Estimation of Site Effects in the Iranian Plateau Using the Quarter-Wavelength Method

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ESTIMATION OF SITE EFFECTS IN THE IRANIAN PLATEAU USING THE QUARTER-WAVELENGTH METHOD

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ABSTRACT

Abstract-The characteristics of strong ground motion at a given site depend upon the source mechanism, the transmission path together with the geological characteristics of source to the site, and the local soil conditions at the site, mostly known in the engineering and seismological literature as site effects. In the context of the stochastic simulation methods (e.g. Boore 1983), site effects play a significant rule in ground-motion studies. The objective of this paper is the assessment of site effects (both crustal amplification and near surface attenuation) in the Iran plateau. The effects in different parts of Iran were estimated based on the average shear wave velocity of upper 30 m that is presented in site classification system of NEHPR. For deeper depths the global data of CRUST 2.0 model were used and shear wave velocity profiles in different depths were assessed accordingly. Afterwards, using the quarter-wave length method the crustal amplification have been determined for a grid of 1° by 1° over the whole country. In addition the near surface attenuation effect was estimated using the empirical correlation between kappa and shear wave parameters proposed by chandler et al. (2006). The final results are presented as site effects contours in the frequency range of most interest to engineers for the Iranian plateau.

INTRODUCTION

Ground motion characteristics in a site depends on several factors such as source mechanism, path effect and soil specifications. The soil specification in earthquake engineering literature is known as site effect which is of interest of geotechnical and earthquake engineers. The site effect considerations are intended to investigate the characteristics and effects of strong ground motion and the destructive potential of earthquakes, on the buildings. In most of design codes, before 1994, the site effect was considered as a multiplication factor multiplied to the response spectra. The factor was defined according to different site classifications which are a combination of the quality and quantity of the soil type, stiffness and its depth. The site effect amplification factors are also used in the stochastic simulations of ground motion. The site effect in the context of stochastic simulations for generic rock site was surveyed by Boore and Joyner (1997) using the shear wave velocity data gained by the borehole investigations and velocity studies in the crust. They calculate the frequency- dependent amplification factor, in some parts of United States.

Silva and Darragh (1995) and Steidl (1996) investigate the amplification in the generic rock sites. Afterwards, Klimis and Margaris (1999) provided the amplifications factors in different frequencies according to the NEHRP classification system. They used the Greece data from down-hole surveys and the site-dependent amplification functions are represented as a function of the average shear wave velocity over the upper 30 m. Chandler et al (2005), using the shear wave velocity modeling in crustal rock, introduced the relations for assessing the amplification and attenuation factors which is used in seismic hazard analysis and stochastic simulations. Also, Chandler et al (2006) developed a new attenuation modeling approach using Hong Kong as a case study and investigated the upper-crust amplification factor in combination with predicted attenuation parameters to determine the upper-crust modification factor.

SITE EFFECTS

The site effects include amplification and near-surface attenuation. In most of the past studies the objective was the calculation of the amplification without attenuation. But it has been accepted that the attenuation is an important factor which exists in all sites and should be considered. The amplification occurs when the natural intensify the ground motion and leads to sever damages in structures.

Several empirical relations have been proposed for near-surface attenuation but in this study the chandler correlations are used (Chandler et al. (2006)). He defined the attenuation factor as a function of shear wave velocity at 30 m depth as following:

$$\kappa = \frac{0.057}{V_{s,0.03}^{0.8}} - 0.02 \rightarrow (0.5\,km/s \le V_{s,0.03} \le 3\,km/s) \qquad (1)$$

The above equation is applicable only in specific rang of shear wave velocity. For the other velocities the suggested empirical values of Anderson et al. (1984) have been used.

