

The effect of 2D slope and valley on seismic site response

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Abstract Evaluation of the ground response is one of the most common and important seismic geotechnical issues. Ground response analysis is used for predicting ground motions and response spectra and is developed to determine the dynamic stress and strain of soil. They are used for geotechnical risk assessment (types of instabilities) calculating the forces that can cause instability resulting from earthquakes and earth retaining structures. In this study, the effect of surface topography has been studied on seismic site response. The influence of different land surface geometries has been studied under real acceleration and earthquakes. Therefore, parameters such as the height and the angle of slope, the distance of earthquake fault, and the material properties have been selected for the seismic response evaluation. The results show that when the height and angle of slope increase, the maximum acceleration on the slope crest becomes greater than elsewhere on the surface for both stiff and soft soils. Moreover, the amplification factor always decreases when the maximum acceleration of the input motion record increases.

Keywords Topography · Amplification factor · Slope · Acceleration · Earthquake

Introduction

Earthquakes are one of the most destructive natural phenomena in the world that cause great loss of life and property every

year. Earthquake-prone areas in the countries including Japan, India, China, Philippines, Turkey, Iran, and the USA are suffering frequently from medium- to large-scale earthquakes. The 8.9 Richter scale earthquake that occurred in 1933 in Japan is the highest measured earthquake in the last century (Hu et al. 1996).

Ground response analysis is the most important part in the prediction of ground surface motions during dynamic loading. By these analyses, the evaluation of liquefaction hazards and earthquake-induced forces, which can make instability of earth retaining structures, is possible (Kramer 1996; Janalizade et al. 2012). Ground response can be generally expressed in terms of acceleration, velocity, or displacement parameters. A number of techniques have been developed so far for ground response analysis in terms of one-, two-, and three-dimensional ground response (Choobbasti et al. 2009).

The amplification of seismic waves is very important in some specific sites such as dams, bridges, industrial plants, residential areas, and source location. Scattering and reflections of seismic waves near the surface, at layers' interfaces or around topographic irregularities, often strengthen the consequences of earthquakes (Semblat et al. 2000). Hence, such an analysis can also be carried out by using numerical methods. Finite difference method treats seismic wave's propagation in a bounded domain in which the region is discretized into a number of grid points that have individual material parameters. The wave motion at each grid point is evaluated by solving the equations of motions of the discretized form (Takenaka et al. 1998; Das Braja 1993). The response of structure rapidly increases when it enters the resonance that leads to serious damages. The response of those structures depends on their Eigen frequencies as well as the characteristics of seismic event.

Moreover, if the wavelength is comparable to topographic dimensions (Assimaki and Kausel 2002) the soil above the

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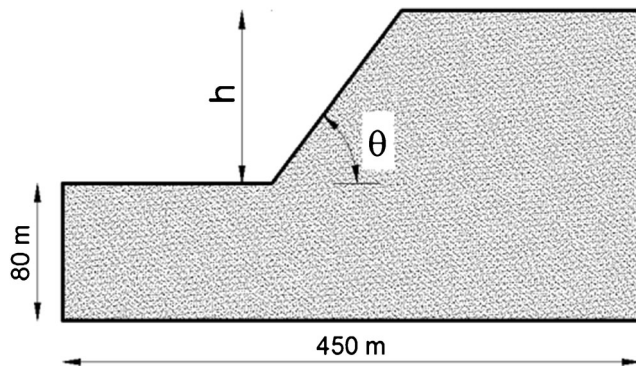


Fig. 1 The slope site

bedrock will play an important role in the determination of the ground surface motions as they generally enhance the PGAs (peak ground accelerations). (Kamalian et al. 2007) in spite of the significant effect of topographic conditions on strong ground motion, there are only few building codes which have considered this issue in their procedures. This is due to the complex nature of seismic wave scattering by topographical structures which can only be solved, accurately and economically, by advanced numerical methods under real conditions. Generally, ground response is controlled by geometry of subsurface and surface materials as well as by the interaction between source, path, and site effects. The site conditions influence on the properties of the event such as amplitude, frequency content, and duration. According to the literatures, ground response depends on the following three factors: source effect, path effect, and site effect (Bararpour et al. 2012; Gatmiri and Nguyen 2007).

