STARTING ESTIMATES OF SEISMIC SITE COEFFICIENTS ALONG 2D SEMI-ELLIPTICAL SHAPED HILLS

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ABSTRACT:

In the recent past, there have been numerous cases of recorded motion and observed earthquake damage pointing toward topographic amplification as an important effect. Very high recorded accelerations during earthquakes have been sometimes attributed to topographic effects of hills as one basic type of local surface irregularities. In this paper the results of a comprehensive parametric study for estimating the site coefficients in areas with 2D semi-elliptical shaped hills has been presented. Using adequate number of accelerograms as well as numerically calculated transfer functions of 2D semi-elliptical shaped hills, the extension capability of the Borcherdt's method to 2D semi-elliptical shaped hills has been investigated. By frequency domain analysis and then inverse Fourier transform, the amplified accelerograms along the hills were obtained. The achieved results accentuated the efficiency of the Borcherdt's method in 2D microzonation studies. Moreover, it has been shown that the site coefficients vary between 1.0 and 1.7, are comparable to the 1D site coefficients usually suggested by the seismic codes, differ from short to long periods and exceed the maximum value of 1.4 proposed by the AFPS (1990) code for seismic design of structures in topographic areas.

KEYWORDS: site effect, topography, semi-elliptical shaped hill, amplification, response spectra, site coefficient

1. INTRODUCTION

In the last decades, the damage distributions after earthquakes have emphasized the major role of the topographic irregularities in amplifying the ground motions. The ground motion amplification at Pacoima dam during the 1971 San Fernando earthquake (Trifunac and Hudson, 1971) and at the Tarzana hill during the 1994 Northridge earthquake (Spudich et al., 1996) have been at least partly attributed to the topographic effects. Because of the recent experiences, it can be expressed that the topography has a considerable effect in seismic microzonation studies. However, there are only two seismic codes have assigned a section for considering the 2D site effects in their design provisions (AFPS 1990 and Eurocode 8, 1998). This is because conclusive results from only field measurements are difficult to obtain. Indeed, complexity of the wave scattering phenomena produced by the topographic structures, leads to solve the problem accurately, economically and under realistic conditions only by advanced numerical methods. Circular and semi-elliptical shaped hills are one of the most common surface irregularities encountered frequently in the nature. Because circular hills have simple geometry; thus, most of the studies have been done in clarifying the seismic behavior of this kind of hills. In addition, the previous studies were mostly qualitative and could not be used for quantitative modifications of the standard design spectra needed for earthquake resistant design of structures to be located on the hills. Sanchez-Sesma and Campillo (1991, 1993) were the first who presented a method to compute the diffraction of P, SV, and Rayleigh waves by 2D semi-elliptical shaped hills in an elastic half-space. Although they considered both cases of the incident SV and P waves, but their study was restricted to only one shape ratio and one Poisson's ratio.

Pederson et al. (1994) studied seismic behavior of a semi-circular shaped hill subjected to P and S waves with different incident and azimuth angles. They showed that the amount of amplification depends on the geometry of the hill, the type of the incident wave, the incidence angle and the azimuth angle and varies along the hill.
Review of the literature shows that perfect parametric studies on seismic behavior of 2D semi-elliptical shaped hills subjected to incident SV waves have been seldom published. The published works were almost limited to some specific shapes and some specific values of shape ratio and predominant frequency of the incident wave. In addition, they were neither practical nor applicable in calculating design spectra for seismic microzonation studies of areas with 2D hills. This parametric study was mainly aimed to find out and clarify the answers of the following questions: How does amplification affect the response spectra? Where does the maximum amplification of the response spectra occur along the hill? Does increasing the height of the hill necessarily mean intensifying the spectral parameters at any point along it? Is it possible to extend the Borcherdt's method to the 2D topographic irregularities? Can some preliminary site coefficients be calculated which can be used in design provisions?
The study is performed using the time-domain boundary element (BE) method and presents the results of a numerical parametric study on amplification pattern of 2D homogenous semi-elliptical shaped hills subjected to vertically propagating incident SV waves. Owing to the fact that incident P and SH waves have less important effect on 2D hills compared to the SV wave (Geli et al., 1988), they are not concerned in this paper.