Site classification methods determine the type of the site by the shear wave velocity at shallow depths (up to 30 m). NEHPR accepted a site classification method which defines five different classes for the sites: Hard Rock, Rock, Very dense soil and soft rock, Stiff soil profile, Soft soil profile. The Iranian seismic code (2800 code), divided the sites base on the average shear wave velocity at 30 m depth and/or the geological properties of site. Four different classes proposed by the 2800 code are presented in Table 1.

Table 1.Classification based on shear wave velocity

Soil Type	(m/s)$\overline{\boldsymbol{V}}_{\boldsymbol{s}}$
I	Over 750 $375 \le \overline{V}_s \le 750$
II	$375 \le \overline{V}_s \le 750$ $375 \le \overline{V}_s \le 750$
III	$175 \le \overline{V}_s \le 375$ $175 \le \overline{V}_s \le 375$
IV	Less than 175 m/s

Ghasemi et al. (2008), introduced a new site classification specifically for Iran. This classification which is used in this paper classified different strong motion stations of the country such as Manjil, Talesh, Tabas, and Ghaen into four groups as presented in Table 2. These sites have all had recorded a catastrophic earthquake during recent years.

Table 2. The four class site categorization according to H. Ghasemi et al. (2008)

Group	(m/s)$\overline{V_{s30}}$
1	$\overline{V_{s30}} \ge 700$
2	$500 \le \overline{V_{s30}} < 700$
3	$300 \le \overline{V_{s30}} < 500$
4	$\overline{V_{s30}} < 300$

THE QUARTER-WAVELENGTH APPROXIMATION METHOD

The quarter-wavelength approximation for computing site amplification was first introduced by Joyner et al. (1981).

They stated that ‘’for a particular frequency, the amplification is given by the square root of the ratio between the seismic impedance (velocity times density) averaged over a depth corresponding to quarter wavelength and the seismic impedance at the depth of the source’’. Afterwards in 1996, Day modified the method and provided some theoretical justification.

The Comparisons of this method to the exact theoretical amplifications indicated that the quarter-wavelength approximation is highly capable of estimation of the mean values of the response ((Boore and Joyner (1997)). According to Boore and Joyner (1997) the algorithm is as follow: the S travel time Stt(z) from the surface to depth z either is taken from down-hole surveys or is computed using shear velocity as a function of depth; the average velocity to depth z, β(z), is z/Stt(z), and the frequency corresponding to the depth, f(z), is 1/[4 ×Stt(z)]; a travel-time-weighted average is taken of the density, $\bar{\rho}(z)$ and the amplification is given by Eq. (2)

$$A[f(z)] = \sqrt{\rho_s \beta_s / \bar{\rho}(z)\bar{\beta}(z)} \qquad (2)$$

where the subscript s represents values adjacent to the source.

Of course, the site response includes both amplification and attenuation, but we have considered them separately to be able to parameterize the attenuation by the following Eq.:

$$\exp(-\pi\kappa_0 f) \qquad (3)$$

It is worthy to mention that using a parameter such as Q to represent the attenuation is not an accurate way, because it only gives a phenomenological description including intrinsic and scattering attenuation mechanisms (Boore and Joyner (1997)).

SITE EFFECTS CONSIDERATION IN THE IRANIAN PLATEAU

To estimate the amplification factor using the quarter wave length approximations the shear wave velocity in different depths from the ground surface to the depth of the earthquake sources is required. In shallow depths the shear wave velocity can be assessed by several ways such as borehole data and shear wave travel-time measurements made in boreholes. In this paper, due to lack of data for every point of Iranian Plateau and variability of soil type in upper 30 meters, the average shear wave velocities proposed by the 2800 code and Ghasemi et al. (2008) study, are used. For deeper depths the CRUST 2.0 a global crustal model was used which represents the crustal data for each point of the world, in 7 seven layers; 1.Ice2.Water, 3.Soft sediments, 4.Hard sediments, 5.Upper crust, 6.Middle crust and 7.Lower crust.

