings and related numerical analyses for seven (7) cases not included in the database and presented in detail in this paper.

2. LIST OF SYMBOLS

$H$ Thickness of soil column
$V_s$ Shear wave velocity in uniform soil
$V_{s,o}$ Average elastic shear wave velocity in soil column
$T_s$ Fundamental soil period
$T_{s,o}$ Fundamental elastic soil period
$T_e$ Predominant excitation period
$T_{str}$ Fundamental structural period
$V_b$ Shear wave velocity in (uniform) bedrock
$T_b$ Fundamental (uniform) bedrock period ($=4H/V_b$)
$a_{max}^b$ Peak horizontal acceleration at outcropping bedrock
$a_{max}$ Peak horizontal acceleration at soil surface
$A_a$ Outcropping bedrock to soil surface peak horizontal acceleration amplification ratio
$S_a$ Spectral horizontal acceleration at 5% critical damping
$S_a^s$ Horizontal spectral acceleration for 5% critical damping at soil surface
$S_a^b$ Horizontal spectral acceleration for 5% damping of critical at outcropping bedrock
$A_{Sa}$ Outcropping bedrock to soil surface amplification ratio of horizontal spectral acceleration

Submitted: Oct. 30, 2002 Accepted: July 1, 2004
(S_a^*)^* \text{ Normalized horizontal spectral acceleration at soil surface for 5% critical damping}
(S_a^h)^* \text{ Normalized horizontal spectral acceleration at outcropping bedrock for 5% critical damping}
A_{Sa}^* \text{ Normalized outcropping bedrock to soil surface amplification ratio of horizontal spectral acceleration (for 5% damping)}
A_{Sa,p}^* \text{ Peak value of } A_{Sa}^*
R_{Sa,p}^* \text{ Relative error in the estimation of } A_{Sa,p}^*
A_{Sa,r}^* \text{ Residual value of } A_{Sa}^*
R_{Sa,r}^* \text{ Relative error in the estimation of } A_{Sa,r}^*
A \text{ Number of equivalent uniform cycles of excitation}
D \text{ Depth to hypocenter of earthquake}
R \text{ Distance to epicenter of earthquake}

3. METHODOLOGY OUTLINE

Rather than the spectral acceleration itself, the emphasis here is placed on the (5% damped) normalized spectral acceleration \( S_a^* = S_a^* / a_{max} \), and the corresponding soil surface-to-bedrock outcrop amplification ratio:

\[
A_{Sa}^* = \frac{\left(S_a^*\right)_{\text{soil}}}{\left(S_a^*\right)_{\text{bedrock}}} \quad (3.1)
\]

This ratio can be equivalently written as:

\[
A_{Sa}^* = \frac{A_{Sa}}{A_{g}} \quad (3.2)
\]

where \( A_{Sa} \) is the actual amplification ratio of the spectral acceleration, while \( A_{g} \) is the amplification ratio for the peak ground acceleration, estimated as proposed in [3].

As an example, Fig. 1 shows typical equivalent-linear numerical predictions for the variation of \( A_{Sa}^* \) in terms of the structure-to-soil fundamental period ratio \( (T_s/T_e) \). The predicted \( A_{Sa}^* \) spectra procure by applying the same site to two (2) excitations with the same \( a_{max}^b = 0.30 \text{g} \), but with widely different frequency content. Observe that:

a) The frequency content of the excitation has a secondary effect on \( A_{Sa}^* \).

b) For rigid structures \( (T_s/T_e \equiv 0) \), \( A_{Sa}^* \equiv 1 \).

c) For structures with \( T_s/T_e \) (resonance), the \( A_{Sa}^* \) reaches a peak, hereafter denoted by \( A_{Sa,p}^* \), and

d) For more flexible structures \( (T_s/T_e > 1) \), the \( A_{Sa}^* \) gradually decreases and tends asymptotically to a residual value, denoted by \( A_{Sa,r}^* \).