2. METHODOLOGY OF STUDY

This study is performed using BE formulation, which is implemented in a general-purpose two-dimensional nonlinear two-phase BEM/FEM code named HYBRID (Kamalian, 2001, Taghavi, 2008 and Kamalian et al., 2001, 2003, 2006, 2007, 2008). The geometry of the 2D homogenous semi-elliptical shaped hills investigated by the parametric study was defined as follows:

$$\begin{aligned} \xi(x) &= \sqrt{h^2\left(1-\left(x^2/b^2\right)\right)} \qquad && |x| \le b \\ \xi(x) &= 0 && |x| \ge b \end{aligned} \tag{2.1}$$

where b and h denote the half-width and height of the hill, respectively. Results in time-domain have been shown in dimensionless forms. In time-domain the dimensionless time is defined as $T=tc_2/2b$, where t, b and c_2 denote time, half width and shear wave velocity of the hill, respectively. In addition, all results in frequency-domain have been presented in dimensionless forms, using the dimensionless frequency or its inverse, the dimensionless period. The dimensionless frequency is defined as the ratio of the width of the hill to the wavelength of the shear wave, $\Omega=\omega b/\pi c_2$, where ω presents the angular frequency of the wave. The hills were subjected to vertically propagating incident SV wave of the Ricker type:

$$f(t) = \left[1-2\cdot(\pi\cdot f_p\cdot(t-t_0))^2\right]e^{-(\pi\cdot f_p\cdot(t-t_0))^2} \tag{2.2}$$

in which f_p and t_0 denote the predominant frequency and an appropriate time shift parameter, respectively. In all cases, the incident Ricker wave had a predominant dimensionless frequency of 1.5 and a dimensionless time shift parameter of 0.9. Based on engineering interests, a dimensionless period interval of 0.25 to 8.33 was considered, which corresponds to incident waves with wavelengths of 0.25 to 8.33 times the width of the hill. This broad period interval was divided into the following five subintervals: 0.25 to 0.50 (P1), 0.50 to 1.00 (P2), 1.00 to 2.00 (P3), 2.00 to 4.17 (P4) and 4.17 to 8.33 (P5), corresponding to incident waves with very short, short, medium, large and very large wavelengths, respectively. The amplification curves were attained by dividing the Fourier amplitude of the horizontal component of the motion to the relevant Fourier amplitude in the free field motion. By averaging the corresponding amplification curve over the short, intermediate, mid and long period bands (P1 to P5); five distinct spectral ratios were obtained for every point along the hill. The calculated amplification factors are called "AHSA", average horizontal spectral amplification (Borcherdt et al., 1991, 1994).

3. SEISMIC BEHAVIOUR OF 2D SEMI-ELLIPTICAL SHAPED HILLS

This section presents the most important results obtained by the executed parametric study, which demonstrate how amplification of ground motion induced by 2D semi-elliptical shaped hills is affected by the wave length of the incident wave and shape ratio (ratio of the height of the hill, h, to its half width, b) of the hill. Figure 1 demonstrates the dependency of the amplification potential of a 2D semi-elliptical shaped hill on the wavelength and shape ratio. The hill has a Poisson’s ratio of 0.33 and is subjected to vertically propagating incident SV waves. The amplification curves are categorized according to the wavelength of the incident waves. Both of horizontal and vertical components of amplification are shown. It can be seen that, the amplification or de-amplification potential of the hill increases with the shape ratio; however, the increasing rate depends on the wavelength and varies along the hill. Indeed, increasing the shape ratio (height) of the hill does not necessarily mean intensifying the amplification potential of all points along it by the same amount. In the case of hills with shape ratio of less than 0.1, the topography effect could be ignored. It is obvious that irrespective of the shape ratio, the wavelength plays a key role in determining the amplification curve of the hill.