Compression and shear wave velocity, density and thickness of each layer is provided in this comprehensive model in 2X2 degrees (180*90=16200points) and the model specify a code to each point.
Using CRUST 2.0 model the data and codes for all point of Iran was derived and then the shear wave velocity profile was drawn using the chandler et al (2005) model.

In addition, the density was required to be known at different depths; therefore the simple interpolation relation proposed by Boore and Joyner (1997) was used to calculate the density as a function of shear wave velocity. The results of this simple relation are in agreement with the CRUST 2.0 data.

To estimate the site amplification factor which is the objective of this paper, density and shear wave velocity near the source should be calculated using the Chandler model. It was assumed that the near source velocity is approximately equal to the velocity value at 9 km depth. Due to humble importance of the frequencies less than 0.1 Hz, and because the calculations are continued up to quarter wave length, the earthquake source depth was chosen between 8-9 km (Boore and Joyner (1997)).

$$\lambda = \frac{\beta}{f} = \frac{3.5km}{0.1Hz} = 35km \quad => \frac{1}{4} \times 35 = 8.75km \qquad (4)$$

While the site amplification is of interest the amount of Q is considered very large (near infinity, 10000) to minimize the geometrical path effect on amplification (Haskell (1960)).

The frequency dependent amplification and attenuations were calculated for three incidence angles (0, 30 and 45 degree), considering all classifications proposed by 2800 code and Ghasemi et al. (2008), for all points of Iran with 2X2 degree resolution. The results are reported in charts to be used in stochastic simulations of strong ground motion. Then, the amplification factor counters are drawn in some significant frequencies (100 different frequencies between 0.02 to 60 Hz) and assuming the average shear wave velocity to be 750 m/s. (See Fig. 2.)

As mentioned above one of the important factors in calculating the amplification factor is the shear wave velocity in upper 30 m. According to Ghasemi et al. (2008) study, the average shear wave velocity in upper 30 m assumed to be 300, 400, 600 and 700m/s and according to the 2800 code, this velocity assumed as 175, 275, 625 and 750 m/s.

As an example for point A which is located in northwest of Iran (latitude and longitude 38E and 46W degree, respectively), the crustal data (i.e. shear and compression wave velocity, density and thickness) were derived from CRUST 2.0 and are presented in Table 3.

Table 3. The data of point A obtained from the CRUST 2.0 model

46,38=p6	p-wave km/s	s-wave km/s	Density gr/cm^3	Thickness km
Water	3.81	1.94	0.92	0
Ice	1.5	0	1.02	0
Soft sediments	2.5	1.2	2.1	0.5
Hard sediments	4	2.1	2.4	0
Upper crust	6.1	3.5	2.75	18
Middle Crust	6.3	3.6	2.8	16
Lower Crust	7.2	4	3.1	8.5

Afterwards, the shear wave velocity model that was developed by Chandler and Lam (2004) was used to derive the shear wave profile. The model divide the site to three zones including upper sedimentary crustal layer, lower sedimentary crustal layer and Crystalline sedimentary layer as shown in Fig. 1 and according to the zone, different formulations are suggested in this model.

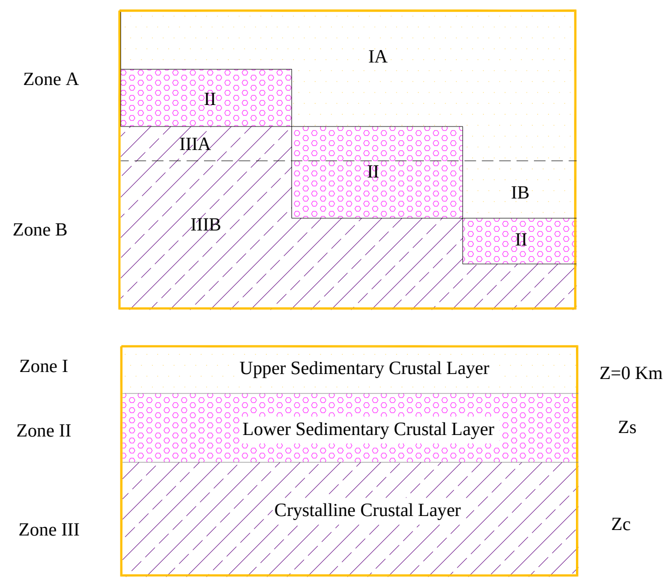

Fig. 1. S-wave velocity profiles in non-glaciated conditions.

