Non-linear Seismic Ground Response Analysis Considering Two-dimensional Topographic Irregularities

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Abstract

In the event of an earthquake, local site conditions such as soil characteristics, dimension of topographic irregularities, seismic bedrock depth, etc. and also characteristics of incident wave have important effects on seismic ground response. In this study, Finite Element Method (FEM) coupled to Viscous Boundaries is used to evaluate the effect of empty two-dimensional valleys on amplification or attenuation of seismic waves. Parametric studies carry out and the effects of dimension of the topography, frequency of the incident wave and bedrock depth on the seismic ground response are considered using non-linear method in a time domain analysis. Results are shown by means of horizontal and vertical amplification ratio in valley span and its surrounding area. It is concluded that displacement variation on ground surface due to topographical effects is a considerable factor to select a site location or design structures in the valley mount and its surrounding area.

Keywords: topographic irregularity, FEM, Viscous Boundary, non-linear method

1. Introduction

Evaluation of surface ground motion due to seismic excitation at bedrock is one of the most important issues in geotechnical earthquake engineering. In common seismic events, body waves travel from the source mostly across a bedrock and finally end in soil layers. This is while most of the changes in the characteristics of ground motions occur in the soil layers [1]. These changes are generally discussed with focusing and scattering phenomenon of seismic waves. Due to the drastic variation of the nature of seismic waves passing through soil layers, it is very important to incorporate realistic and precise seismic excitation models into the analysis of structural seismic response. Hence, vulnerability of structures can be a function of an important factor known as the site seismic response. Ground response analyses can properly satisfy the needs for realistic and precise seismic excitation in analysis of structures or in soil-structure interaction.

Site effects are generally divided into two categories: effects of local deposits and those of topography. In this regard, the effect of topographic irregularities on ground motions is of great importance. Recent studies have indicated that topographic irregularities (e.g., mountain ridges or valley notches) have caused significant changes to strong ground motions during earthquakes. Investigations on many earthquakes occurred in the past have also indicated the effect of surface topographic changes on ground response. Evidences of topographic effects are available in Alaska 1964 [2], Canal Beagle Chile 1985 [3, 4], Northridge 1994 [5, 6], Athens 1999 [7], Umbria-Marche 1997 [8] and many others. The significance of local topographic irregularities is shown by the fact that earthquake causes vast damages to some certain regions and only slight damages to others.

Generally numerical studies on the effect of topographic irregularities on the ground response are multidimensional analyses which use various approaches such as Finite Element Method (FEM) (e.g. [9,10]), Boundary Element Method (BEM)(e.g. [11,12]), Spectral Element Method (SEM)(e.g. [13]), Finite Difference Method (FDM)(e.g. [14]), and Hybrid methods such as coupled Finite and Infinite Element method (FE-IFE) (e.g. [15,16]), coupled Finite and Boundary Element Method (FEM-BEM) (e.g. [17,18]). Detailed explanation on multidimensional analyses and comparison of results may be found in some references (e.g. [9, 19, 20]).

Extensive researches have been conducted to optimize ground seismic response analysis (e.g. [21-29]). For example Lermo and Chávez-García [30] referred to the limitations of the classic method of spectral analysis, especially limitations imposed on field operation and the process of recording data. They also proposed a new method to study site effects. Following well-known Nakamura method, they used the ratio of the spectral amplitude of the horizontal to the vertical component of minor earthquakes. They also compared their results with those of the classic spectral approach. LeBrun et al. [31] carried out an experimental study on the topographic effects of a large hill with a height of 700m, width of 3km and length of up to 6km on seismic analysis. In the course of investigation, seven seismographs were installed on a hill and a total of 58 earthquake records were obtained. They studied the ground motion with different methods: the Classical Spectral Ratios (CSR) and the horizontal to vertical spectral ratios calculated both on noise, so called Nakamura's method (HVNR), and then on earthquake data, so called Receiver Function technique (RF). The comparison between these two methods showed that the H/V method was able to suggest the fundamental frequencies of a hill. Fu [32] investigated effect of scatter in surface waves by comparison of different theories. He also examined these waves by study on the propagation of SH waves through two-dimensional models. He compared accuracy of different theories according to dimension of model and incident wavelength. Bouckovalas and Papadimitriou [14] analyzed the effect of topography on seismic waves using the Finite Difference Method (FDM). Their study was based on a site with uniform slope and on a visco-elastic soil medium. Study was also conducted on the effects of different parameters on seismic ground motion which was based on the vertical propagation of SV waves. Kamalian et al. [17] studied the effects of topography on a medium with heterogeneous materials. They used two-dimensional modeling method based on FEM-BEM. They also modeled distant boundaries using confining elements. They showed that their proposed method needed smaller time step compared with the BEM scheme. They also discussed on the effective dimension of irregularities on seismic ground motion. Gatmiri et al. [18] investigated the effect of alluvial valleys on the amplification or attenuation of seismic waves. They also used a coupled model of FEM-BEM in which nearby field was modeled using FEM while the far field was modeled using BEM. They verified the accuracy of their method by numerical study and discussed that artificial waves developed at the truncation points of the model would be vanished easier if an optimized method was used. Asgari and Bagheripour [33] performed a non-linear one-dimensional analysis of ground response using hybrid frequency–time domain (HFTD) approach. They used the advantages of both the time domain and the frequency domain methods to optimize the solution procedure. They showed the accuracy of their method by different illustrative examples. Di Fiore [10] considered the effect of incident wave frequency and gradient of slopes as a form of topographic irregularities on the amplification or attenuation of seismic waves using FEM. Investigations showed that amplification of seismic wave is increased with increasing the gradient of slope. Also Analysis of 0.5 to 32Hz incident wave frequencies revealed that the largest amplification of seismic waves was seen at frequencies 4 to 12 Hz. Bazrafshan Moghaddam and Bagheripour [34] proposed a new method for non-linear analysis of ground response using HFTD approach. This method was based on a non-recursive process and used a matrix-notation. Comparison of the results of the proposed method and those obtained by SHAKE and NERA software using records collected on the site of several actual earthquakes showed accuracy and efficiency of the proposed method. Tripe et al. [35] conducted a study using time domain approach into the contribution of slopes of homogeneous and linear-elastic soils to the amplification or attenuation of seismic waves using FEM.

One of the important problems in ground response analysis is the limitation or inability of numerical methods to simulate infinite boundaries and the development of mathematical models for the passage of seismic waves as well as reduction of reflected waves from the boundaries into the models developed for soil layer. Such a deficiency greatly influences the results.