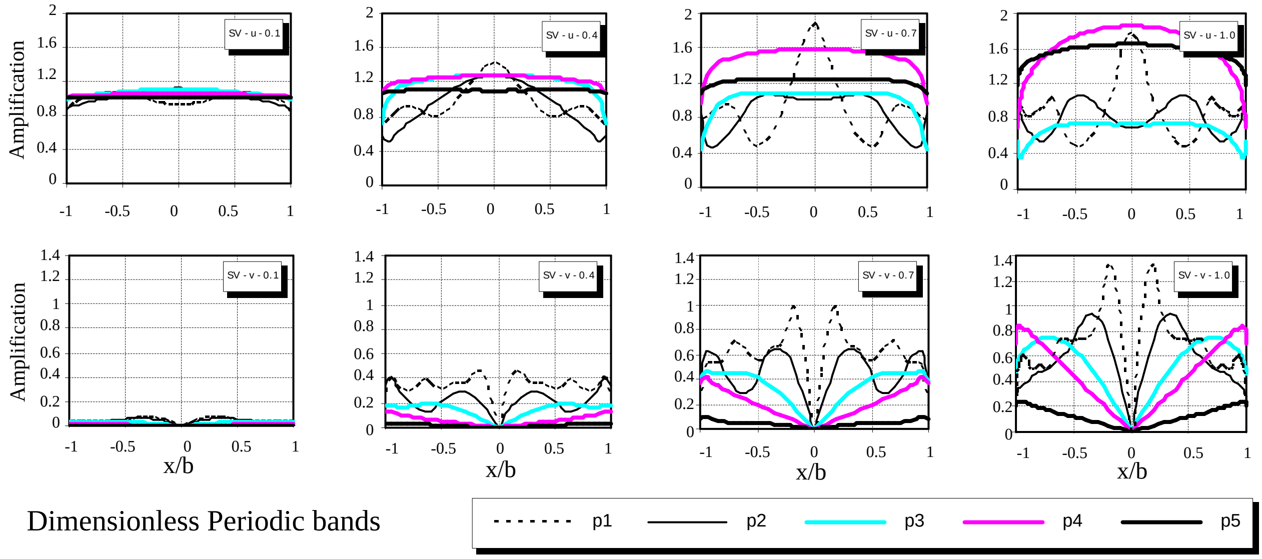

Figure 1 Amplification curves along the semi-elliptical shaped hills with a Poison’s ratio of 0.33. The hills are subjected to vertically propagation incident SV waves. From left to right the hills have a shape ratio of 0.1, 0.4, 0.7 and 1. The figures of the first row refer to horizontal component; while, the second row refer to vertical component of motion.

Regarding the horizontal component of the motion, if the incident wave possesses a long or very long wavelength, each point across the hill will experience amplification factor of greater than one increasing with shape ratio. Furthermore, the maximum amplification factor occurs at the crest and the amplification curves decay toward the bases. In the case of an incident wave with a medium wavelength, except the circular hills where points experience de-amplification, there is amplification at the crest. Moving from the crest to the toe of the hill the amount of amplification decreases; moreover, in some areas near the bases the amplification replaces with de-amplification. In an incident wave with a short or very short wavelength, the number of de-amplification zones along the hill would increase. In this case, each point across the hill experiences its maximum amplification factor in medium shape ratios. In addition, the amplification curves of the hill may experience their maximums at points other than the crest.
Concerning the produced vertical component, irrespective of the shape ratio, amplification curves start from a value of zero at the top, increase with distance from the crest; reach their maximum at a point on the flank and decay towards the base. In general, at any point across the hill, the vertical amplification factor increases with the shape ratio and decreases by increasing the wavelength.

4. SPECTRAL RATIO CURVES ALONG 2D SEMI-ELLIPTICAL SHAPED HILLS

This section presents how the acceleration history on the hill may differ from the free-field motion. Furthermore, the variation of spectral ratio curves along the semi-elliptical shaped hills have been investigated and compared with the relevant amplification curve.

4.1. Acceleration History

By selecting adequate number of accelerograms, the seismic behavior of the semi-elliptical shaped hills has been investigated. The hills are homogenous with shape ratios of 0.1, 0.4, 0.7 and 1.0. The medium is assumed to have a linear elastic constitutive behavior; hence, for the sake of comparison, only the accelerograms recorded at the rocky sites has been selected. The frequency range of the study is between 0.25 and 8 Hz; therefore, by means of a bandpass butterworth filter, the unwanted frequencies has been eliminated. Fourier spectra of the filtered accelerograms have been obtained using a fast Fourier transform function (FFT). Multiplying Fourier spectra by the calculated transfer functions, the new accelerograms has been achieved for the selected points along the hill. It is worth noting that, dividing the Raker Fourier spectrum of a point on the hill to the free-field motion the transform function of that point can be calculated. Finally, by an inverse Fourier function the new accelerograms have been calculated for the points on the hill.
Figure 2 depicts the acceleration history of the points located on a hill with shape ratio of 0.7 as well as the free-field motion values. As can be seen, the acceleration values have been amplified in crest and its adjacent places. On the other hand, in toe of the hill and some other places next to it, these values have been decreased with respect to free-field motion. It can be summarized that, moving from the crest to the toe of the hill the acceleration values have been decreased.