Generally, site effect refers to the effects on the ground motion while seismic waves interact with the complex geological environment in the first 100 or so meters of the earth crust. The low seismic velocities and impedances in shallow sediments can lead to extremely high and locally varying amplitudes during ground motion. Moreover, in this domain, wave propagation during ground motion is often nonlinear and can cause strong amplitude-dependent attenuation effects (The National Academies press 2003). It has been often reported that buildings located on hilltops experience more intensive damage than those at the base of the hills. A lot of literatures can be found on such events, which are well

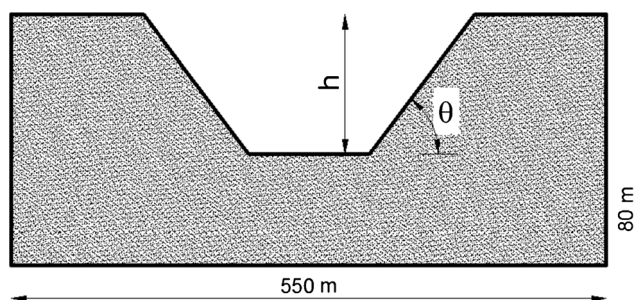


Fig. 2 The trapezoidal valley

Table 1 Properties used for the surface topographical modeling

Topography geometry	Slope, valley
Slope elevation (h)	20 m, 50 m
Slope angle (θ)	30°, 60°, 90°
Earthquake	Northridge and Tabas
Distance from fault	Near field and far field
Tantamount PGA	0.2 and 0.7 g

documented for the special destructive earthquake at the particular area. It is generally seen that the ridges of mountains are amplified more than the base, but the surface topographical effects are not fully understood and that is why no empirical relationships for these effects exist until now (Sanchez-Sesma and Campillo 1993; Kim et al. 2003). In the past, lots of investigations were carried out in the field of ground response analysis, seismic micro-zoning, and the effect of topography on the ground motion throughout the world. Among different structures, the slope topography has drawn the least attention in literature despite its importance in engineering practice.

Davis (Davis and West 1973) found that the crest of mountain is amplified more than its base, but he also recommends that the amount of amplification and the periods at which it occurs are probably a function of the relationship between the wavelengths of the incoming signal and the dimension of the mountain. Havenith (Havenith et al. 2003) studied the influence of topographical and site-specific amplification effects in the Ananevo rockslide in the northeastern part of Tien Shan Mountain and pointed out that the site effect can be made by large-scale gravitational movements during strong earthquakes. Loria (2003) performed the numerical assessment for the earthquakes of Colombia (1999) and El Salvador (2001) using the finite difference software FLAC and tried to find out the effect of topography on the amplification of the ground. She found that amplification changes faster along steeper slopes, but more research should be done about it. Paolucci (2002) addressed the amplification of the seismic waves by surface irregularities using analytical and numerical methods. He estimated the fundamental

Table 2 Site classification based on the USGS

Type of profile	Shear wave velocity (m/s)	Description
A	>750	Stiff stone
B	750–360	Stone
C	360–180	Average soil
D	<180	Soft soil

Table 3 Used time history

Station	Earthquake name	Occurrence place	PGA (g)	Fourier amplitude	Distance to fault (km)	Energy flux (cm ² /s)
P1003	Northridge-Rancho Cucamonga—Deer Can	USA	0.071	0.06	80	25
P0996	Northridge-Pacoima Dam (upper left)	USA	1.285	0.46	8	4000
P0141	Tabas—Ferdows	IRAN	0.108	0.065	94.4	245
P0140	Tabas—Dayhook	IRAN	0.222	0.1	17	630

frequency of the simple topographical profiles using Rayleigh’s method and concluded that usually, resonance occurs for the wavelengths which are slightly larger than the base of the slope. He offered that topographical effects can be neglected on slope angles which are less than 15°.

Leenders (2000) evaluated soil response and amplification factors for the topography of the Brasilia Nueva area in Armenia. He found that the maximum horizontal amplification generally occurs on the top of the hill (particularly along the ridges). Geli (Geli et al. 1988) carried out an experimental and theoretical study to find the effect of topography on earthquake ground motion. They offered that hillsides undergo complex amplification attenuation patterns especially in the upper parts of the hill. They mentioned that the complex subsurface layering might not be responsible for large crest/base amplification and warned that topographical effects cannot be isolated from other effects as ground layering, and, therefore, the amplification on top of the geomorphology complex sites cannot be predicted by a priori estimations based solely on topography. Bouchon (1973) studied the effect of the slope steepness and its topography on the amplification. He found out that amplification occurs toward the top of the ridge and attenuation along the ridge flanks. The values of both of them increase regularly along the steepness of the slope ridge. Y. Gao and N. Zhang found (Gao and Zhang 2013) that the topographic effect is a function of incident wave sources, and near-source topographic effects

are strongly affected by source locations. Whether the ground motion at a particular site is amplified or not and how strong the amplification or reduction can be altered by the source location.

Vincenzo (Di Fiore 2010) evaluated seismic site amplification induced by topographic irregularity. The input motion used in the analysis was a SV seismic wave with variable frequency. The numerical approach allowed an extensive study that considered varying slope angle. Zhang et al. (2015) investigate whether and how the source characteristics affect the site amplification effects. An analytical model of a line source of cylindrical waves impinging on an alluvial valley is proposed to link the source and site. Y. Gao and et al. (Gao et al. 2012) show the effects of symmetrical and nonsymmetrical U-shaped canyons on the surface ground motion; a parametric analysis is carried out in the frequency domain. Surface and subsurface transient responses in the time domain demonstrate the phenomenon of wave propagating and scattering. It is found that a zone of amplification can obviously take place at the bottom of a U-shaped canyon with nearly vertical walls.