To obtain the shear wave velocity profile in shallow sediment layers in different depths the functions IA ، II ،III and IIIB are used. These general functions are presented in Table 4 and the corresponding functions for point A are presented in Table 5.

Table 4.The suggested Equations by Chandler to investigate the shear wave velocity in different depths

Eq. Number	Depth range	Equation
1	$0 < Z < Zs < 4$	$V_s = V_{s,0.03}\left[\frac{Z}{0.03}\right]^{1/4}$
2	$Zs < Z < Zc$	$V_s = V_{s,Zc}\left[\frac{Z}{Zc}\right]^{n*}$
3	$Zc < Z < 4$	$V_s = V_{s,4}\left[\frac{Z}{4}\right]^{1/6}$
4	$4 < Z$	$V_s = V_{s,8}\left[\frac{Z}{8}\right]^{1/12}$
Zs is the soft sedimentation thickness and Zc is the total thickness of sediment layers and Vs, 4and $V_{s,8}$ are the shear wave velocity at 4 and 8 km, respectively. $* \, n = \frac{\log\left(\frac{Vszc}{Vszs}\right)}{\log\left(\frac{Zc}{Zs}\right)}$		

Table 5.Shear wave velocities for point A, at different depths

Depth range	Equation
$0 < Z < 0.5$	$V_s = 0.3\left[\frac{Z}{0.03}\right]^{1/4}$
$Zs = Zc$	
$0.5 < Z < 4$	$V_s = 2.71\left[\frac{Z}{4}\right]^{1/6}$
$4 < Z$	$V_s = 3.32\left[\frac{Z}{8}\right]^{1/12}$
For point A the Zs and Zc are both equal to 0.5 km and because it is less than 4 km it is fallen in shallow sediments group according to Chandler Model.	

Using the power regression function for the data derived from CRUST 2.0, the shear wave velocity is assessed for desired depths (at 4 and 8 km depth the velocities are 2.71 and 3.32 respectively). The chandler et al. shear wave model then was utilized to obtain shear wave profile in all depths.

The shear wave velocity profile Vs depth for four different velocities suggested by Ghasemi et al. (2008), is presented in Fig. 2.

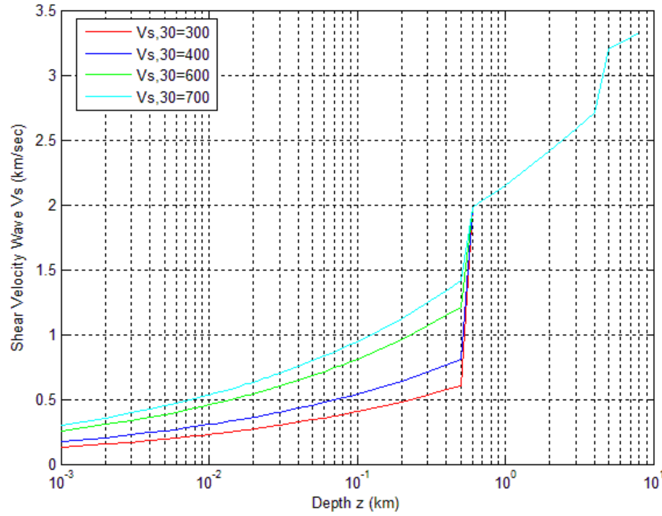

Fig. 2. Shear wave velocity profile at point A versus depth for different velocities

Conduction of linear interpolation in CRUST 2.0 data, gives the density as a function of velocity and then using the shear velocity profile the densities at all depths are calculated. Afterwards, by sitea3.1 software that was presented by Boore, and using the calculated values of shear velocity and density, the amplification factor was calculated without considering the attenuation and then using the code written in Matlab the attenuation effect was imposed by the exp(-κπf) function. The calculated attenuation and amplification factors versus frequency were drawn in Fig. 3 for different velocities.