As shown in Fig. 1, the numerical predictions for the normalized spectral amplification ratio \( A_{Sa}^* \) can be simulated by this relatively simple analytical expression:

\[
A_{Sa}^* = \frac{1 + B_1}{2B_2} \left( \frac{T_e}{T_s} \right)^{3/2} \quad (3.3)
\]

According to Eq. (3.3):

\[
A_{Sa,p}^* = \frac{1 + B_1}{2B_2} \quad (3.4)
\]

\[
A_{Sa,r}^* = B_1 \quad (3.5)
\]

Equivalently, the parameters \( B_1 \) and \( B_2 \) can be written as:

\[
B_1 = A_{Sa,r}^* \quad (3.6)
\]

\[
B_2 = \frac{1 + A_{Sa,r}^*}{2A_{Sa,p}^*} \quad (3.7)
\]

This means that Eq. (3.3) can be readily defined in terms of \( A_{Sa,p}^* \) and \( A_{Sa,r}^* \) alone. Hence, the results from the equivalent-linear predictions regarding the amplification of the elastic response spectra were tabulated in the database in terms of these two (2) factors. Subsequently, two independent statistical analyses were performed correlating \( A_{Sa,p}^* \) and \( A_{Sa,r}^* \) to the four (4) parameters found to affect soil amplification in [3]: the normalized soil period \( T_s/T_e \), the bedrock-to-soil fundamental period ratio \( T_b/T_s \), and the excitation characteristics \( d_{max}^b \) and \( n \). Of the above parameters, \( d_{max}^b \) is provided by a seismological study in practical applications, \( T_s \) is estimated as described in [3], \( T_b = 4H/V \), where \( H \) is the soil column thickness, and only \( T_s \) and \( n \) need further explanation. In particular, \( T_s \) is the predominant excitation period that is defined as the period for which its spectral acceleration \( S_a \) (for 5% critical damping ratio) takes its peak value, while \( n \) is the number of cycles in the excitation time-history that exceed a level of acceleration equal to \( a_{max}^b (M-1)/10 \), where \( M \) is the earthquake magnitude.

Further details concerning the database and the statistical analysis are presented in [2] and [3]. It is merely noted here, that data were analyzed via an appropriately weighted multivariable (least-square) regression analysis with the Newton-Raphson method, considering the four (4) aforementioned parameters affecting soil amplification as the free independent variables. Table 1 outlines the range of these parameters in the database, which also defines the limits of application of the proposed relations.
4. STATISTICAL ANALYSIS - RESULTS

4.1. Factors affecting $A_{Sa,p}^*$

Fig. 2 shows examples of the variation of $A_{Sa,p}^*$ as a function of the normalized soil period $T_s/T_e$, the most crucial of the four (4) independent variables. Specifically, the data in this figure are presented in pairs of groups, by maintaining two (2) of the three (3) other variables within a small range. Specifically, Fig. 2a explores the effect of shaking duration, for $n = 0.5 - 1$ and $n = 4 - 8$, while Fig. 2b, explores the effect of soil to bedrock impedance, for $T_s/T_e = 0.05 - 0.15$ (high contrast profiles) and $T_s/T_e = 0.6 - 0.8$ (relatively low contrast profiles). Finally, Fig. 2c, explores the effect shaking intensity, for $a_{max}^b = 0.01 - 0.35g$ and $a_{max}^b = 0.40 - 0.45g$.

In all cases, the effect of $T_s/T_e$ is similar, namely $A_{Sa,p}^*$ increases with $T_s/T_e$ from its value 1.0 at $T_s/T_e = 0$ to a more or less constant value for $T_s/T_e > 4$. Furthermore, $A_{Sa,p}^*$ decreases with increasing $T_s/T_e$ and $n$, especially for $T_s/T_e > 1$ (Figs. 2a and 2b), but it is not significantly affected by the intensity of shaking (Fig. 2c).

The above trends have been best-fitted by (Eq. 4.1):

$$A_{Sa,p}^* = \frac{T_s}{T_e} \left( \frac{n}{n+1} \right) \left( \frac{T_s}{T_e} \right)^{1.5}$$

where: $c_{p1} = 0.318$, $c_{p2} = 0.058$, $c_{p3} = 0.279$, $c_{p4} = -0.504$, $c_{p5} = -0.613$.