It should be noted that one-dimensional ground response analysis methods are suitable for horizontal or gently sloping grounds and perhaps for soil profiles having parallel set of layers. However, other problems such as slopes, non-linear ground surfaces, topographic irregularities, presence of heavy and stiff structures, buried structures, and tunnels require two- or even three-dimensional analysis [1].

In present study, non-linear time domain analysis is carried to investigate the effect of two-dimensional valleys on the amplification or attenuation of seismic waves using PLAXIS which is one of the most powerful and applicable software to simulate infinite or semi-infinite soil and rock medium and has been based on FEM. Using this software, one may apply proper boundaries to the

FE models to simulate the infinite extent of a soil medium and prevent reflecting of artificial waves to the model.

Results are presented in non-dimensional amplification diagrams for both horizontal and vertical directions. In this investigation, a realistic numerical simulation of the medium is conducted to avoid reflection of seismic waves at boundaries using special boundary conditions known as "Viscous Boundaries". In fact, these boundaries are coupled to the rest of model's area simulated by FEM.

Application of such boundaries proposed in this research develops a powerful FE tools which diminishes difficulties caused by coupling infinite elements to finite elements, FE-IFE. Such an approach also helps developing a more rational method and hence achieving more acceptable results [9].

Amongst different types of seismic sites, empty valleys have been given less attention compared with other topographic irregularities. However, these types of valleys have importance in theoretical studies and engineering applications since these valleys may have large numbers of inhabitants due to various life resources. In addition some of the important structures like dams, bridges and briefly many infrastructures have been built in these types of valleys. In the following, the theoretical approach adopted in this study is discussed.

2. Proposed Theoretical Approach

2.1. Equation of Motion in Multidimensional Analysis

The basic equation of motion for a system affected by a dynamic load in a finite element approach can be derived as:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{f\} \tag{1}$$

where [M], [C], and [K] are mass, damping, and stiffness matrices, respectively. Also $\{\ddot{u}\},\{\dot{u}\},\{u\}$

and $\{f\}$ are acceleration, velocity, displacement and force vectors, respectively which vary with time. In the following, like Yoshida's manner [20], matrix and vector notations are not used for simplicity.

Generally in the engineering practice and especially in the case of ground response analysis relative displacement is considered, thus [20]:

$$u = u_r + Iu_b \tag{2}$$

In equation (2), u_r is the relative displacement vector related to the displacements of the base, u_b is the displacement vector for the base and I is a vector whose components are unity when the directions of the degree of freedom and that of loading are the same. These components are reduced to zero when those directions are different. Substituting relation (2) into (1), one can be inferred that:

$$M\left(\ddot{u}_r + I\ddot{u}_b\right) + C\left(\dot{u}_r + I\dot{u}_b\right) + K\left(u_r + Iu_b\right) = 0 \tag{3}$$

Since u_b is a rigid displacement in the domain, then we have:

$$Ku_b = 0 \tag{4}$$

Considering movement of domain in the air, one can obtain:

$$C\dot{u}_b = 0 \tag{5}$$

Further, the following relation can be inferred using equation (3) to (5):

$$M\ddot{u}_r + C\dot{u}_r + Ku_r = -MI\ddot{u}_b \tag{6}$$

The subscript *r* is further omitted for the simplicity in the following, assuming that *u* indicates relative displacement. Mass matrix can be formed using two different formulations: consistent mass matrix in which the same interpolation function is applied in its development, and lumped mass matrix in which more simplified interpolation function is used. However, the latter is a diagonal matrix and is easier to apply in the various problems [20]. Detailed discussion on mass matrix formulations can be found in various references (e.g. [36]). In this study, lumped mass matrix formulation is adopted.

2.2. Evaluation of Damping Matrix

In finite element formulation damping matrix is often formulated as a Rayleigh damping using mass and stiffness matrices;

$$C = \alpha M + \beta K \tag{7}$$

In the above equation, α and β are coefficients which are obtained in the following. Such a formulation for damping ensures that when the first part of above equation is dominant, more of the low-frequency vibrations are damped conversely if the second part is dominant, more of the high-frequency vibrations are damped [37].

Substitution of equation (7) into (6) leads to [20]:

$$\ddot{u} + (\alpha + \beta\omega_0^2)\dot{u} + \omega_0^2\dot{u} = 0 \tag{8}$$

Also according to equations (6) to (8), for Single-Degree-Of-Freedom (SDOF) system it can be inferred that:

$$\xi = \alpha/2\omega_0 + \beta\,\omega_0/2 \tag{9}$$

For multi-degree-of-freedom system using separation to the group of the SDOF system, one may reach to the following relation:

$$\xi_i = \alpha/2\omega_i + \beta\,\omega_i/2 \tag{10}$$

where subscript *i* show i^{th} mode parameters.

Important range of deformations in engineering practices occurs in the low-frequency modes. Since there are only two parameters in the Rayleigh damping, only two conditions can be satisfied at maximum. When the damping ratios at the first and second modes are determined, two parameters are obtained as [20]:

$$\alpha = 2\omega_1\omega_2 \frac{\xi_1\omega_2 - \xi_2\omega_1}{\omega_2^2 - \omega_1^2} \tag{11-a}$$

$$\beta = 2(\frac{\xi_2\omega_2 - \xi_1\omega_1}{\omega_2^2 - \omega_1^2}) \tag{11-b}$$

The stiffness part of Rayleigh damping relation is more important than the mass part, therefore, one can evaluate β from the damping at the predominant period considering $\alpha = 0$ [20].

2.3. Numerical Integration Scheme

Generally in seismic ground response problems, methods are categorized into linear, equivalent linear and non-linear with different soil behavior assumption. Analyses by these methods can be carried either in time or frequency domain. The equivalent linear procedure is among the frequency domain methods and most of non-linear methods use time domain approach.

In the time domain analysis, equation of motion is solved by integrating in a small time intervals, which is called step by step time integration method. In this method time intervals should be small in order to accurately follow loading variation and also to fully account for change in materials properties.

Time integration schemes can be categorized into explicit and implicit approaches. Despite some limitations, explicit scheme is relatively simple to formulate. Implicit schemes is rather complicated, however, the process of calculation is more trustworthy and accurate. Among implicit schemes, Newmark method is often adopted.