In this paper, according to the previous investigations, we try to evaluate the influence of topography geometry on near and far field actual earthquakes and soil properties. The results have been shown for the maximum surface acceleration, velocity, displacement, and amplification factor.

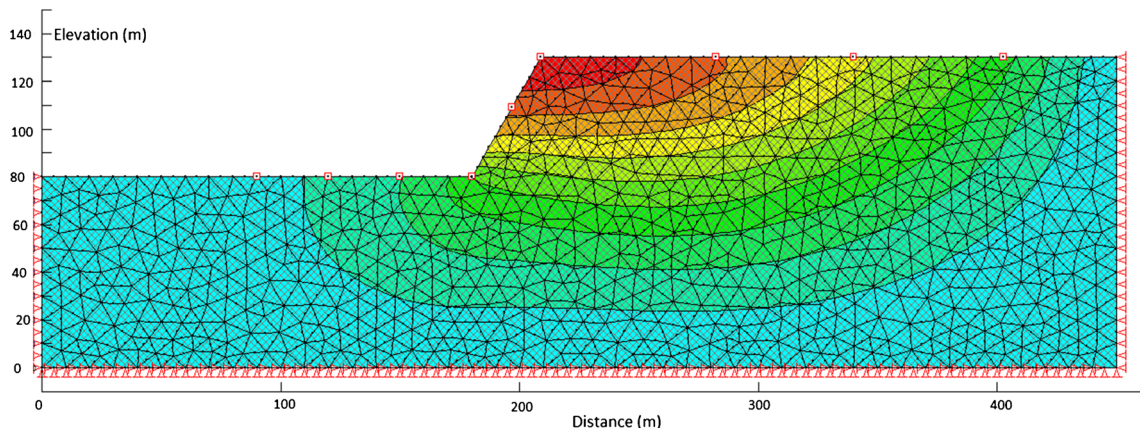
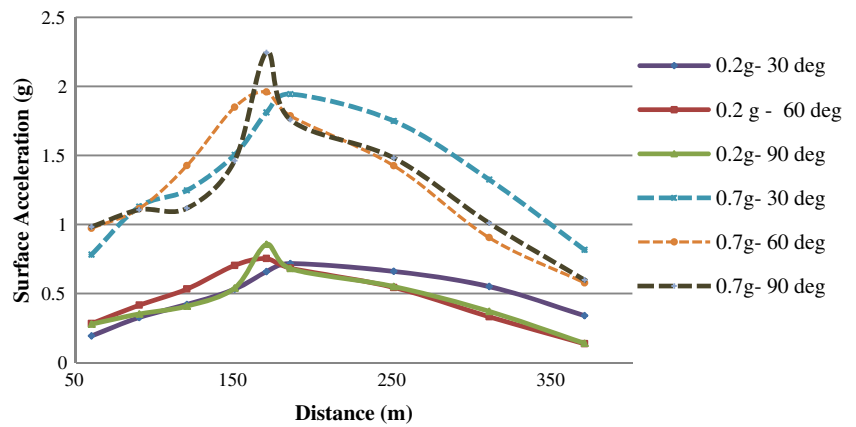


Fig. 3 Counters of acceleration changes on the slope surface

Fig. 4 Effect of slope angle and PGA on the surface acceleration under the Tabas earthquake (height 20 m, $V_s = 500$ m/s)



Introduction of Quake/w

In this study, modeling and analysis were performed using 2D equivalent linear method in Quake/w software. Quake/w is a geotechnical finite element software product for the dynamic analysis of earth structures subjected to earthquake shaking, or point dynamic forces from a blast, or a sudden impact load. It determines the motion and excess pore-water pressures that arise due to shaking. Its comprehensive formulation makes Quake/w well suited for analyzing a wide range of problems (International Ltd 2004).

Generalized material property functions allow us to use any laboratory or published data. Three constitutive models are supported: a linear elastic model, an equivalent linear model, and an effective stress nonlinear model. Quake/w uses the direct integration method to compute the motion and excess pore-water pressures arising from inertial forces at user-defined time steps.

The response and behavior of earth structures subjected to earthquake shaking is highly complex and multifaceted. Generally, there are following issues:

- The motion, movement, and inertial forces that occur during the shaking
- The generation of excess pore-water pressures

- The potential reduction of the soil shear strength
- The effect on the stability of the inertial forces, excess pore-water pressures, and possible shear strength losses
- The redistribution of excess pore-water pressures and possible strain softening of the soil after the shaking has stopped
- The permanent deformation, which sometimes may be tolerable but can also be very large and cause severe damage when there is extensive liquefaction

Due to the estimation of software accuracy before modeling, it has been validated by modeling Bouckovalas and Papadimitriou’s paper (Bouckovalas and Papadimitriou 2005; Bararpour 2012).