The constants in Eq. (4.1) were determined using a stepped multi-variable regression analysis of the results of all numerical simulations. Specifically, the first analysis corroborated the implication of Fig. 2c, i.e. that $a_{max}^b$ does not affect $A_{Sa,p}^*$ in a systematic manner. Subsequently, an analysis was performed for merely the data that fall within the range of $1 \leq T_s/T_e \leq 4$. This analysis provided the values of all constants in Eq. (4.1), except for $c_{p1}$. The latter was estimated by merely the data that fall in the range of $T_s/T_e > 1$. Obviously, by performing independent analyses for the three sets of data outlined by the ranges of $T_s/T_e$ in Eq. (4.1), one could have obtained more precise estimates. But such a methodology would not ensure the continuity of the proposed relations at $T_s/T_e = 1$ and 4.

Fig. 3 presents a one-to-one comparison of $A_{Sa,p}^*$ predictions to the corresponding numerical results (‘data’) for all the cases in the database. In addition, Fig. 4 presents the relative error in these $A_{Sa,p}^*$ predictions ($R_{Sa,p}^*$), defined as the difference between predictions and data normalized against the latter. Observe that the $A_{Sa,p}^*$ values from Eq. (4.1) agree well with the ‘data’ for all cases in the database (standard deviation of the error is (21.3%) and that the error proves unbiased.
4.2. Factors affecting $A_{sa,r*}$

The general procedure in the analysis of the data for $A_{sa,r*}$ is the same as that followed for $A_{sa,p*}$. Hence, Fig. 5 shows examples of the variation of $A_{sa,r*}$ as a function of $T_s/T_e$. In this case, the initial decrease of $A_{sa,r*}$ for $T_s/T_e < 1$, becomes an increase for $T_s/T_e > 1$, while $A_{sa,r*}$ levels off for $T_s/T_e > 6$. Furthermore, Figs 5a and 5b show that an increase in $T_b/T_s$ and $n$ results in a decrease of $A_{sa,r*}$, especially for $T_s/T_e > 1$. Finally, Fig. 5c shows that the $a_{max}$ does not significantly affect the value of $A_{sa,r*}$.

These trends are expressed analytically by Eq. (4.2):

$$A_{sa,r*} = 1 + c_{r1} + c_{r2} + c_{r3} + c_{r4} + n c_{r5} + T_s/T_e c_{r6} + n c_{r7} + 10 c_{r8} + T_s/T_e c_{r9} + n c_{r10}$$

Estimated as for $A_{sa,p*}$, the constants of Eq. (4.2) are:

$$c_{r1} = -0.302, c_{r2} = 0.219, c_{r3} = -0.474, c_{r4} = -4.06.$$
estimation of $A_{sr}^*$, defined similarly to $R_{sa,r}^*$. Observe that the agreement between approximate predictions and numerical ‘data’ is fairly systematic, with an unbiased error having a standard deviation equal to ±26.1%, for all the cases in the database on which the statistical analysis was based.

5. VERIFICATION CASE STUDIES

This section presents the application of the proposed multi-variable relations in a series of ‘well-documented’ cases of soil amplification, 2 cases in the Northridge earthquake and 5 cases in the SMART-1 accelerometer array in Taiwan. The term ‘well-documented’ means that the sites have well known geological and geotechnical properties.

Furthermore, the term ‘well-documented’ means that the digitized acceleration records for each event were available at both the soil surface and the outcropping bedrock.

The predicted values of $A_s$ and $A_v$ for all seven (7) cases are evaluated in [3]. Here, the emphasis is on the elastic response spectra, which are predicted from a joint application of the relations for $A_{sr}^*$ and the relations for $A_s$ and $T_s$ proposed in [3]. Hence, besides the purpose of verification, this section also serves as a guide on how to apply the proposed relations in practice.

5.1. Northridge Earthquake

The Northridge earthquake struck the densely populated Los Angeles basin on January 17th 1994 at 04:30 PST. It was a strong earthquake ($M_L = 6.4$) that occurred at an approximate depth of 19 km. The epicenter region of the earthquake was
the San Fernando Valley, an east-west-trending, deep alluvial valley, whose basin floor is relatively flat. Fig. 8 shows the main geographic characteristics of the San Fernando valley, locates the Northridge earthquake epicenter and depicts the 3 sites of interest here: LDF: Los Angeles Dam, RRS: Rinaldi Receiving Station and SFY: Arleta Fire Station.

![Figure 8: Map with site and earthquake epicenter locations.](image)

Figure 8: Map with site and earthquake epicenter locations. Σχήμα 8: Χάρτης με θέσεις εδαφικών τομών και επικέντρου.