In this study in order to solve the equation of motion in time domain, displacement and velocity in time $t + \Delta t$ can be derived using Newmark method as follows [37]:

$$u^{t+\Delta t} = u^t + \dot{u}^t \Delta t + ((1/2 - a)\ddot{u}^t + a\ddot{u}^{t+\Delta t})\Delta t^2 \tag{12-a}$$

$$\dot{u}^{t+\Delta t} = \dot{u}^t + ((1-b)\ddot{u}^t + b\ddot{u}^{t+\Delta t})\Delta t \tag{12-b}$$

$$u^{t+\Delta t} = u^t + \Delta u \tag{12-c}$$

In the above equations, Δt is time step and coefficients *a* and *b* determine the accuracy of the numerical time integration. The applicable range for *a* and *b* to ensure a stable solution is as follows [37]:

$$b \geq 0.5 \tag{13-a}$$

$$a \geq 1/4(0.5+b)^2 \tag{13-b}$$

Interested readers can find some various recommended value for *a* and *b* in different references. However, common value for them in references [20, 37] as *a=0.3025* and *b=0.60* are adopted here. Equations (12) can also be rewritten as [37]:

$$\ddot{u}^{t+\Delta t} = \lambda_0 \Delta u - \lambda_2 \dot{u}^t - \lambda_3 \ddot{u}^t \tag{14-a}$$

$$\dot{u}^{t+\Delta t} = \dot{u}^t + \lambda_6 \ddot{u}^t + \lambda_7 \ddot{u}^{t+\Delta t} \quad \text{, or} \tag{14-b}$$

$$\ddot{u}^{t+\Delta t} = \lambda_0 \Delta u - \lambda_2 \dot{u}^t - \lambda_3 \ddot{u}^t \tag{15-a}$$

$$\dot{u}^{t+\Delta t} = \lambda_1 \Delta u - \lambda_4 \dot{u}^t - \lambda_5 \ddot{u}^t \tag{15-b}$$

in which the coefficients λ_0 to λ_7 were introduced in the time step and in *a* and *b* integration coefficients.

Using the implicit scheme, equation (1) at $t + \Delta t$ is written generally as follows [37]:

$$M\ddot{u}^{t+\Delta t} + C\dot{u}^{t+\Delta t} + Ku^{t+\Delta t} = f^{\,t+\Delta t} \tag{16}$$

Using equation (14) to (16) and further mathematical operations and then simplification, one can obtain:

$$(\lambda_0 M + \lambda_1 C + K)\Delta u = F_{ext}^{t+\Delta t} + M(\lambda_2 \dot{u}^t + \lambda_3 \ddot{u}^t) + C(\lambda_4 \dot{u}^t + \lambda_5 \ddot{u}^t) - F_{\text{int}}^t \tag{17}$$

According to equation (12), Δu can be obtained and added to earlier displacement (u^t).

2.4. Boundary Conditions and Element Characteristics

Among the methods employed for the analysis of ground response, FEM is one of the most powerful one because of capability of simulating complicated geological and geotechnical conditions which are the matter of concern in this paper. Nevertheless, accurate simulation of boundary conditions and radial attenuation of wave energy is of particular importance to FE dynamic analysis. Application of boundaries with any constrain may lead to so called “trap box” effect for seismic waves in the model and hence to fictitious results.

In static deformation analysis, the vertical boundaries of the mesh are often fictitious boundaries and thus they do not affect the deformation behavior of the environment to be modeled [37]. For dynamic analysis, however, boundaries have to be placed far enough and farther than to be the boundaries in static analysis. Further, introduction of boundaries at far distance virtually means large mesh required in FE model with excessive elements which entails also extra calculation time and core memory. As the size of the divisions decreases, the influence of boundary conditions becomes a prime concern.

Since seismic ground response analysis domain is mainly rectangular shape, it can be assumed most of the waves traveling in horizontal direction are surface waves and their wavelengths are larger than body waves, thus one can use wide and thin elements [20]. In addition adoption of large elements for a FE model filters high-frequency components whose short wave length cannot be simulated with nodal points with long intervals.

Considering the mechanism governing the propagation of seismic waves, it has been found that size of elements should be less than 1/5 to 1/6 of the wavelength corresponding to the highest frequency content of the input motion [20].

2.4.1. Viscous Boundaries

When viscous boundaries are applied, equivalent dampers are used instead of commonly used boundary constraints. Such equivalent dampers absorb stresses induced to the boundary. It further means that such dampers act when stress waves are travelling outward the domain.

Components of absorbed normal and shear stress are defined as follows when an equivalent dampers is introduced in *x* direction.

$$\sigma_n = -c_1 \rho v_p \dot{u}_x \tag{18-a}$$

$$\tau = -c_2 \rho v_s \dot{u}_y \tag{18-b}$$

In the above equations, ρ is the density of materials, v_p and v_s are respectively the velocity of the compressional and shear waves, while c_1 and c_2 are relaxation coefficients that are applied to the model to enhance the performance of the viscous boundaries. The interesting point is that if incident compressional waves reach the model's vertical boundaries, c_1 and c_2 coefficients are reduced to unity (c_1=c_2=1). However, in presence of shear waves, the damping effect of viscous boundaries would not be adequate if coefficients c_1 and c_2 are neglected. In fact, the effect of these boundaries is increased directly with the increase in c_2 value. Recent studies have shown that application of $c_1=1$ and $c_2=0.25$ would optimize the absorbing effect of these boundaries [37]. Fundamental formulation of these viscous boundaries is based on the procedure described in [38].

3. Problem Definition

To investigate the effect of topographic irregularities and site effect parameters on seismic ground response, a valley environment is adopted as shown in Figure 1. To evaluate the amplification ratio due to interaction between topography and soil layer, a two-dimensional FEM approach is considered for parametric study. Soil layer was assumed overlain rigid bedrock and seismic excitation adopted is an in-plane vertically propagating SV wave induced to bedrock. Response obtained was investigated at the ground level at various points for the effect of soil layer and topographic irregularities on amplification or attenuation of seismic waves.

Fifteen-node elements were used to model the soil medium because they provide more accurate results since they benefit a better interpolation scheme (Figure 1). These elements have two degrees of freedom defined at every node and have 12 Gaussian points.

The accuracy of the proposed method was shown by comparison of results obtained using current method with those of FE-IFE method including non-dimensional diagrams for horizontal and vertical displacement amplitude, through the valley span and its surrounding area [9]. The satisfactory agreement between the results of two methods proved an acceptable performance of viscous boundaries in simulation of semi-infinite and infinite environments. Hence, the existing model is capable of simulating similar conditions.

3.1. Frequency Content of Seismic Excitation

Two-dimensional site effects are important where the dimension of topography is approximately equal to the wavelength of the seismic wave [39]. In earthquake engineering, it has been shown that the frequency content of a strong earthquake almost ranges from 0.1 to 20Hz. Further, the velocity of seismic waves near the ground surface lies between 0.1 to 3 km/s, then topographies having dimensions larger than tens of meters to several kilometers usually behave as in two-dimensional site response models (e.g. [1,10,40]).