Theoretical models

To evaluate the topographical effects on the seismic site response, two geometries such as slope and trapezoid-shaped valleys are considered. As shown in Figs. 1 and 2, body slope angles of 30°, 60°, and 90° and body heights of 20 and 50 m have been selected for the evaluation of the topographical effects (Table 1). Also, the

Fig. 5 Effect of slope angle and earthquake on the amplification factor of the near field earthquake

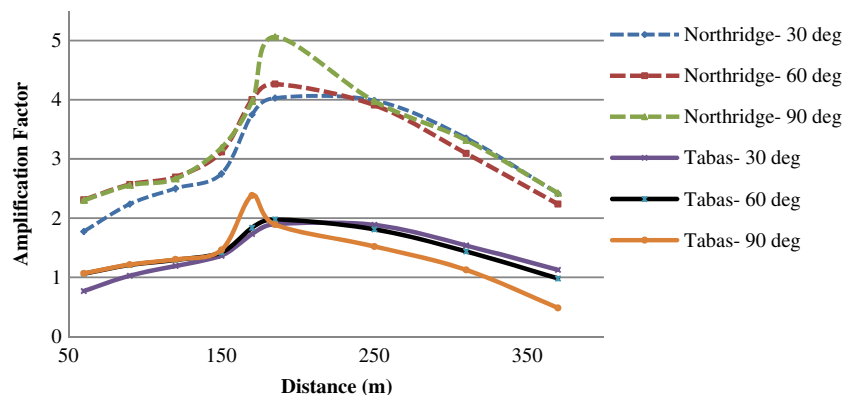
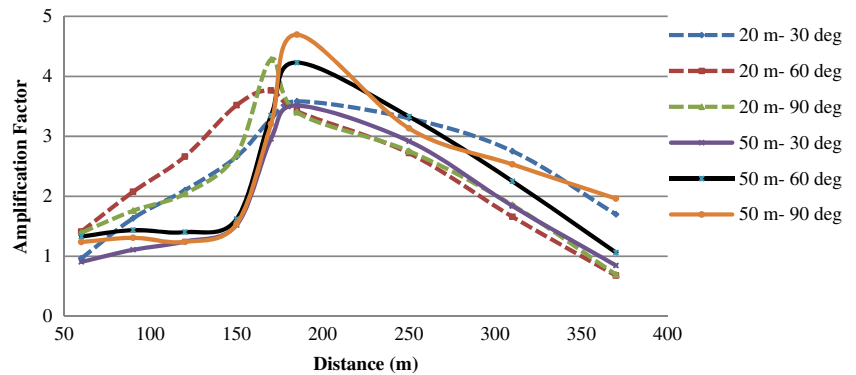


Fig. 6 Effect of slope angle and elevation on the amplification factor, $V_s = 500$ m/s



classification of site soil properties is based on the US Geological Survey (USGS) (Table 2).

The first step in dynamic analysis of topography is the estimation of seismic motion of the bedrock and the selection of the appropriate time history (Semblat et al. 2000). All of the earthquake records of this paper have been on the layers of stiff rock (type of profile is A). Thus, in this paper, two time history analyses have been used in near and far field of Northridge and Tabas earthquake (Table 3). Also, for the tantamount of accelerations (PGA), each of the time history analyses was converted to 0.2 and 0.7 g. For comparing between the characteristic of earthquakes, PGAs tantamount to two parts; one of them is more than 0.4 g, that is 0.7 g, and the other one is less than 0.4 g, that is 0.2 g. Earthquakes with PGA more than 0.4 g lead to nonlinear mode in site and PGA less than 0.4 g lead to elastic mode in site (Das Braja 1993).

Results and interpretations

Results of the slope

The slope has been analyzed by finite element method according to the above analysis of two-dimensional geometry. Graphs and counters of surface acceleration indicate

that the maximum acceleration is on the crest of slope, and surface acceleration is reduced in other points of the surface. This trend is shown in Fig. 3. Nodal displacements are most often specified to give the analysis a frame of reference—usually, the displacement is zero. Take, for example, the case in Fig. 3. Along the base of the problem, the displacement is specified as zero. This means the computed motion will be relative to base being fixed on both the x and y directions. It is deemed appropriate to allow vertical motion at the ends of the problem, but not horizontal motion.

Also, the size of the elements (Δl), should be approximately smaller than $\frac{1}{10}$ to $\frac{1}{8}$ of the wavelength (λ) that is the highest frequency of input acceleration (Kramer 1996).