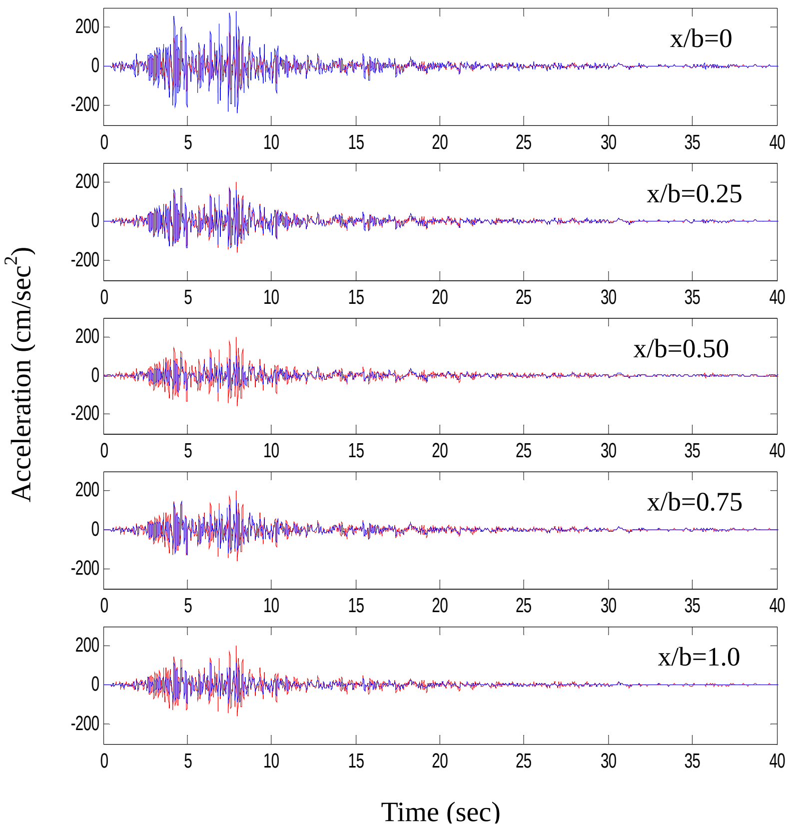

Figure 2 The acceleration history of the selected points along a semi-elliptical shaped hill with a shape ratio of 0.7 has been shown in blue. The free field acceleration history has been demonstrated in red. The hills are homogenous with a Poison’s ratio of 0.33.

4.2. Comparison of Spectral Curves and Amplification Curves

The amplification curves for estimating the ground response in areas with 2D semi-elliptical shaped hills have been calculated using SV Raker waves. By performing analysis with HYBRID, the new Raker waves have been produced on the crest and other points of the semi-elliptical shaped hills with different shape ratios. Dividing the Fourier spectra of Raker wave of points located on the hill by the Fourier spectra of the free-field motion (which has amplitude as large as two times of the incident Raker wave) the amplification curves have been calculated.
In the previous section using adequate number of accelerograms the acceleration history of the points located on the various semi-elliptical shaped hills have been estimated. The spectral ratio curves may be calculated by dividing the response spectra of the points on the hill to the response spectra of the free-field motion. Owing to the fact that the ordinary value of damping in buildings is about 5%, therefore, the elastic response spectra have been calculated for damping values of 5%. Moreover, this amount of damping often has been used in the prominent seismic codes. Figure 3a presents the obtained response spectra on the crest of a homogenous semi-elliptical shaped hill with a shape ratio of 0.4 as well as on the free field. The obtained spectral ratio curve is depicted in figure 3b. These steps have been followed for other accelerograms. Figure 3c shows the spectral ratio curves obtained for the crest of the mentioned hill. The thick black line refers to the average spectral ratio curve. As can be seen all of the spectral ratio curves have almost the same variation trend. In addition, the curves not only have a characteristic period but also a secondary resonance period. These periods have been separated with a debilitating period.