In order to facilitate study on the effect of the frequency content of the input harmonic wave, a non-dimensional parameter known as the dimensionless frequency, a_o , is defined based on the following relation:

$$a_o = \frac{\omega h}{\pi V_s} \tag{19}$$

where, ω is the angular frequency of the incident wave induced to the bedrock, h is the maximum valley depth and V_s is the velocity of shear wave travelling through the soil medium.

To simplify evaluation of the impact of different parameters on seismic ground response analysis, results are shown in terms of amplification factor in horizontal and vertical directions as follows:

$$HA = u_x/u_o \qquad (20\text{-a})$$

$$VA = u_y/u_o \qquad (20\text{-b})$$

where, *HA* and *VA* are respectively the Horizontal and Vertical Amplification. In the above equations u_x and u_y denote displacement amplitude along *x* and *y* directions respectively also u_o is the amplitude of the incident wave. The incident wave amplitude is selected so that the maximum input acceleration (in depth) is equal to 0.35g. Diagrams of seismic amplification help understanding the pattern of response along the valley span and its surrounding area.

4. Parametric Study and Discussion

As seen in a Figure 2, the valley considered in this study is symmetric whose maximum depth is *h* while *H* refers to depth of the bedrock. *L* and *l* are respectively half of the top and bottom span of valley and are adopted in this study to fixed values as 100 m , 50 m.

Poisson's ratio was assumed to be constant and equal to 0.33, while soil' modulus of elasticity was adopted as 2.4×10^7 KN/m^2. The unit weight of soil considered to be 23.54 KN/m^3. The valley dimension of real situation are basically within the range studied [15].

In this study the effect of valley ratio (*h/H*), frequency content of incident wave, and the depth of the bedrock on seismic ground response are considered. Generally in this paper because of the geometric symmetry and the vertically planar SV seismic excitation, the results for the half of the valley are shown.

4.1. Effect of Valley Ratio

In order to evaluate the effect of valley ratio, constant values as *h/H=0, 1/4, 2/4* and *3/4* were adopted. In this part, the depth of the bedrock is *200* meters.

Figure 3(a) showed that in the case of free field, amplification of the horizontal component nearly doubles which reflects the extent of outcrop motion to the corresponding bedrock. In other shape ratios, as the distance from the valley center increases, the conditions of free field are also observed. Therefore, ground surface motions are always amplified compared with other points at depths.

As the parameter *h/H* increases, amplification of the horizontal component of displacement in the center of the valley is increased. However, in all cases except the free field condition, which has a uniform amplification, the locus of maximum *HA* occurred in the valley center. Increasing *h/H*, causes *HA* to reach a double quantity in the farther distances with respect to the center. It is important to note that the area affected by topographical problem varies depending on topographic dimensions. Therefore, model dimensions are determined based on topographic dimensions. It further implies that an increase in the area of the valley, free field conditions is attained in a farther distance.

According to Figure 3(b), although the incident wave considered to be an SV wave propagating in vertical direction, the vertical component of the output wave at the ground surface did not vanished even in the case of free field conditions. However in the case of topographic irregularities, *VA* is larger than that of free field condition. This phenomenon can be attributed to the interference of incident waves and their consecutive reflections in soil medium. At the valley center, due to the assumed symmetry of the valley and the upward propagation of incident wave, *VA* is virtually reduced to zero.

Increasing *h/H*, cause the maximum of the *VA* to increase correspondingly. As seen in Figure 3(b), its maximum occurred in $h/H = 3/4$ and has continued to a relatively large distance from the edge of the valley. However, the locus of the maximum shifts from the body to top of the valley and sustains over farther distances as the depth of the valley increases. As well as the *HA*, increasing *h/H*, cause the surrounding area to undergo more amplification.

It was found that increasing in the depth of the valley, not only increase the maximum value of the *HA* and *VA* but also the amplification of the topography was sustained over farther distances. In other words, the effect of topographic irregularity on seismic ground motion became more considerable. Different behaviors with different depth of the valley can be attributed to two major factors: Firstly increasing in valley's body slope, demonstrated by increase in depth while top and bottom span of valley is fixed, cause increase in amplification. The reason behind such a phenomenon is, in fact, explained earlier by current investigators [9]. Secondly, increasing the valley depth and consequently an increase in its area cause more amplification by surface waves and their interference with incident and reflected waves.

4.2. Effect of Frequency Content of Input Wave

As mentioned earlier, frequency content of input wave is referred here as in a_o parameter. In this study, constant values as $a_o=0.25, 0.5$ and 1 were adopted for this non-dimensional frequencies of seismic excitation and the shape ratio of the valley considered as $h/H = 1/2$ (where $h=100\ m$ and $H=200\ m$). The wavelengths of the incident waves were considered one, two and four times of the valley depth.

As can be inferred from Figure 4(a), *HA* is increased in almost all parts of valley mount and its surrounding area as frequency content decreases. However, in frequency ratios as $a_o=0.25, 0.5$ the locus of maximum took place at the top of the valley but in $a_o=1$, it was happened at its bottom. In other words, frequency content of the incident wave is one of the effective parameter to determine the locus of maximum of the *HA*. Decreasing the frequency content, cause more oscillation in *HA* and this component reached to a value as double of the input wave in the farther distances from the center.

According to the Figure 4(b), maximum *VA* occurred at the top of valley in different frequencies. Decreasing the frequency, cause *VA* at the farther distance from the valley center to reach a minimal value.

It should be noted that in addition to the surface topographical and mechanical properties of soil layer, different frequency content of the incident wave due to changing a_o is also affective in determination of model dimensions to attain free field conditions. However, this frequency content also affect on the quantities and locus of maximum and minimum of *HA* as well as *VA*. It further implies that for sites having the same topographical but different seismological conditions, numerically simulated model may not have the same dimensions since different frequency contents of seismic input wave necessitate different model's extension to reach free field conditions.

4.3. Effect of Bedrock Depth

In order to study the effect of bedrock depth, dimension of topography was kept constant while various ratios of *H/h* as *1.5*, *2*, *2.5*, *3* and *3.5* were adopted. In this part the height of valley was considered constant and equal to *100 m*.

According to Figure 5(a) it can be inferred that an increase in the bedrock depth, cause *HA* to decrease in the valley bottom but does not vary in the top of the valley. This phenomenon can be attributed to sharp angle at the bottom of topography which may cause the waves to trap and to reflect in multiple manner. This effect is vanished by increasing the depth of the bedrock. It is also important to note that the effect of topographic dimension on the ground seismic response is not considered an absolute impact. In fact, it is rational to evaluate topographical dimensions in relations to the bedrock depth since the ratio of the topographical dimension to the bedrock depth is of important. Generally, in a particular topographical environment, increase in bedrock depth significantly reduces the effect of topographical conditions on the ground response.