Similarly, the results and analysis of all parameters have been shown in other diagrams. To evaluate the influence of topography on the seismic site response, the most obvious method is the comparison of the amplification factors on the surface. According to the performed analysis, the increase of amplification factor in the stiff site is more than the soft sites (Chopra 1996).

Figure 4 shows that the numerical ground acceleration values can be related to the intensity of the input record maximum acceleration. In particular, when the maximum acceleration of the input motion record increases from 0.2 to 0.7 g, the surface acceleration reaches the maximum values. In all cases, the maximum surface acceleration

Fig. 7 Effect of slope angle and PGA on the amplification factor under far field earthquake $V_s = 200$ m/s

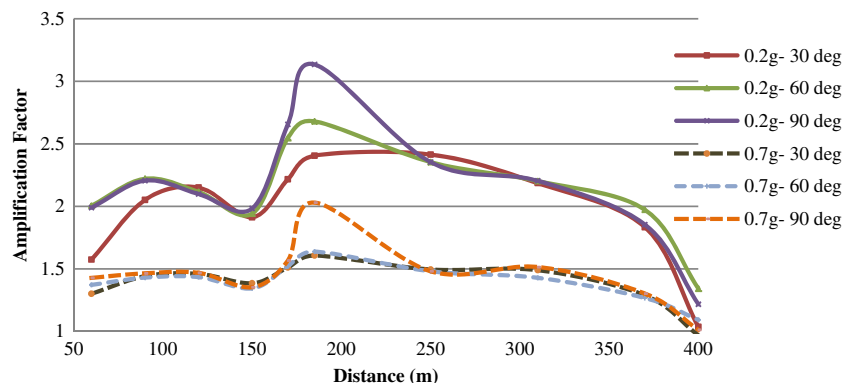
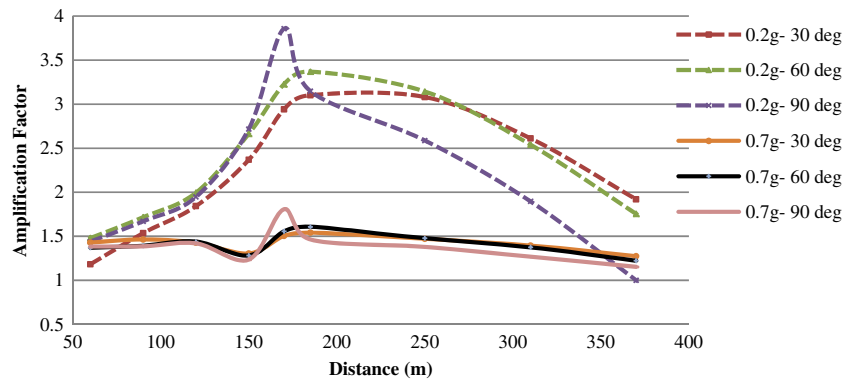


Fig. 8 Effect of slope angle and PGA on the amplification factor under near field earthquake $V_s = 200$ m/s



values occur for the slope angle of 90° at the slope crest because of the wave concentration.

Figure 5 shows the analyzed results of a slope surface with the height of 20 m and the shear wave velocity of 500 m/s for both of earthquakes. While the energy flux and Fourier amplitude of Northridge earthquake are more than the Tabas, the amplification factors for all slope angles of Northridge earthquake are bigger than the Tabas. It can be pointed out that earthquakes with the same PGA can have a different destruction versus of various energy flux and time durations.

Figure 6 shows that by increasing the height of the slope from 20 to 50 m, the amplification factors of slope crest have been increased, but they are reduced by being dispersed of the waves on other points around the crest (with height increase). As shown in equations, it seems that effective stress of site becomes more with increasing height, which leads to an increase in the maximum shear modulus.

Laboratory tests have shown that soil stiffness changes with cyclic strain amplitude under dynamic cyclic loading conditions (Raamachandran 2000). The secant shear modulus of soils decreases with the increase of cyclic shear strain amplitude. The variation of secant shear modulus versus cyclic shear strain amplitude can be described by G-Reduction function.

$$\frac{G}{G_{\max}} = K(\gamma, PI) (\sigma'_m)^{m(\gamma, PI) - m_0} \tag{1}$$

$$K(\gamma, PI) = 0.5 \left\{ 1 + \tanh \left[\ln \frac{0.00102 + n(PI)^{0.492}}{\gamma} \right] \right\} \tag{2}$$

$$m(\gamma, PI) - m_0 = 0.272 \left\{ 1 - \tanh \left[\ln \left(\frac{0.00056}{\gamma} \right)^{0.40} \right] \right\} (-0.0145PI^{1.3}) \tag{3}$$

Quake/w uses an empirical relationship between G_{\max} and the initial mean principal stress as follows:

$$G_{\max} = K(\sigma_o)n \tag{4}$$

Where K and n are constants and σ_o is the mean principal effective confining stress. A stress independent G_{\max} can be obtained by setting the exponent constant n equal to zero. K is a stress unit-dependent constant that may depend on soil conditions, such as soil density and over consolidation condition.