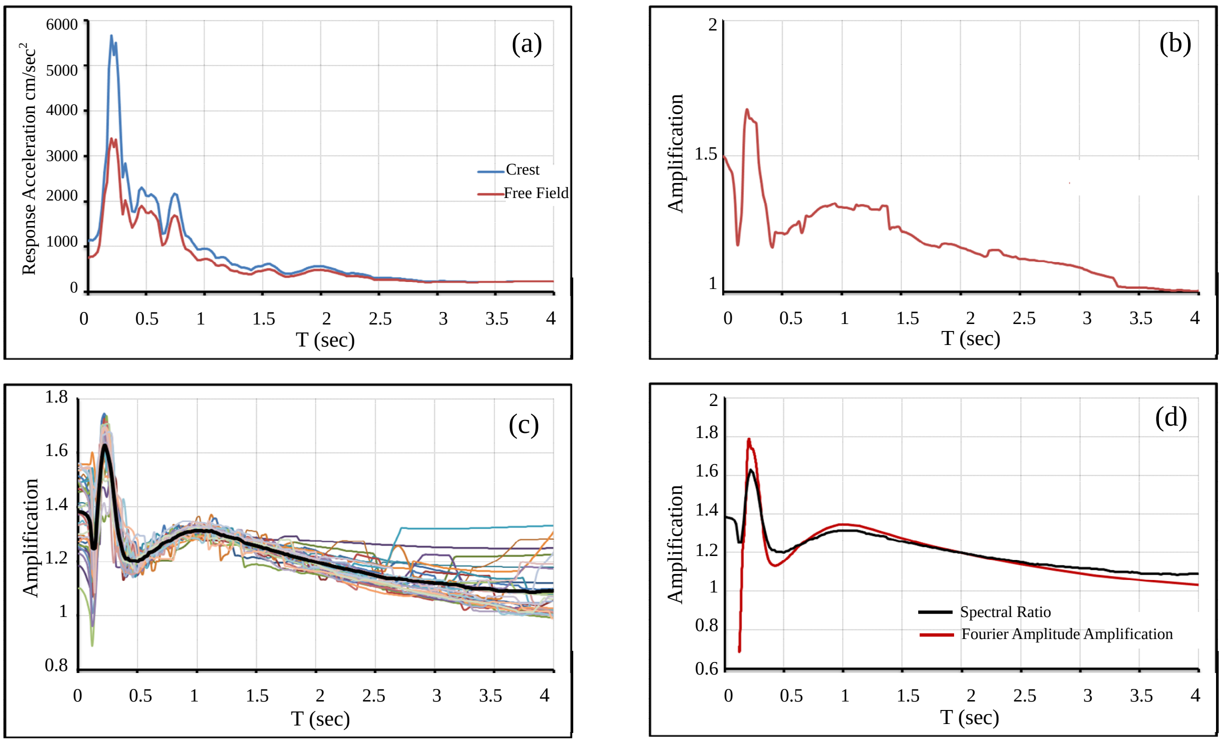

Figure 3 (a) Response spectrum on the crest of a semi-elliptical shaped hill with a shape ratio of 0.4 as well as in the free-field; (b) The spectral ratio curve has been calculated by dividing the response spectrum curve of the crest by the free-field; (c) The spectral ratio curves calculated using different accelerograms. The average spectral ratio curve has been presented with a thick black line; (d) Comparison between average spectral ratio curve and amplification curve

Figure 3d compares the obtained average spectral ratio curve and the calculated amplification curve. It is obvious that the average spectral ratio curve has been obtained by dividing the response spectra of the points on the hill to the free-field motion; while, the transfer function has been calculated by dividing the Fourier spectra of the points on the hill to the Fourier spectra of free-field motion. Figure 3d demonstrates that the spectral ratio curve and the transfer function curve have the same variation pattern and an appropriate conformity. The nominal differences of the curves are because the Fourier spectra only depend on the geometrical and mechanical characteristics of the hill; while, the response spectra also depend on the specifications of 1-degree freedom structure. Therefore, it can be inferred that using free-field response spectra and an appropriate transfer function one can calculate the desired response spectra of every point on the hill. The obtained response spectra can be used in estimating the design response spectra of the areas with 2D topographic irregularities.