Figure 9 presents the geological profile and the measured shear wave velocity variation with depth at the 3 sites. Observe that while the RRS and SFY sites are relatively soft near the surface ($V_s \leq 400$ m/s for the top 16m), site LDF is consistently stiffer ($V_s > 600$ m/s for all depths). Given these geotechnical properties, as well as the close distance between the sites (less than 4 miles) and the proximity between the respective epicentral distances (approximately 8 - 10 miles), LDF is considered the bedrock outcrop site and RRS and SFY the associated soil sites. The Northridge earthquake was recorded at the surface of all 3 sites. The horizontal acceleration time-histories and respective elastic response spectra (5% damping) of these recordings were retrieved by the University of California Santa Barbara web database (http://smdb.crustal.ucsb.edu/). Table 2 outlines the corresponding values of the peak horizontal acceleration $a_{max}$ and velocity $V_{max}$ values.

![Table 2: $a_{max}$, $V_{max}$ for the 3 sites and the Northridge earthquake.](image)

<table>
<thead>
<tr>
<th></th>
<th>LDF</th>
<th>RRS</th>
<th>SFY</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{max}$ (g)</td>
<td>0.291</td>
<td>0.819</td>
<td>0.344</td>
</tr>
<tr>
<td>$V_{max}$ (m/s)</td>
<td>0.756</td>
<td>1.640</td>
<td>0.401</td>
</tr>
</tbody>
</table>

The first step for applying the proposed multi-variable relations is to quantify the seismic excitation in terms of: $a_{max}^h$, $n$ and $T_e$. In this case, the recording at LDF serves as the seismic excitation, and specifically its NS component that led to the most severe peak horizontal acceleration and velocity. For this recording, $a_{max}^h = 0.291$g, $n = 4$ and $T_e = 1.0$ sec.

The second step is to estimate the linear periods of the soil $T_{S,o}$ and the bedrock $T_b = H / V_s$. This entails assuming the bedrock depth (and hence the thickness of the soil layers $H$), and then estimating $T_{S,o}$ and $T_b$ based on the measured
VS - profile. Hence, depths \( H = 73.5 \text{m} \) and \( H = 33.5 \text{m} \) were assumed for the RRS and SFY sites, respectively, and the simplified version of the Rayleigh procedure [1] was used to obtain the values of \( T_s \) presented in Table 3, along with the respective values of \( T_s^o \).

The third and final step is to apply the proposed relations, by first estimating the non-linear soil period \( T_s \), the cornerstone of the methodology. The values of \( T_s \) for the two soil sites during the Northridge earthquake are also presented in Table 3.

Table 3: Soil site characteristics for the RRS and SFY sites.

<table>
<thead>
<tr>
<th></th>
<th>( H ) (m)</th>
<th>( \sqrt{V_{SO}} ) (m/s)</th>
<th>( T_s^o ) (sec)</th>
<th>( T_s ) (sec)</th>
<th>( T_S ) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRS</td>
<td>73.5</td>
<td>494</td>
<td>0.59</td>
<td>0.37</td>
<td>0.72</td>
</tr>
<tr>
<td>SFY</td>
<td>33.5</td>
<td>408</td>
<td>0.33</td>
<td>0.21</td>
<td>0.42</td>
</tr>
</tbody>
</table>

The high relative difference between the \( T_S \) and \( T_s^o \) values implies that considerable soil non-linearity is predicted for both sites. This is reasonable, given the intense shaking caused by the Northridge earthquake at these small epicentral distances.

Figs. 10a and 11a present a comparison of the predicted elastic response spectra to the two horizontal recorded spectra for the RRS and SFY sites, respectively. Specifically, each of Figs 10a and 11a consist of 3 plots: the upper plot that compares the normalized amplification response spectra, \( A_s^* \), the intermediate that compares the response spectra at the soil surface, \( S_s \), and the lower plot that gives an estimate of the error in the prediction in terms of the ratio of predicted-over-recorded values of \( S_s \).

For comparison, equivalent-linear analyses with SHAKE91 [6] were also performed for the 2 soil sites with characteristics shown in Fig. 9. The digitized time-histories at LDF were used as seismic excitation in these analyses, applied at bedrock outcrop. The results of these analyses for the RRS and SFY soil sites are compared with the records in Figs 10b and 11b, respectively, by using the same three-partite plotting scheme. Finally, Figs 10c and 11c compare the foregoing numerical results to predictions obtained with the proposed multi-variable relations. Note that these numerical analyses were not included in the database.