In addition, performed analyses show that the surface acceleration under the PGA of 0.7 g is much more than the surface acceleration under 0.2 g, but when converting them to the amplification factor in those

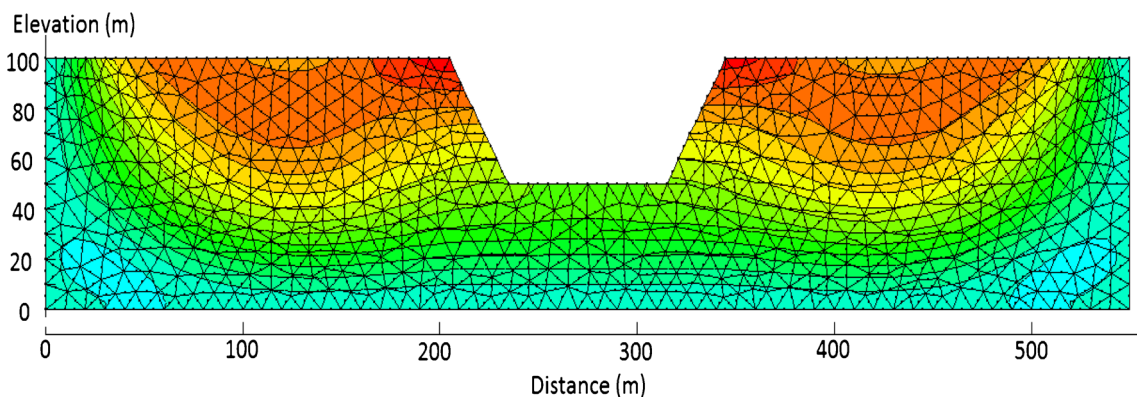


Fig. 9 Variation in acceleration level meter valley

Fig. 10 The effect of slope angle and PGA on the amplification factor under **a** Tabas earthquake, **b** Northridge earthquake (near field, 20-m elevation, $V_s = 500$ m/s)

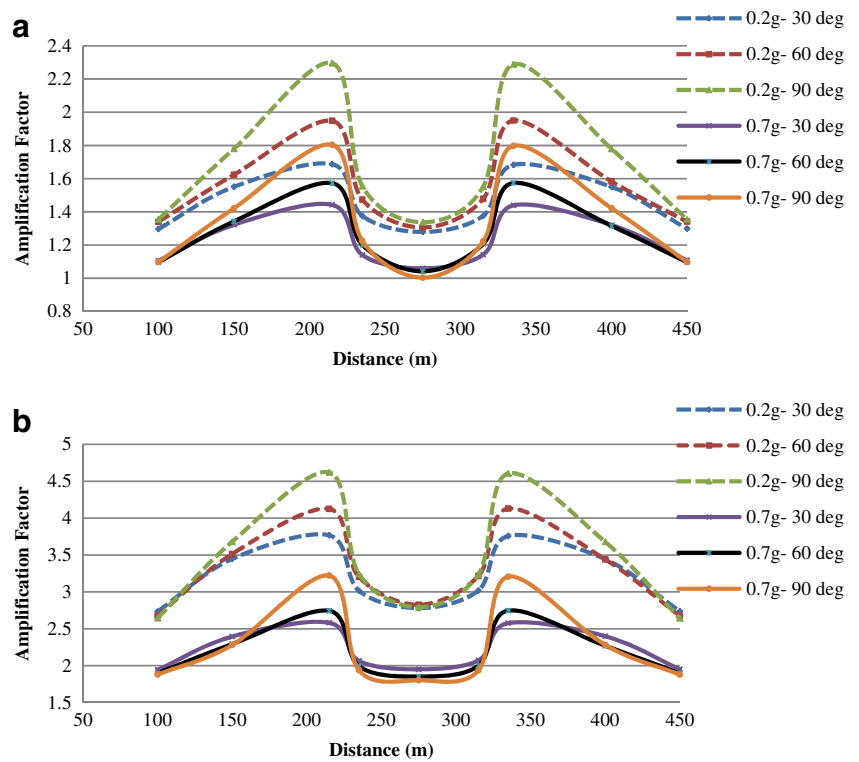


Fig. 11 The effect of slope angle and PGA on the amplification factor under Tabas earthquake, far field, 20-m elevation **a** $V_s = 500$ m/s, **b** $V_s = 200$ m/s