Investigation into Figures 5(a) reveals that when the bedrock depth became more than double of valley height, the locus of maximum of the *HA* is moved to top of the valley, however, in other cases it would be at the valley bottom.

It is noted that variation in soil layer thickness results in alternation of natural frequency of the soil layer which, in turn, induce a significant impact on the *HA* component of the response particularly at the valley bottom. The effect of this parameter is very evident on the *VA* as will be discussed in the following.

Evaluation of Figure 5(b) show that in all bedrock depths considered here, the locus of maximum *VA* occur in the top of the valley. However, at $H/h=1.5, 2.5, 3.5$, its value is larger than other ratios considered.

Since the natural frequency of the soil layer depends mostly on the shear wave velocity and the thickness of the soil layer, it is seen that, in $H/h=1.5, 2.5, 3.5$, the natural frequency of the soil mass occur almost close to the frequency of harmonic incident load and as a result, the resonance occurred. This phenomenon caused that maximum amplitudes reach to the highest value in these three states. It is noteworthy that because the wave energy dissipation is considered as the damping ratio in the model, the amplifications reach to a local maximum but never attain an infinite value.

In order to investigate the sensitivity of soil mass variation, (due to change in bedrock depth), various values for ratio H/h in the range $1.5<H/h<2$ were considered for the simulated model. For this purpose, the values of H/h as $1.5, 1.7, 1.8, 1.9$ and 2 were adopted and compared upon the results reached. As can be inferred from Figures 6, increasing the bedrock depth, cause *HA* and *VA* decrease from the value corresponding to first natural frequency.

According to the results, variations of displacements were seen inside the valley and also on the surrounding environment. Displacement variations were caused by surface waves and their interference with incident and reflected waves. Consequently such variations could have a significant effect on the seismic response of structures which may be constructed in and surrounding area of the valley. Therefore, seismic design in such environments requires complementary investigations.

It is deduced, from the discussion given in preceding sections that topographical effect on seismic ground response may directly affect on the selection of appropriate site location for important projects such as dams, pipelines, etc. It further implies that comprehensive studies, especially in regards to topographical impact on seismic response, are required to optimize the safety factor and hence to reduce the seismic risk and the cost of projects. Evaluation of the results also reveals that, for a structure built inside and around a steeper valley banks, stronger *HA* and *VA* should be considered, irrespective to the fact that incident earthquake wave has only the horizontal acceleration component.

5. Conclusion

In this study the seismic response of a site was considered regarding topographical irregularities. Horizontal and vertical amplification factor due to two-dimensional topographic effect were evaluated using a realistic model based on FEM coupled with viscous boundaries. The solution was based on fully non-linear soil behavior in time domain. Using the numerical approach allowed a parametric study on effects of valley ratio, frequency of incident wave and bedrock depth on *HA* and *VA*.

Basic conclusions drawn from the numerical simulation are as follow:

- The locus of maximum and minimum of the *HA* and *VA* depends not only on the geometric characteristics of the site but also on the frequency content of the incident wave. It was shown that different sites with the same geometric characteristics might require different seismic ground response and special consideration according to seismic zone of the site.
- It was also concluded that the severity of the effects of the incident wave frequency on seismic response is controlled by the geometric characteristics of the site.

- Dimension of the mesh domain in numerical studies in seismic ground response analysis depends on both geometric characteristics and seismic zone of the interested site.
- To obtain an optimized model size and to reach free field condition, the valley dimension should not be regarded as unique parameter. Rather, these dimensions should be normalized with respect to bedrock depth.
- It was concluded that displacement variation on ground surface due to topographical effects is an important parameter to select the site location or design of important structures especially those with linear behavior.

References

[1]. Kramer, S.L., *"Geotechnical Earthquake Engineering",* In *Prentice-Hall International Series in Civil Engineering and Engineering Mechanics*, Prentice-Hall, New Jersey (1996).

[2]. Idriss, I. "Finite element analysis for the seismic response of earth banks". *Journal of Soil Mechanics & Foundations Div,* 94, pp. 617-636 (1968).

[3]. Celebi, M. "Topographical and geological amplifications determined from strong-motion and aftershock records of the 3 March 1985 Chile earthquake". *Bull. Seismol. Soc. Am.,* 77, pp. 1147-1167 (1987).

[4]. Celebi, M. "Topographical and geological amplification: case studies and engineering implications". *Struct. Saf.,* 10, pp. 199-217 (1991).

[5]. Bouchon, M. and Barker, J. S. "Seismic response of a hill: the example of Tarzana, California". *Bull. Seismol. Soc. Am.,* 86, pp. 66-72 (1996).

[6]. Celebi, M. "Northridge (California) earthquake: unique ground motions and resulting spectral and site effects". *International Conference on Seismic Zonation*, pp. 988-995 (1996).

[7]. Gazetas, G., Kallou, P. and Psarropoulos, P. "Topography and soil effects in the MS 5.9 Parnitha (Athens) earthquake: the case of Adames". *Nat. Hazards.,* 27, pp. 133-169 (2002).

[8]. Marsan, P., Milana, G., Pugliese, A., Sano', T., "Local amplification effects recorded by a local strong motion network during the 1997 Umbria–Marche Earthquake". *Proc. 12th World Conference on Earthquake Engineering*, Aukland New Zealand, Paper No. 1046. (2000).

[9]. Soltani, N., Bagheripour, M. H. "Seismic Wave Scatter Study in Valleys Using Coupled 2D Finite Element Approach and Absorbing Boundaries".*Scientia Iranica, (In Press)*

[10]. Di Fiore, V. "Seismic site amplification induced by topographic irregularity: Results of a numerical analysis on 2D synthetic models". *Eng. Geol.,* 114, pp. 109-115 (2010).

[11]. Kham, M., Semblat, J. F., Bouden-Romdhane, N. “Amplification of seismic ground motion in the Tunis basin: Numerical BEM simulations vs experimental evidences”. *Engineering Geology.*,154, pp.80-86 (2013).

[12]. Nguyen, K. V., Gatmiri, B. “Evaluation of seismic ground motion induced by topographic irregularity”. *Soil Dyn. Earthquake Eng.*, 27, pp. 183–188 (2007).

[13]. He, CH. H., Wang, J. T., Zhang, CH. H and Jin, F. “Simulation of broadband seismic ground motions at dam canyons by using a deterministic numerical approach”. *Soil Dyn. Earthquake Eng.*,76, pp. 136-144 (2015).

[14]. Bouckovalas, G. D. and Papadimitriou, A. G. “Numerical evaluation of slope topography effects on seismic ground motion”. *Soil Dyn. Earthquake Eng.,* 25, pp. 547-558 (2005).