The proposed relations under-predict \( S_s \) for the RRS site (Fig. 10a), by practically the same amount for all structural periods \( T_{str} \), and slightly over-predict the recorded values for the SFY site (Fig. 11a). However, Figs 10b and 11b show that the numerical predictions offer similar results with respect to the records. This is better shown in Figs 10c and 11c, where the predictions from the proposed relations are directly compared to the numerical results. Observe that the former are usually within \( \pm 30\% \) of the latter.

Figure 10: Evaluation of proposed relations for the elastic response spectra for the RRS site during the Northridge earthquake.

Σχήμα 10: Αποτίμηση των προτεινόμενων σχέσεων για τα ελαστικά φάσματα απόκρισης στη θέση RRS και το σεισμό του Northridge.
5.2. SMART-1 Accelerometer Array

The SMART-1 accelerometer array is located in the Lanyang plain of northeastern Taiwan. In brief, SMART-1 consists of a total of 39 triaxial surface accelerometers, configured in 3 concentric circles [9]. The array is located on a flat plain in a basin of triangular shape that is 15 km wide and 8 km long [5]. The geologic materials of the flat plain consist of practically horizontal recent soil and alluvium layers (thickness 30 - 80m) at the surface and a stiffer
Pleistocene layer (thickness 170 - 540m) that overlies the Miocene rock basement [10].

Of special interest to this study are two stations: (a) soil site O-07 and (b) bedrock outcrop site E-02 that is installed at approximately 2.8 km south of O-07, where the bedrock formation appears on the surface. Fig. 12 presents the \( V_s \) profile with depth at the O-07 [10]. Observe that it is a soft soil site, with \( V_s \) as low as 120m/s near the surface and greater than 400m/s at a depth of 80m. The \( V_s \) contrast at this depth led us to assume that it corresponds to the seismic bedrock, although it is not clear whether it also corresponds to an interface with Pleistocene materials.

For the \( V_s \) profile of Fig. 12, the simplified version of the Rayleigh procedure [1], yields \( T_s = 0.58s \). In this paper, 5 seismic events recorded at both the O-07 and E-02 sites have been used, and their seismological characteristics are presented in Table 4.

The application of the proposed relations starts by first estimating the non-linear periods \( T_s \) of site O-07 \( (V_s = 283m/s) \) for the 5 events. Their values are provided in Table 5, along with the seismic excitation parameters \( a_b, n \) and \( T_s \) of the same events.

Note that due to soil non-linearity, the difference between \( T_s \) and \( T_s \) is larger for the stronger events 39, 40 and 45 than for the weaker ones 29 and 41.

Figures 13 through 17 present a comparison of the predicted spectra against both components of elastic response spectra from the recordings, as well as the results from equivalent-linear analyses with SHAKE91 [6], which are not included in the database. The format in these figures is the same as that in Figs 10 and 11.

Note that the site parameters used as input for the numerical analyses are presented in Fig.12. Based on Figs 13a through 17a it is deduced that the proposed methodology provides reasonable prediction of the recorded amplification.

More importantly, observe that results obtained from the numerical analyses are of similar accuracy (Figs 13b through 17b). This becomes more evident in Figs 13c through 17c, where the numerical results are compared directly to the predictions from the multi-variable relations. Overall it is argued that the proposed relations essentially reproduce the numerical results. It should be underlined here that whenever the numerical method fails to simulate the recorded amplification, so do the proposed relations (as in Fig.14). In other words, the proposed relations inherit the shortcomings of the numerical method on which they were based.

For example, the numerical method assumes that the outcropping bedrock is similar to that underlying the soil column and that the impeding seismic waves are vertical. Whenever these conditions are not fulfilled then the results
of both the numerical method and the relations will not be accurate. In general, the proposed relations should be used with the same reservations (and safety factor) as the equivalent-linear method of one-dimensional analysis on which they were based. Further elaboration on the accuracy of the numerical method, or in general on the difficulties encountered when seismic records are interpreted in terms of theoretical models are beyond the scope of this paper.

Figure 14: Evaluation of proposed relations for the elastic response spectra for the Ο-07 site during event #39.