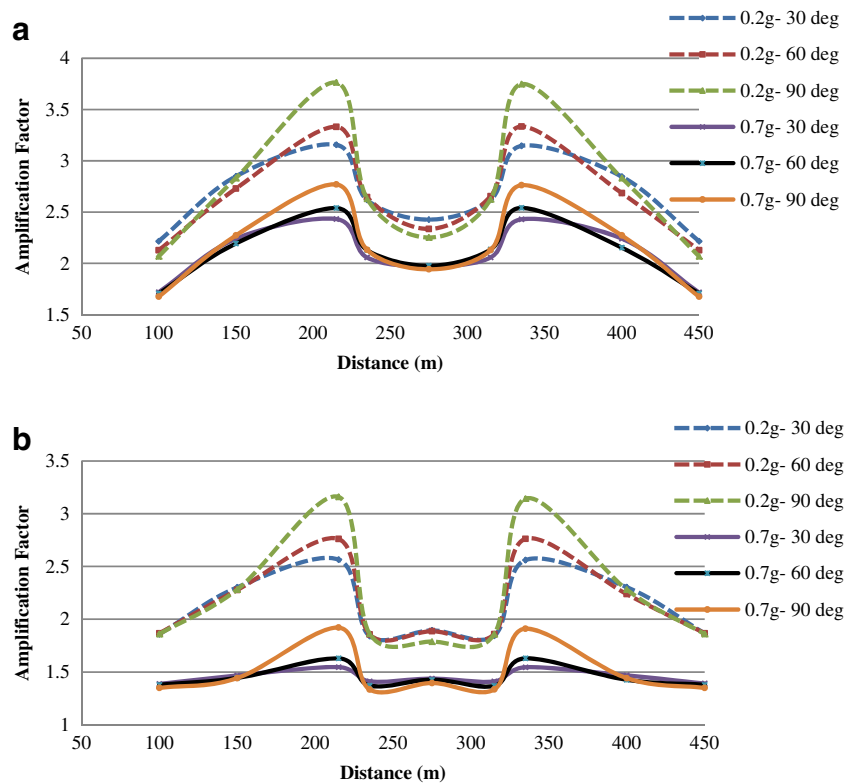
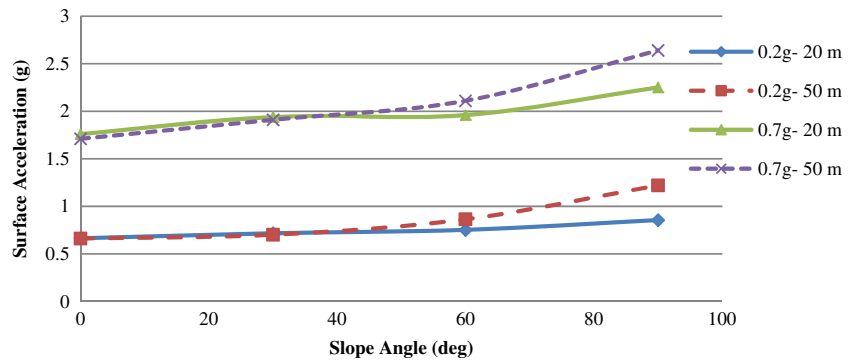


Fig. 12 Surface acceleration versus slope angle for different slope heights and input signal PGA values



points on the surface, the amplification factor of 0.2 g becomes more than the amplification factor of 0.7 g. This difference on the crest of slope is more than 30 %. This shows that with increasing the acceleration, the soil becomes more plastic and its damping increases.

A comparison of Figs. 6, 7 and 8 clearly shows that when the shear wave velocity of soil decreases from 500 to 200 m/s, the maximum amplification factor decreases. Moreover, a comparison of Figs. 7 and 8 reveals that when the fault distance decreases, the maximum amplification factor becomes about 1.5 times larger, due to a lower duration of the near-fault ground motion record that causes a larger maximum ground acceleration.

The results of the trapezoid-shaped valley site

Similar to the assessment of surface topography effect on seismic site response, trapezoid-shaped valleys are considered to be two dimensional. The model of valley site is also very useful in the analysis of dams and power plant construction. Figure 9 shows the counters of acceleration variations that increase from the base to the head of the valley.

In the following figures, the analyzed results for valley site under different parameters are shown. Figure 10 depicts the analyzed results of the influence of slope angles and PGA on the amplification factors under near field

Northridge earthquake. In the analysis of high PGA (>0.4 g), soil gets plastic and its damping increases. Thus, it leads to low amplification factors in surface. The results show that because of the distribution of waves, there is minimum demolition and amplification factor in the foot of the valley.

As previously mentioned, in addition to PGAs, earthquake effective duration and their frequency could produce different effects on acceleration of topography surface.

As shown in the above figures and Fig. 9, almost the amplification factors are alike in the floor of valley and ends of the site surface. By coming nearer to the valley ridge, especially in the site valley with slope angle of 90°, the amplification factors are increased.