5. ENGINEERING APPLICATION

The results presented so far in this paper indicate that considering all homogenous rocky sites as similar amplification-free reference sites is neither reasonable nor conservative. However, in the current practice of seismic microzonation studies, this site classification is being done for every point of ground surface, irrespective of being located on the toe or top of the hill or on the flat half-plane. Table 1 approximate the average horizontal spectra amplification factors (AHSA) of the crest, midpoint and toe of a 2D homogenous elliptical shaped hill subjected to vertically propagating incident SV waves, respectively. The amplification factors are calculated as functions of the shape-ratio and the predominant dimensionless period. The Poisson ratio is considered 0.33, which is a typical value for hills. Such tables enables one not only to prepare distribution maps of period dependent site amplification factors throughout a study area, but also to estimate conservative values of the well-known short period (F_a) and long period (F_v) site coefficients required for evaluating proper design spectra for structures located on rocky hills (figure 4). The extensive experimental studies conducted by Borcherdt et al. (1991, 1994) showed that the short period site coefficient could be approximated as the spectral amplification averaged over the period interval 0.1 to 0.5 second, whereas the long period site coefficient could be approximated as the spectral amplification averaged over the period interval 0.4 to 2.0 second.

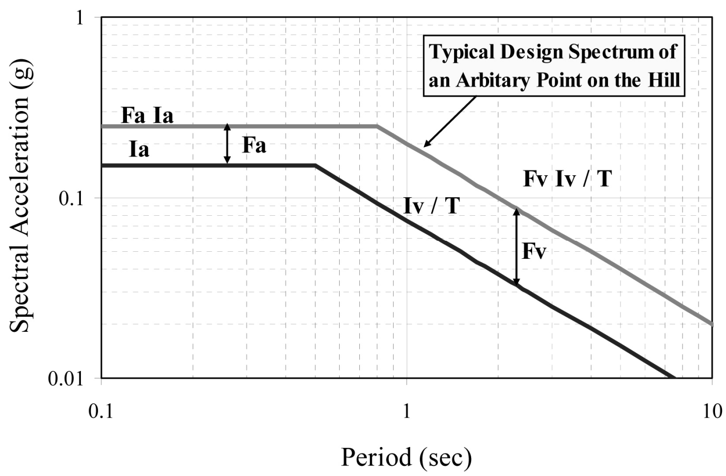

Figure 4 Schematic design spectrum of 2D rocky hills in terms of short period (I_a) and long period (I_v) seismic hazard levels as well as short period (F_a) and long period (F_v) spectral amplification factors

Following Borcherdt's empirical idea, table 1 could be simply used in order to evaluate conservatively the crest, midpoint and toe spectral amplification with respect to rocky reference site, averaged over the above mentioned short and long period intervals. Considering a 2D elliptical shaped hill with a shear wave velocity of 1000 m/s and a width interval of 100 to 1000 meters, figure 5 demonstrates the dimensionless period bands (P1 to P5) encountered in averaging the spectral amplification over the period intervals 0.1 to 0.5 as well as 0.4 to 2.0 seconds.

Table 2 demonstrates the short and long period site coefficients of crest, midpoint and toe of the aforementioned 2D elliptical shaped hill as a function of its shape ratio and width. The values of this table have been calculated using a weighted averaging procedure. For example, considering a 200m width hill, the long period interval (0.4 to 2.0 second) encounters the dimensionless periodic bands P4 and P5, which results in average horizontal amplification factors 1.7 and 1.1 respectively for crest and toe of an elliptical hill, assuming a shape ratio of 1.0.