[15]. Zhao, C. and Valliappan, S. “Incident P and SV wave scattering effects under different canyon topographic and geological conditions”. *Int. J. Numer. Anal. Methods Geomech.,* 17, pp. 73-94 (1993).

[16]. Duzgun, O. A., Budak, A.,“A study on soil–structure interaction analysis in canyon-shaped topographies”. *Sadhana., Indian Academy of Sciences.,* 35, pp. 255–277 (2010).

[17]. Kamalian, M., Jafari, M. K., Sohrabi-bidar, A., Razmkhah, A. and , Gatmiri, B., “Time-domain two-dimensional site response analysis of non-homogeneous topographic structures by a hybrid BE/FE method”. *Soil Dyn. Earthquake Eng*, 26, pp. 753–765 (2006).

[18]. Gatmiri, B., Arson, C. and Nguyen, K. “Seismic site effects by an optimized 2D BE/FE method I. Theory, numerical optimization and application to topographical irregularities”. *Soil Dyn. Earthquake Eng.,* 28, pp. 632-645 (2008).

[19]. Lo Presti, D., and Ferrini, M. Special Issue of the Italian Geotechnical Review: The seismic response (2002).

[20]. Yoshida, N. *“Seismic Ground Response Analysis”*, Springer (2015).

[21]. Bagheripour, M. H. and Marandi. S. M. “A Numerical model for unbounded soil domain in earthquake SSI analysis using periodic infinite elements”. *Int. J. Civ. Eng.,* 3, pp. 96-111 (2005).

[22]. Bagheripour, M. H., Rahgozar, R. and Malekinejad, M. “Efficient analysis of SSI problems using infinite elements and wavelet theory”. *Geomech. Eng.*, 2(4), pp. 229–252 (2010).

[23]. Nimtaj, A. and Bagheripour, M. H. “Non-linear seismic response analysis of the layered soil deposit using hybrid frequency–time domain (HFTD) approach”. *European Journal of Environmental and Civil Engineering,* 17, pp. 1039-1056 (2013).

[24]. Kara, H. F. and Trifunac, M. D. “Two-dimensional earthquake vibrations in sedimentary basins–SH waves”. *Soil Dyn. Earthquake Eng.,* 63, pp. 69-82 (2014).

[25]. Ghaemian, M. and Sohrabi-Gilani, M. “Seismic responses of arch dams due to non-uniform ground motions”.*Scientia Iranica,* 19, pp. 1431-1436 (2012).

[26]. Khanbabazadeh, H. and Iyisan, R. “A numerical study on the 2D behavior of the single and layered clayey basins”. *Bull Earthquake Eng*., 12, pp. 1515-1536 (2014).

[27]. Javdanian, H., Jafarian, Y., Haddad, A. “Predicting damping ratio of fine-grained soils using soft computing methodology”. *Arabian Journal of Geosciences*, 8, pp. 3959-3969 (2015).

[28]. Jafarian, Y., Haddad, A., Javdanian, H. “Predictive model for normalized shear modulus of cohesive soils”. *Acta Geodynamica et Geomaterialia*, 11, pp. 89-100 (2014).

[29]. Soltani, N., Bagheripour, M. H. “Boundary Simulation with Dampers Using Finite Element Method in Non-linear Seismic Ground Response Analysis”. *Geodynamics Research International Bulletin*, 3, pp. 16-26 (2015).

[30]. Lermo, J. and Chávez-García, F. J. “Site effect evaluation using spectral ratios with only one station”. *Bull. Seismol. Soc. Am.*, 83, pp. 1574-1594 (1993).

[31]. LeBrun, B., Hatzfeld, D., Bard, P. and Bouchon, M. “Experimental study of the ground motion on a large scale topographic hill at Kitherion (Greece)”.*J. Seismolog.*, 3, pp. 1-15 (1999).

[32]. Fu, L. Y. “Rough surface scattering: comparison of various approximation theories for 2D SH waves”. *Bull. Seismol. Soc. Am.*, 95, pp. 646-663(2005).

[33]. Asgari, A., and Bagheripour, M. H. “Earthquake response analysis of soil layers using HFTD approach”. *The GeoShanghai 2010 International Conference*, Shanghai, China (2010).

[34]. Bazrafshan Moghaddam, A. and Bagheripour, M. H. “Ground response analysis using non-recursive matrix implementation of hybrid frequency-time domain (HFTD) approach”. *Scientia Iranica*, 18, pp. 1188-1197 (2011).

[35]. Tripe, R., Kontoe, S. and Wong, T. “Slope topography effects on ground motion in the presence of deep soil layers”. *Soil Dyn. Earthquake Eng.*, 50, pp. 72-84 (2013).

[36]. Desai, C. S. and Kundu, T. *“Introductory finite element method”*, CRC Press (2001).

[37]. Brinkgreve, R. *“Plaxis: finite element code for soil and rock analyses: 2D-Version 8:[user's guide]”*, Balkema (2002).

[38]. Lysmer, J. and Kuhlemeyer, R. L. “Finite dynamic model for infinite media”. *Journal of Engineering Mechanics Division*, 95, pp. 859-878 (1969).

[39]. Bouchon, M. “Effect of topography on surface motion”. *Bull. Seismol. Soc. Am.*, 63, pp. 615-632 (1973).

[40]. Pagliaroli, A., Lanzo, G. and D'Elia, B. “Numerical evaluation of topographic effects at the Nicastro ridge in Southern Italy”.*J. Earthquake Eng.*, 15, pp. 404-432 (2011).

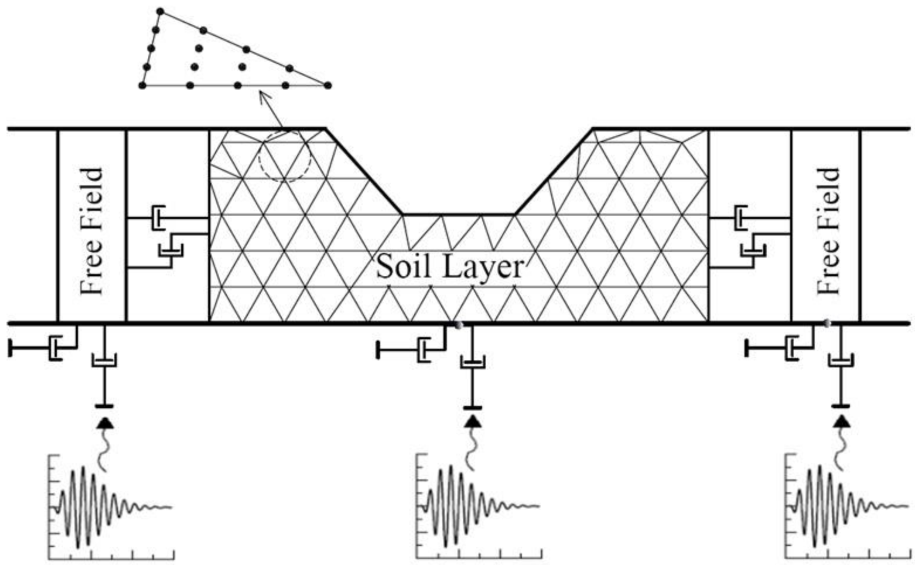

Figure 1. Schematic image of the model and fifteen-node element used in this research