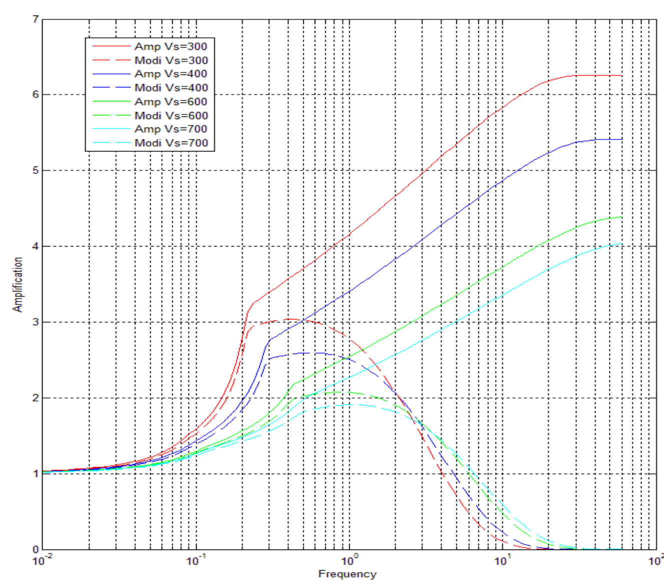

Fig. 3.Amplification and modified amplification for region A

RESULTS AND VERIFICATION

In this paper the simultaneous effect of amplification and attenuation is calculated in different frequencies and shear wave velocities. These factors in different points (in a 2X2 mesh) of Iran were estimated and were drawn in frequency contours on Iran's map. Fig.4 represents a sample of the contours at 2 Hz frequency and 750 m/s shear wave velocity. (The average incidence angles are 0, 30 and 45 degree)

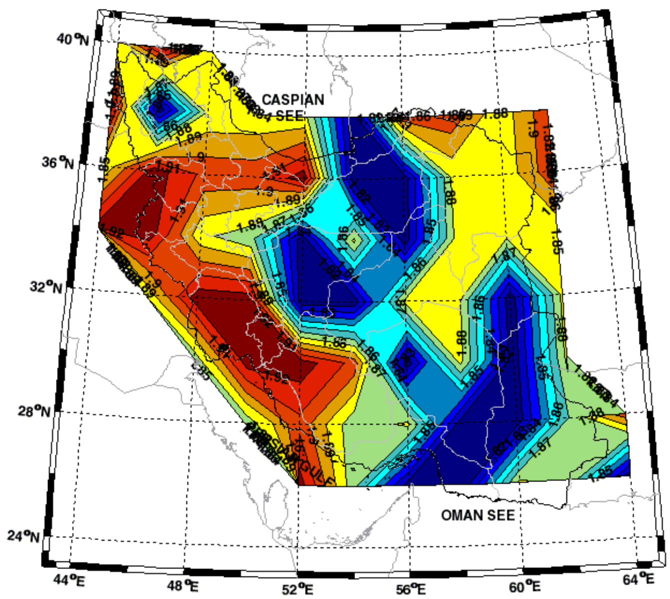

Fig. 4. a sample of the contours at 2 Hz frequency and 750 m/s shear wave velocity for Iran. (The average incidence angles are 0, 30 and 45 degree)

To verify the accuracy of the results gained by this method, the same process was done for Greece and Hong Kong country as well as Iran and the data of these countries was also derived from CRUST 2.0. The frequency dependent amplification factor in combination with attenuation effect was calculated and illustrated in a unique chart with the past results, to be compared to the previous study done by Klimis and Margaris (1999) and Chandler et al. (2006) for Greece and Hong Kong, respectively.