Table 1 Horizontal Amplification Factors

	Dimensionless Period Bands														
	P1			P2			P3			P4			P5		
SR \ x/b	0	0.5	1	0	0.5	1	0	0.5	1	0	0.5	1	0	0.5	1
0.1	1.0	1.1	1.0	1.1	1.0	1.0	1.1	1.1	1.0	1.1	1.0	1.0	1.0	1.0	1.0
0.4	1.5	1.0	1.0	1.3	1.1	1.0	1.3	1.2	1.0	1.3	1.3	1.1	1.1	1.1	1.1
0.7	1.9	1.0	1.0	1.1	1.1	1.0	1.1	1.1	1.0	1.6	1.6	1.1	1.2	1.2	1.1
1.0	1.8	1.0	1.1	1.0	1.1	1.0	1.0	1.0	1.0	1.9	1.7	1.0	1.7	1.6	1.2

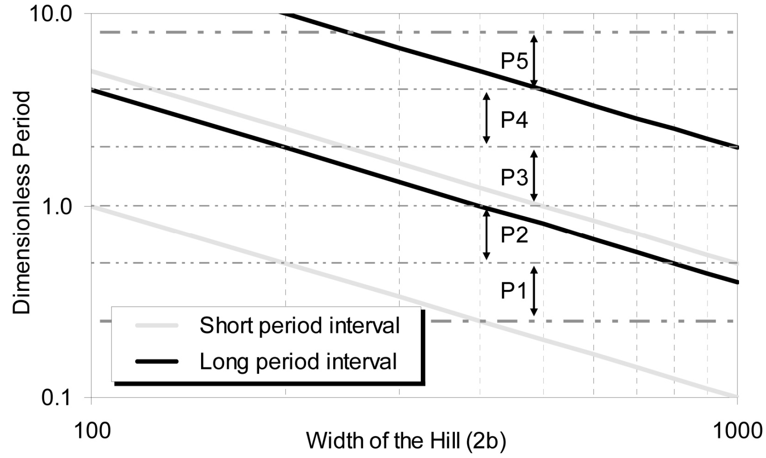

Figure 5 Dimensionless period bands (P1 to P5) encountered in averaging the spectral amplification over the short period (0.1 to 0.5 sec) and long period (0.4 to 2.0 sec) intervals, assuming shear wave velocity of 1000m/s.

It can be seen that, the site coefficients of crest varying between 1.0 and 1.7 are comparable to the 1D site coefficients usually recommended by the worldwide standard seismic codes such as UBC97 and IBC2006 for site classes C and D. Besides, in some locations these coefficients exceed the maximum value of 1.4 proposed by the AFPS (1990) code for seismic design of structures in topographic areas. Also, the site coefficients proposed by table 2 are period dependent and therefore more representative the amplification pattern of 2D hills, whereas the constant topography factors proposed by AFPS (1990) and Eurocode8 (1998) do not take this important controlling factor into account.

Table 2 Short and long period coefficients along 2D semi-elliptical shaped hill with shear wave velocity of 1000m/s

	The width of the hill (2b)																	
	100-300						400-700						800-1000					
SR	x/b=0		x/b=0.5		x/b=1		x/b=0		x/b=0.5		x/b=1		x/b=0		x/b=0.5		x/b=1	
	F_a	F_v	F_a	F_v	F_a	F_v	F_a	F_v	F_a	F_v	F_a	F_v	F_a	F_v	F_a	F_v	F_a	F_v
0.1	1.1	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.0	1.0
0.4	1.3	1.2	1.2	1.2	1.0	1.1	1.4	1.3	1.1	1.2	1.0	1.1	1.5	1.3	1.0	1.2	1.0	1.0
0.7	1.3	1.3	1.2	1.3	1.0	1.1	1.5	1.4	1.1	1.4	1.0	1.1	1.7	1.2	1.1	1.2	1.0	1.0
1.0	1.3	1.7	1.3	1.6	1.0	1.1	1.4	1.5	1.1	1.4	1.1	1.0	1.6	1.1	1.1	1.1	1.1	1.0

6. CONCLUSION

This paper presented clear perspectives of amplification patterns of 2D homogenous semi-elliptical shaped hills subjected to vertically propagating SV incident waves. Preliminary tables are proposed which could be used as starting points in estimation of important engineering indexes in seismic microzonation studies of areas with topographic structures. It is shown that:

- The topography effect can be ignored, only if the hill has a shape ratio of less than 0.1.
- On the topographic irregularities like horizontal surfaces, the spectral ratio curves have an acceptable conformity with the amplification curves.
- Extending the Borcherdt's method to hills makes it possible to calculate site coefficients along these topographic irregularities. Estimated seismic site coefficients for the crest of 2D rocky hills vary between 1.1 and 1.7. The coefficients encourages one to classify a site, according to site standard categorization procedures, as soil profile types S_C and S_D instead of S_B, depending on the shape ratio.