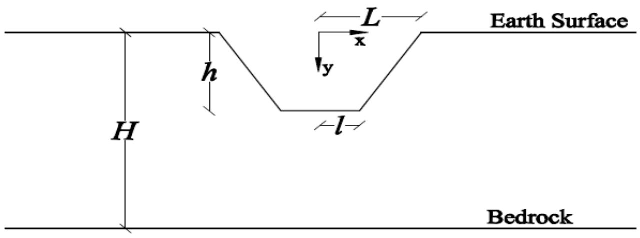

Figure 2. Configuration of adopted valley

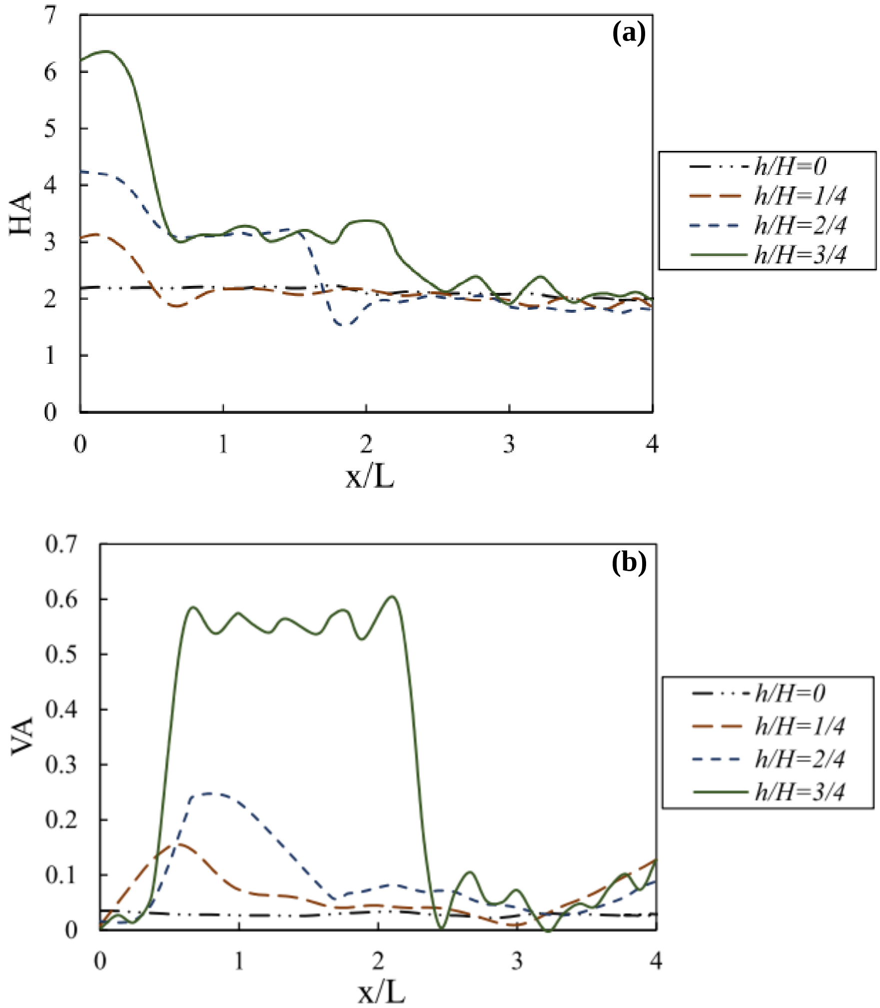

Figure 3. Seismic amplification comparison for different valley shape ratio (a_o=*1*)

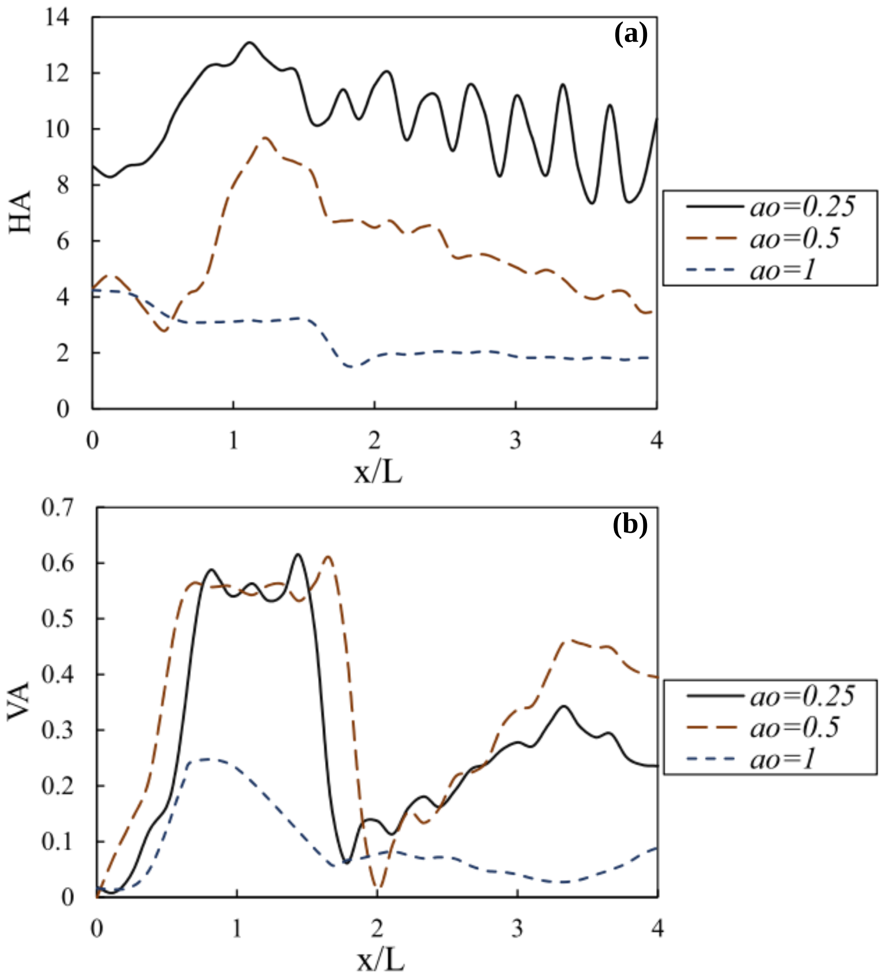

Figure 4. Seismic amplification comparison for different wave characteristics (*h/H=1/2)*