Σχήμα 14: Αποτίμηση των προτεινόμενων σχέσεων για τα ελαστικά φάσματα απόκρισης στη θέση Ο-07 και το σεισμό #39.

Figure 15: Evaluation of proposed relations for the elastic response spectra for the Ο-07 site during event #40.

Σχήμα 15: Αποτίμηση των προτεινόμενων σχέσεων για τα ελαστικά φάσματα απόκρισης στη θέση Ο-07 και το σεισμό #40.
Figure 16: Evaluation of proposed relations for the elastic response spectra for the O-07 site during event #41.
Σχήμα 16: Αποτίμηση των προτεινόμενων σχέσεων για τα ελαστικά φάσματα απόκρισης στη θέση O-07 και το σεισμό #41.

Figure 17: Evaluation of proposed relations for the elastic response spectra for the O-07 site during event #45.
Σχήμα 17: Αποτίμηση των προτεινόμενων σχέσεων για τα ελαστικά φάσματα απόκρισης στη θέση O-07 και το σεισμό #45.
6. CONCLUSIONS

Soil effects on the normalized spectral amplification ratio (for 5% damping) \( a_{so}^* \) have been quantified with a set of approximate relations, based on results from more than 700 equivalent-linear analyses of one-dimensional seismic ground response. Combined with similar relations for \( a_{max}^*, V_{max}^* \) and \( T_s \) presented in [3], they comprise an integrated tool for estimating seismic site response in engineering practice. In summary it was found that:

a) The value of \( a_{so}^* \) is a function primarily of the normalized periods \( T_{so}^*/T_s \) and \( T_{so}^*/T_L \) and secondarily of the impedance ratio \( T_{so}^*/T_s \) and the number of cycles \( n \). The effect of \( a_{max}^* \) is statistically insignificant.

b) The relations for the peak \( A_{so}^* \) and residual \( A_{so,r} \) values of \( A_{so}^* \) are in fair agreement with the respective numerical predictions, with the error having a standard deviation ranging from ±21.3 - 26.1%.

c) Given the seismic excitation, predictions of the soil surface spectral acceleration \( S_a^* \) with the proposed relations compared to recordings and numerical analyses verified the above accuracy in seven (7) cases that are not included in the database.

The limits of application of the proposed relations for the \( A_{so}^* \) are defined by the range of the site and excitation parameters in the database on which they were based [3]. Overall, the set of relations presented here and in [3] aim at the preliminary evaluation of soil effects. Also, they can be used as a user-friendly alternative to the equivalent-linear method, when the latter is too cumbersome to implement, as in GIS-aided microzonation studies [7].

7. ACKNOWLEDGEMENTS

This research was funded by the Earthquake Protection and Planning Organization of Greece (O.A.Σ.Π.). The seismological data pertaining to the SMART-1 array were communicated to the authors by Dr. Nickolaos Theodulidis, Director of the Institute of Engineering Seismology and Earthquake Engineering in Thessaloniki (I.T.Σ.Α.Κ.). All these contributions are gratefully acknowledged.

8. REFERENCES


George D. Bouckovalas
Professor, School of Civil Engineering, Geotechnical Department, National Technical University of Athens.

Achilleas G. Papadimitriou
Dr Civil Engineer, School of Civil Engineering, Geotechnical Department, National Technical University of Athens.

Table 4: Seismological parameters for the 5 events and their recording characteristics at E-02 and O-07.

<table>
<thead>
<tr>
<th>#</th>
<th>( a_{max}^* (\text{g}) )</th>
<th>( V_{max}^* (\text{g}) )</th>
<th>( D ) (km)</th>
<th>( R ) (km)</th>
<th>( M_L )</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>0.033</td>
<td>0.074</td>
<td>0.032</td>
<td>0.040</td>
<td>28</td>
</tr>
<tr>
<td>39</td>
<td>0.200</td>
<td>0.172</td>
<td>0.131</td>
<td>0.319</td>
<td>10</td>
</tr>
<tr>
<td>40</td>
<td>0.190</td>
<td>0.165</td>
<td>0.199</td>
<td>0.303</td>
<td>16</td>
</tr>
<tr>
<td>41</td>
<td>0.050</td>
<td>0.033</td>
<td>0.023</td>
<td>0.024</td>
<td>22</td>
</tr>
<tr>
<td>45</td>
<td>0.140</td>
<td>0.109</td>
<td>0.240</td>
<td>0.300</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 5: Input data and results of TS computations for soil site O-07 for the 5 seismic events.