As can be seen in Figs 5 and 6, a reasonable consistency exist between the results gained by the analytical method of this paper and the results of past researches done for these countries, which prove the accuracy of the results for the Iran Plato and indicate that these factors can be safely used in stochastic seismic simulations of strong ground motion.

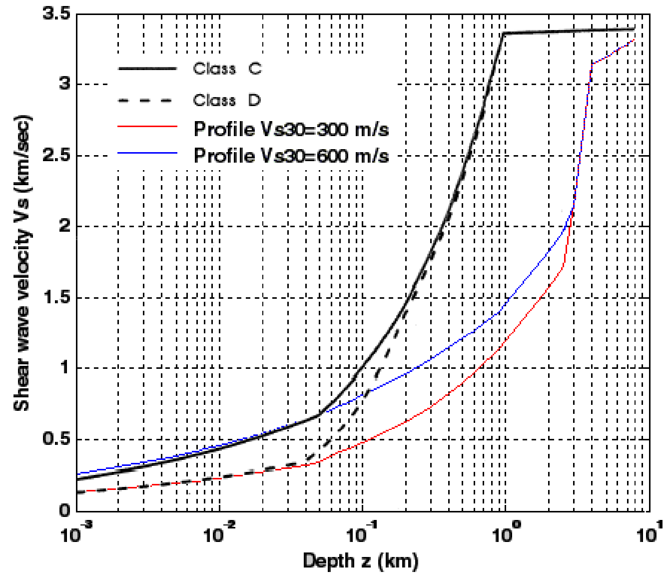

Fig. 5. Comparison of the results (shear wave velocity profile Vs. depth) of the Margaris and Klimis (1999) study and current paper for Greece (40N 22E)

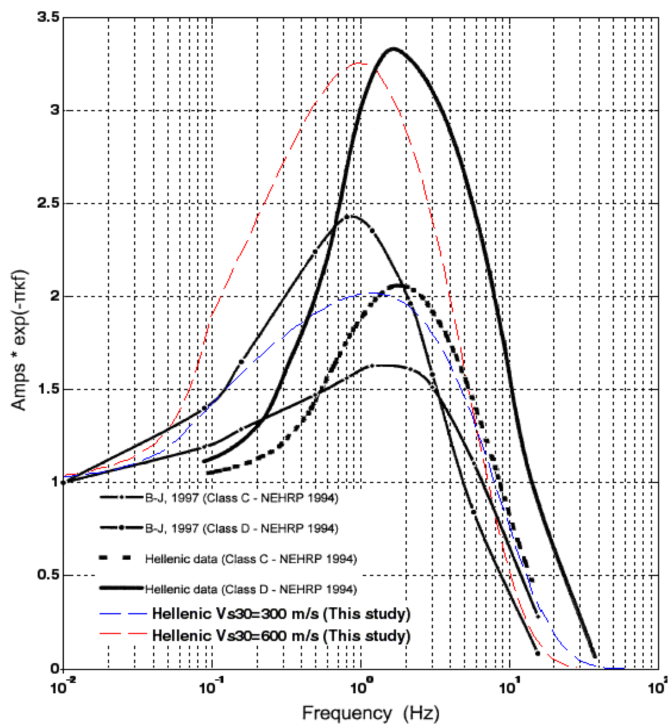

Fig. 6.Comparison of the results (modified amplification Vs frequency) of the Klimis andn Margaris (1999) study, Boore and Joyner (1997) study and current paper