REFERENCES

Trifunac, M.D. and Hudson, D.E. (1971). Analysis of the Pacoima Dam accelerograms – San Fernando earthquake of 1971. *Bulletin of Seismological Society of America* **61:5,** 1393-1411.

Spudich, P., Hellweg, M. and Lee, W.H.K. (1996). Directional topographic site response at Tarzana observed in aftershocks of the 1994 Northridge, California, Earthquake: Implications for main shock motions. *Bulletin of Seismological Society of America* **86:1B,** S193-S208.

Association Française du Genie Parasismique (AFPS). (1990). Recommandations de la AFPS. Paris: AFPS.

Eurocode 8 (EC8). (1998). Design provisions for earthquake resistance of structures.

Sanchez-Sesma, F.J. and Campillo, M. (1993). Topographic effects for incident P, SV and Rayleigh waves. *Tectonophysics* **218:1-3,** 113-125.

Sanchez-Sesma, F.J. and Campillo, M. (1991). Diffraction of P, SV and Rayleigh waves by topographic features: a boundary integral formulation. *Bulletin of Seismological Society of America* **81:6,** 2234-2253.

Pedersen, H.A., Sanchez-Sesma, F.J. and Campillo, M. (1994). Three-dimensional scattering by two-dimensional topographies. *Bulletin of Seismological Society of America* **84:4,** 1169-1183

Geli, L., Bard, P.Y. and Julien, B. (1988). The effect of topography on earthquake ground motion: a review and new results. *Bulletin of Seismological Society of America* **78:1,** 42-63.

Borcherdt, R.D., Wentworth, C.M., Janssen, A., Fumal, T. and Gibbs, J. (1991). Methodology for Predictive GIS Mapping of Special Study Zones for Strong Ground Shaking in the San Francisco Bay Region, California. *Proceedings of Fourth International Conference on Seismic Zonation, Stanford, California*, 545-552.

Borcherdt, R.D. (1994). Estimates of site-dependent response spectra for design (Methodology and Justification). *Earthquake Spectra* **10:4,** 617-653.

Kamalian, M. (2001). Time Domain Two-Dimensional Hybrid FEM / BEM Dynamic Analysis of Non-Linear Saturated Porous Media. Ph.D. Thesis, Tehran University, Tehran, Iran

Taghavi, A. (2008). Study on Seismic Behavior and Amplification Potential of 2D Semi-Elliptical Shaped Hills Subjected to Vertically Propagating Incident Shear Waves. M.Sc. Thesis, Iran University of Science and Technology, Tehran, Iran

Kamalian, M., Jafari, M.K., Sohrabi-Bidar, A. and Razmkhah, A. (2008). Seismic response of 2D semi-sine shaped hills to vertically propagating incident waves: Amplification patterns and engineering applications", *Earthquake Spectra* **24:2,** 405-430.

Kamalian, M., Sohrabi-Bidar, A., Razmkhah, A. and Taghavi, A. (2008). Considerations on seismic microzonation in areas with two-dimensional hills. *Journal of Earth System Science*, Special Issue: Microzonation, (Accepted).

Kamalian, M., Gatmiri, B., Sohrabi-Bidar, A. and Khalaj, A. (2007). Amplification pattern of 2D semi-sine shaped valleys subjected to vertically propagating incident waves. *Communications in Numerical Methods in Engineering* **23:9,** 871-887.

Kamalian, M., Jafari, M.K., Sohrabi-Bidar, A. and Razmkhah, A. (2006). Time-domain two-dimensional site response analysis of non-homogeneous topographic structures by a Hybrid FE / BE method. *Soil Dynamics and Earthquake Engineering* **26:8,** 753-765.

Kamalian, M., Jafari, M.K., Dehghan, K., Sohrabi-Bidar, A. and Razmkhah, A. (2003). Two-dimensional hybrid response analysis of trapezoidal shaped hills in time domain. *Advances in Boundary Element Techniques IV, Ed. Gallego, R. and Aliabadi, M.H.*, 231-236.