<table>
<thead>
<tr>
<th>#</th>
<th>( a_{max}^* (\text{g}) )</th>
<th>( T_s ) (sec)</th>
<th>( n )</th>
<th>( T_{so} (\text{sec}) )</th>
<th>( T_{so}^* (\text{sec}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>0.033</td>
<td>0.22</td>
<td>5</td>
<td>1.13</td>
<td>1.19</td>
</tr>
<tr>
<td>39</td>
<td>0.200</td>
<td>0.16</td>
<td>2</td>
<td>1.13</td>
<td>1.45</td>
</tr>
<tr>
<td>40</td>
<td>0.190</td>
<td>0.20</td>
<td>1.5</td>
<td>1.13</td>
<td>1.44</td>
</tr>
<tr>
<td>41</td>
<td>0.050</td>
<td>0.19</td>
<td>3</td>
<td>1.13</td>
<td>1.22</td>
</tr>
<tr>
<td>45</td>
<td>0.140</td>
<td>0.20</td>
<td>2.5</td>
<td>1.13</td>
<td>1.36</td>
</tr>
</tbody>
</table>
Παραμετρικές Σχέσεις Υπολογισμού της Εδαφικής Ενίσχυσης

ΠΕΡΙΛΗΨΗ

Παρουσιάζεται ένα ομόλογο σχετικά με την εργασία στην Καθηγήτρια Σ. Παπαδόπουλος, ενός σχετικού αριθμού τεχνικών περιπτώσεων (από την Είδηση του Α. Παπαδόπουλου [1998]). Στο παρόν έργο, η παρουσίαση αυτή ολοκληρώνεται με ανάλυση σχέσεις για τα ελαστικά φαινόμενα αποκρίσεων, ως ιδιοπέριοδος της ηλικίας της συστήσης, προσχέδιο, καθώς και την συντονισμένη καταγραφή της αποκρίσεως των εδαφικών συστημάτων (στην Είδηση του Α. Παπαδόπουλου [1998]).

Η αναλυτική συντονισμένη καταγραφή της αποκρίσεως των εδαφικών συστημάτων (στην Είδηση του Α. Παπαδόπουλου [1998]) αναφέρεται στην Είδηση του Α. Παπαδόπουλου [1998], η οποία έγινε στο περιοδικό της τεχνολογίας καλώδιων SMART-1 στην Ταϊνία.

Στο παρόν άρθρο [3] παρουσιάζομε πολύ-παραμετρικές σχέσεις υπολογισμού της εδαφικής επιδράσης στον περιοδικό της τεχνολογίας καλώδιων SMART-1 στην Ταϊνία.}

ΓΕΩΡΓΙΟΣ Δ. ΜΠΟΥΚΟΒΑΛΑΣ
Καθηγητής Ε.Μ.Π.

ΑΧΙΛΛΕΑΣ Γ. ΠΑΠΑΔΗΜΗΤΡΙΟΥ
Δρ Πολιτικός Μηχανικός Ε.Μ.Π.
τρον (Εξισώσεις 8 και 9):
(a) του λόγου της ιδιοσειράς της εδαφικής στήλης προς την
dιαπυρώνηση περιόδου της διέγερσης $T/T_*$,
(b) του λόγου ιδιοσειράς της στήλης εδαφικών ισούν
υψών στήλης χρυσοκίνδυνων υποβάθρου $T/T_*$, και
(c) του αριθμού των ισοδύναμων αρμονικών κύκλων της
dιέγερσης $n$.

Η μέγιστη σεισμική επιτάχυνση στην ελεύθερη επιφάνεια
του χρυσοκίνδυνου υποβάθρου $a_{max}$, η οποία είχε συστημα-
τική επιρροή στους συντελεστές εδαφικής ενίσχυσης της
μέγιστης σεισμικής επιτάχυνσης $A_*$ και ταχύτητας $V_*$, απο-
δεικνύεται τώρα ότι είναι στατιστικά ασάμαντη για τους συν-
tελεστές $A_{sep}*$ και $A_{v}*$ και εξαιρεθήκε από τις αντίστοιχες
προσεγγιστικές σχέσεις.