The comparison in Fig. 11 is made by the analysis of shear wave velocities of the materials. Analysis shows that materials with low shear wave velocity ($V_s = 200$ m/s) have less amplification factors than materials with high shear wave velocity. Also, because of more damping in soft sites, alterations of amplification factors at PGA = 0.2 g became less about 20 % and became less at PGA = 0.7 g about 60 %.

General result

Considering the following graphs, the results of the amplification factor are shown separately for the two sites of

Fig. 13 Amplification factor versus slope angle for different shear wave velocities of soil

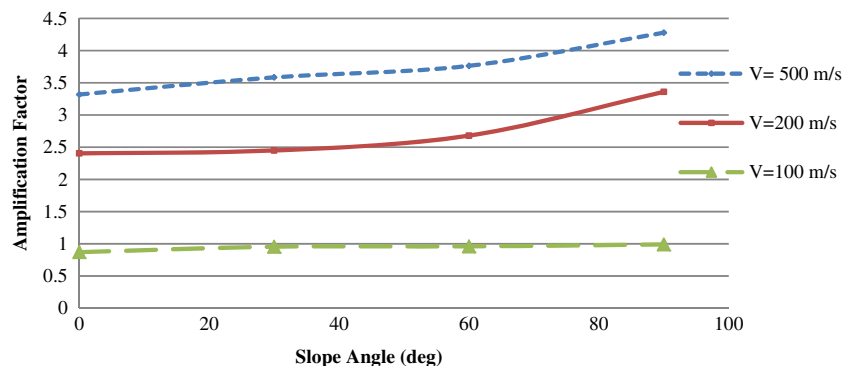
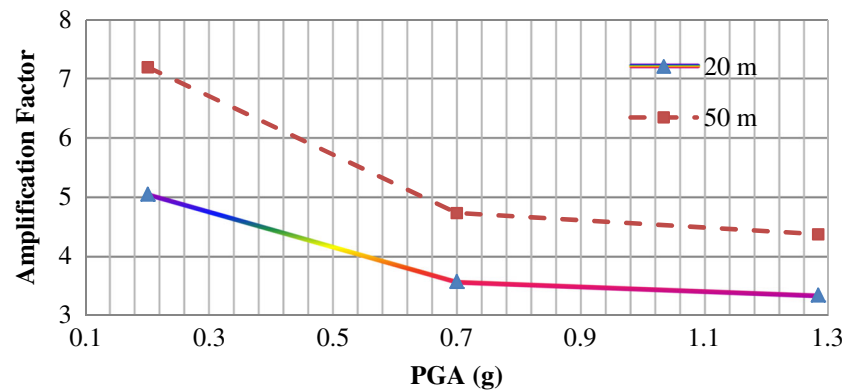


Fig. 14 Amplification factor versus PGA of input motion record for slope heights of 20 and 50 m



slope and valley for different parameters of height and slope angle, soil properties, and so forth on the entire surface. Finally, Figs. 12, 13, and 14 express more clearly, the effect of the above parameters on the crest of the slope.

Generally, as shown in the above graph, because of the energy concentration on the crest of slope, especially for angles higher than 60° , the surface acceleration increases when the angle and height of slope increase.

Figure 13 shows that stiff sites ($V_s = 500$ m/s), which are characterized by smaller shear strain and damping, amplify more than a soft site and the maximum amplification occurs at the slope crest for a 90° angle.

Finally, the 2D numerical modeling, which is carried out in this study on defined topographical models and for different conditions, reveals that the ground motion amplification sensibly reduces when the input motion PGA increases (Fig. 14), due to the soil softening that strongly dissipates the seismic energy.

Conclusion

Nowadays, earthquakes are one of the most destructive natural disasters. From the engineering point of view, earthquakes affect structures such as dams, power plants, bridges, residential areas, and industrial facilities. Topography and soil conditions can play an important role on the seismic site response. Two-dimensional and complex topographical configurations can cause significant differences between the seismic waves emitted from the source and the ones received at the surface.

The 2D dynamic modeling that was performed in this study revealed the following:

- Ground motion amplification factor increases when slope height and angle increase at the slope crest, while it is lower at points far from the crest. Also, surface acceleration at the base of the valley is less than its top.

- In all cases, when the slope angle increases, surface acceleration becomes more and this trend increases faster at angles more than 60° . It has been observed that the maximum acceleration values occur at the slope of 90° .
- Stiff soils, which are characterized by higher seismic velocity, usually present a higher ground motion amplification, which diminishes significantly in soft soils as the strength of ground shaking increases.
- Based on the observations, site materials under low PGA make low shear strain, and there is no significant difference between the resulting and initial damping. Thus, the material behavior looks elastic and leads to high surface acceleration. So the amplification factor due to 0.2 g is more than the amplification factor due to 0.7 and 1.285 g, respectively.

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