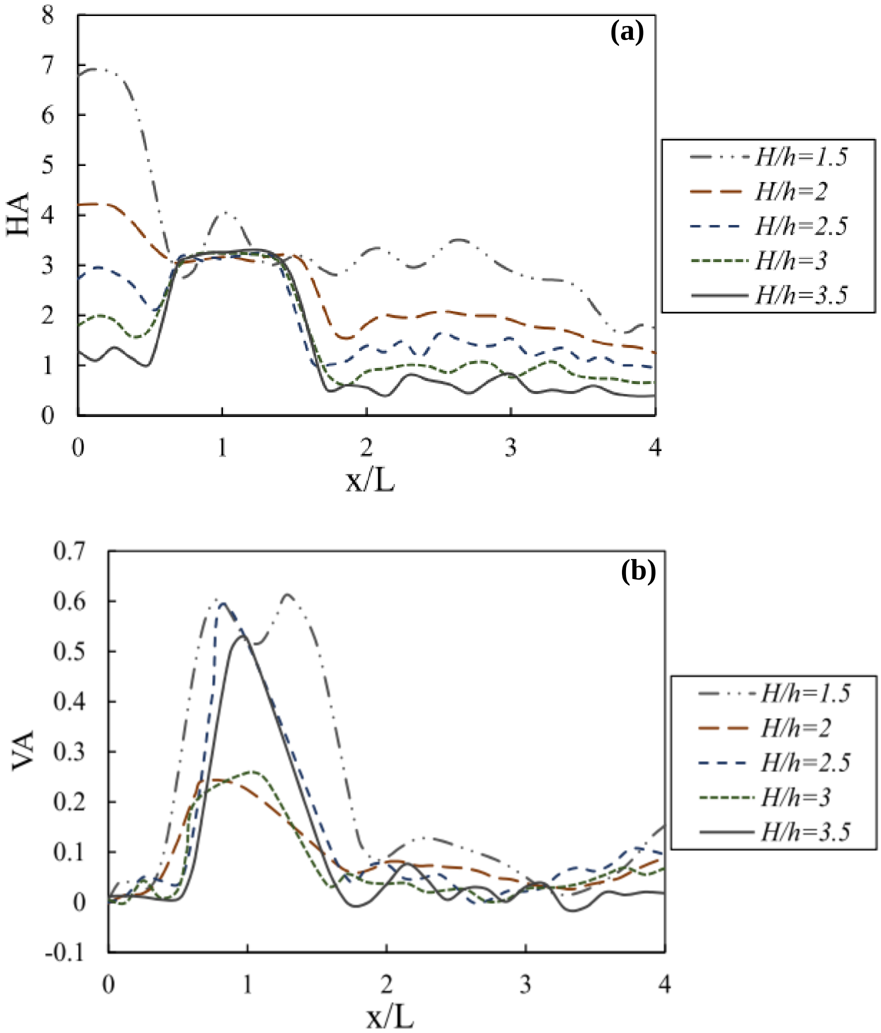

Figure 5. Seismic amplification comparison for different bedrock depth (a_o=*1*)

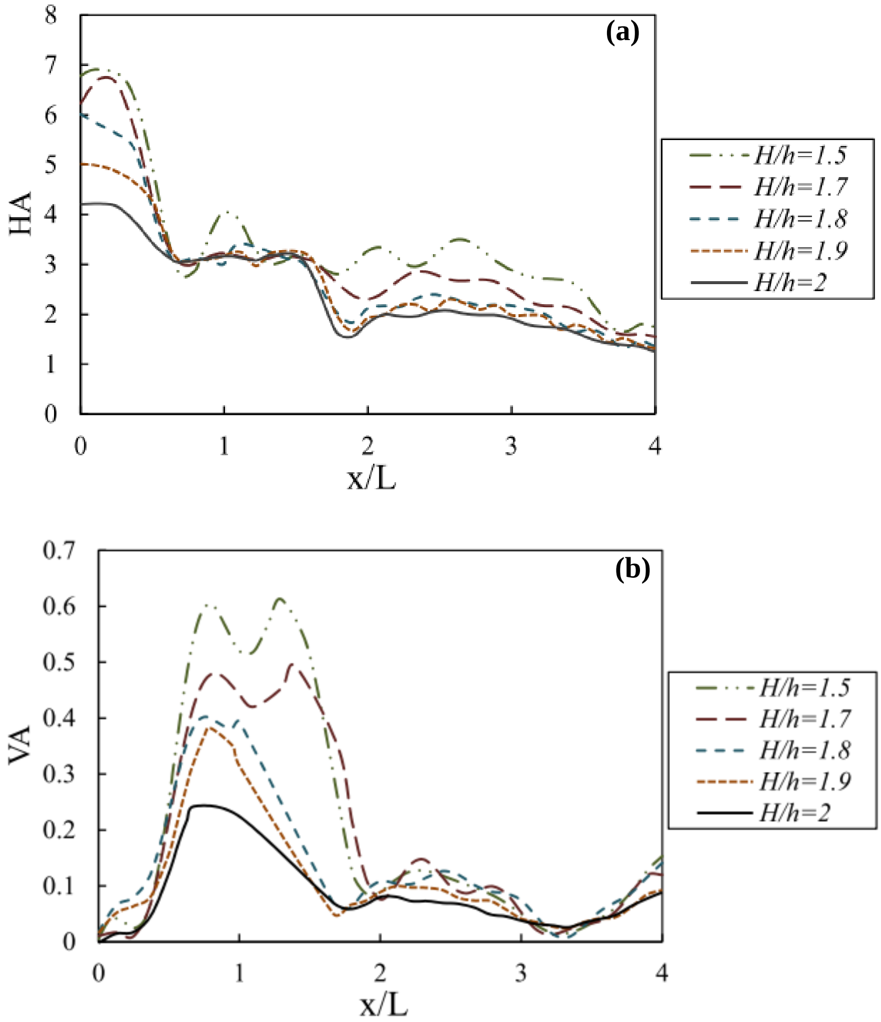

Figure 6. Seismic amplification comparison for sensitivity of bedrock depth ($a_o=1$)

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