Στα σχήματα 3 και 6 συγκρίνονται απευθείας οι προ-
σεγγιστικές τιμές των $A_{sep}*$ και $A_{v}*$ με τα αντίστοιχα
αποτελέσματα των αρμηνικών αναλύσεων. Επιπλέον, στα
Σχήματα 4 και 7 παρουσιάζεται η σχετική απόκλιση των
προσεγγιστικών και αρμηνικών προβλέψεων συναρτήσεις των
ανεξαρτήτων μεταβλητών $T_*/T_*$, $T_*/T_*$ και $n$. Από τις
ανωτέρω συγκρίσεις φαίνεται ότι η απόκλιση των προσεγγι-
στικών από τις αρμηνικές προβλέψεις είναι στατιστικά τυ-
χαία, δηλαδή ανεξήρτητη από τις μεταβλητές που υπεσεύ-
χονται στις προτιμώμενες σχέσεις και παρουσιάζει τυπική
απόκλιση που κυμαίνεται μεταξύ ± 21 - 26% της τιμής των
αρμηνικών προβλέψεων.

Πέραν της αξιολόγησης σε σχέση με τη βάση δεδομέ-
νων και αποτελέσματος από τις αρμηνικές αναλύσεις, οι
προτιμώμενες σχέσεις εφαρμόστηκαν σε επιτύχημα (7) συνολικά
πραγματικές περιπτώσεις εδαφικής ενίσχυσης, με ικανο-
ποιητική τεχνικογεωλογική και σεισμολογική τεκμηρίωση.
Όταν δύο πρωτότυπες αφορούσαν στην κοίλοsa San
Fernando κατά το σεισμό του Northridge (1994, $M_*=6.4$).
Το Σχήμα 8 διέχει τα βασικά γεωγραφικά χαρακτηριστικά της
περιοχής και εντοπίζει το επίκεντρο του σεισμού και τις
τρεις θέσεις καταγραφής που εξετάσθηκαν στο πλαί-
σιο αυτής της άρειας: Los Angeles Dam (LDF), Rinaldi
Receiving Station (RRS) και Arleta Fire Station (SFY).
Οι γεωλογικές τομές και η μεταβολή της ταχύτητας μετάδοσης
σεισμικών (διατηρητικών) κυμάτων με το βάθος στις τρεις
αυτές θέσεις παρουσιάζονται στο Σχήμα 9. Εκ των τριών κο-
ντινών θέσεων, η LDF θεωρήθηκε ως θέση καταγραφής επί
αναδοχώμενου βραχώδους υποβάθρου και οι RRS και SFY ως
θέσεις καταγραφής επί εδαφικών αποθέσεων.

Οι υπόλοιπες πέντε (5) περιπτώσεις αφορούσαν στο πει-
ραματικό σεισμολογικό δίκτυο SMART-1 στην κοίλοsa
Lanyang της Βορειοανατολικής Taiwain. Στο παρόν άρθρο
το ενδιαφέρον επεκτείνεται σε δύο κόμβους του σεισμο-
λογικού δικτύου, τον 0-07 επί εδαφικών αποθέσεων και
τον E-02 επί του αναδοχώμενου βραχώδους υποβάθρου. Η

eπιτύχηση δεν προκύπτει από τις περισσότερες προβλέψεις
και το σεισμικό περιβάλλον, κατά την άσκηση της προ−
προστασίας των άνθρωπων από την προβλέψη, επικεντρώνοντα
τη σεισμική χρηστικότητα των προτιμώμενων σχέσεων στο πλαί-
σιο πρακτικών εφαρμογών, ως ευρύτερων προκαταρκτικών
υποκατάστατων αρμηνικών αναλύσεων.

**ΕΥΧΑΡΙΣΤΙΕΣ**

Η ερευνητική μας προσπάθεια χρησιμοποιήθηκε από
του Οργανισμού Αντισεισμικού Σχεδιασμού και Προστασίας
(Ο.Α.ΣΠ.). Τα σεισμολογικά δεδομένα από το πειραματικό
δίκτυο SMART-1 στην Taiwan μας παραχώρηθηκαν ευγενι-
κά από τον δρ. N. Θεοδολίδη, Διευθύντα του Ινστιτούτου
Τεχνικής Σεισμολογίας και Αντισεισμικών Κατασκευών