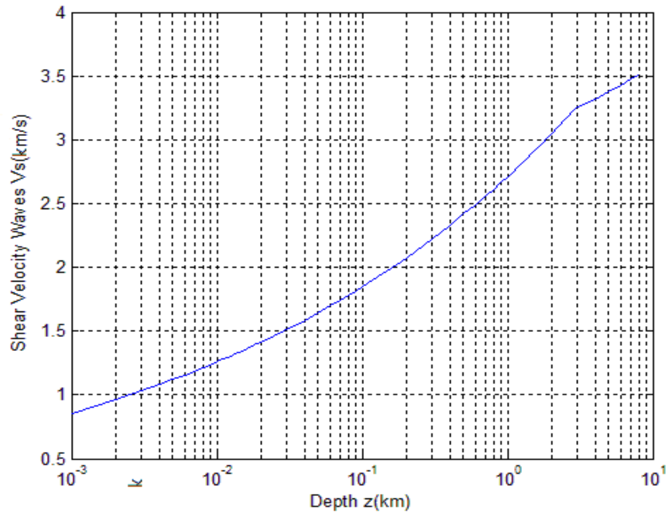

Fig. 7. Shear wave velocity Vs. Depth for Hong Kong

The amplification factor was calculated using Hong Kong data and then the modified amplification considering attenuation was assessed and both are presented in Fig. 8

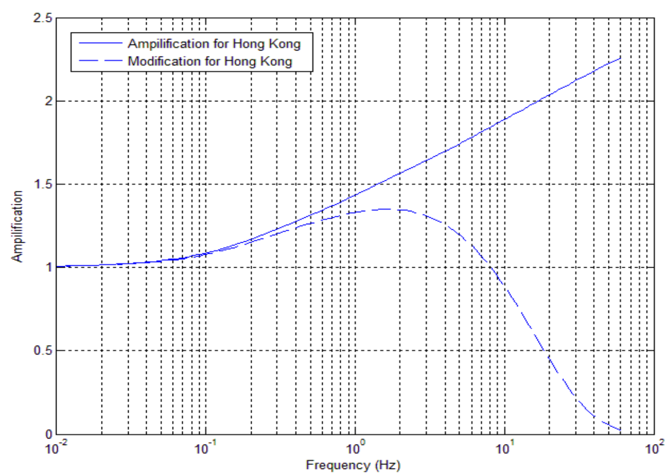

Fig. 8. The comparison of the modified amplification and pure amplification for Hong Kong

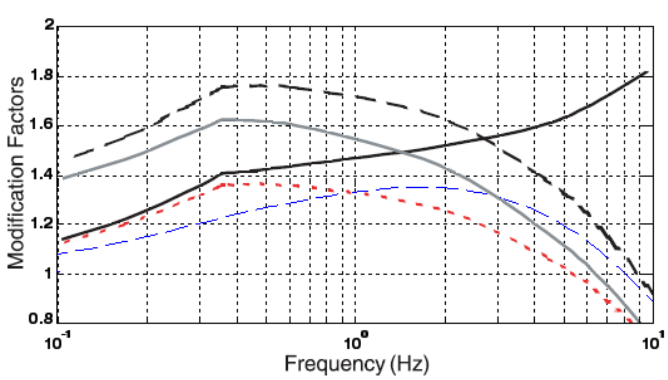

Fig. 9. Site effects (attenuation and amplification)

CONCLUSION

In this paper assuming the probable shear wave velocity at shallow depth (upper 30 m) according to the codes, and using the CRUST 2.0 data for lower depths, the shear wave velocity and density profiles Vs depth was calculated in different points of Iran. The comparison between the results of these paper and chandler for Hong Kong and Morgenstern for Greece was carried out to verify the results accuracy. The same procedure for these countries wad done and indicated a reasonable consistency between the results.

According to the accuracy of the results proved by the comparison it may be declared that this method can be used to estimate the site effects in different parts of the world. To make the results more accurate, it is suggested that in the specific sites, the shear wave velocities in upper 30 m should be estimated by down-hole surveys. The results of this paper can be used as an input data in seismic simulations of strong ground motions in Iran.

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