An Investigation on 2D Site Response of Small-Scale Basins

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ABSTRACT:
Many populated cities have been built on sedimentary basins. There are a lot of researches on the 2D or 3D site effects of large-scale basins. However, different aspects of 2D or 3D site effects of small-scale basins (within tens of meters depth), which for the first time has been introduced by Ghayamghamian (2008), remain in developing stage. In this paper, 2D site response of small-scale sedimentary basins with different slopes is investigated. To this end, a numerical model of small basin is made and subjected to the earthquake motions in horizontal and vertical directions. The 2D site response is investigated by estimating site amplification function using spectral ratio analysis. The surface to base spectral ratio is calculated for different points with respect to the basin edge at surface for combination of different vertical and horizontal components. Then, they are combined in a matrix contains the frequency response of the *i*th direction due to an input motion in the *j*th direction. This matrix is used to explain the effects of cross-coupling between vertical and horizontal components on 2D site response of small-scale basin. The effects of edge slope are parametrically investigated, which shows clear effect on site amplification characteristics, especially at high frequency range, (>1Hz).

Keywords: Small- scale sedimentary basins, 2D site response, cross-coupling effects.

1. INTRODUCTION

Site effects are a major issue in earthquake engineering and engineering seismology, since this phenomenon can strengthen the incident seismic motion and increase severity of structures and buildings damage as well as its spatial distribution during earthquakes. The expression “site effects” is widely used in earthquake engineering and denotes a set of different physical phenomena arising from the propagation of seismic waves in near-surface geological formations or in geometrically irregular configurations at the earth itself such as canyons, ridges, hilltops and etc. Stratigraphic irregularities of sub-surface geology and site’s soil mechanical properties have long been recognized to affect earthquake ground motion significantly in large sedimentary basins. Both types of irregularities tend to produce an increase in amplitude, and often also in the duration, of the ground vibrations generated at the site by the passage of the earthquake waves. On the other hand, on deep sedimentary valleys with a sediment/bedrock interface having a marked 2D or 3D geometry, experimental observations indicate that surface amplification is much different from 1D calculation. The effects of 2D and 3D site response are widely investigated by different researchers (Semblet 2005, Hashash 2004) which mostly effect low frequency range (<1.5 HZ). However, there were no studies on the 2D or 3D site response of small-scale basin with depth of tens meters, which could affect ground motions in high frequency range. Ghayamghamian (2008) for the first time introduced 2D effects of small basin due to cross-coupling of S-wave propagating in different soil conditions at two sides of small basin edge. Generally speaking Small-scale basins have a limited depth (e.g. tens of meters) and limited length (e.g. hundreds of meters) and affect the seismic response in high frequency range (e.g. >1 Hz).

Ghayamghamian (2008) analyzed the 2D site effects using downhole array data at small Sendai basin in Japan. He showed some features of 2D site response of small basin using numerical analysis of a small basin subjected to the input motion in a horizontal direction. However, a better understanding of the complex propagation effects in a 2D or 3D geological structure can be obtained by calculating a 2D or 3D transfer function that takes into account the cross-coupling not only between shear waves propagating but also among all three components of motion at a site (Tumarkin 1998, Paolucci 1999).

In this paper, 2D site response of small basin is numerically studied by subjecting the model to the single horizontal component and two simultaneous horizontal and vertical components. Furthermore, a parametric study on the basin edge slope is conducted subjecting the model to two conditions of input motion. The 2D site effects are investigated by calculating site amplification using spectral ratio of input motion to that of output motion at different points along surface of small basin. Furthermore, the discussion is made on differences based on single and double components of input. The cross coupling effects on the small scale site-response functions and the other characteristics are discussed.

2. METHODOLOGY

The 2D effects of small basin are investigated using FLAC computer program, which is based on finite difference method. The main advantage of this method is that it allows an accurate description of the infinite extension of the medium. The calculation is based on the explicit finite difference scheme to solve the full equations of motion, using lumped grid point masses derived from the real density of surrounding zones.

The small basin is assumed to be filled by alluvium with different dynamic characteristics, which is subjected to one- and two- component of an earthquake. Then, the acceleration time histories are calculated at surface using FLAC 2D computer program. Then, the Fourier spectral ratio of the surface to the base motions is calculated. Before spectral ratio, the Fourier transform of acceleration time histories are smoothed. The spectral ratios are calculated among different horizontal and vertical components to consider the cross-coupling effects. In the following some explanations about modelling in FLAC computer program and its limitations are provided.

3. DYNAMIC ANALYSIS CONSIDERATIONS

There are three significant aspects in the performed analysis here that need to be explained: boundary conditions, damping, and wave transmission through the model, which are discussed in the following parts.

3.1. Boundary Conditions

Numerical methods, relying on the discretization of a finite region of space, require the appropriate conditions be enforced at the artificial numerical boundaries. In dynamic problems, fixed or elastic boundary conditions cause the reflection of outward propagating waves, back into the model and do not allow the necessary energy radiation. The use of a larger model can minimize the problem, because material damping will absorb most of the energy in the waves, reflected from distant boundaries. Whereas, this solution leads to a large computational burden, other alternative is to use quiet/free field (absorbing) boundaries, see Figure 1. The viscous boundary developed by Lysmer and Kuhlemeyer (1969) is used in FLAC software, which it is based on the use of independent dashpots in the normal and shear directions at the model boundaries.

3.2. Wave Transmission

Numerical distortion of the propagating wave can occur in a dynamic analysis as a function of the modelling conditions. Both the frequency content of the input wave and the wave speed characteristics of the system will affect the numerical accuracy of wave transmission. Kuhlemeyer and Lysmer (1973) show that for accurate representation of wave transmission through a model, the spatial element size, Δl, must be smaller than approximately one-tenth to one-eighth of the wave length, associated with the highest frequency component of the input wave. For this reason and because the lowest shear wave velocity in our assumed model is about 200 m/s, element dimension in the model are assumed to be less than 2.5 m.

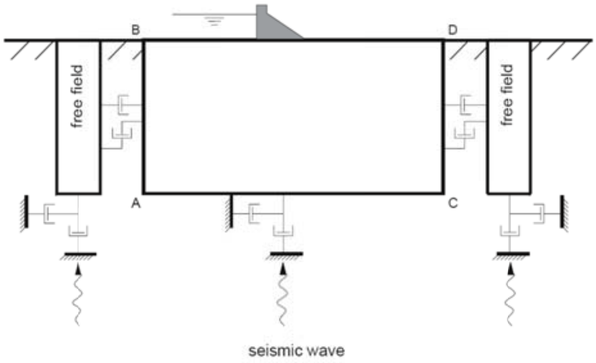

Figure 1. Free field boundaries in seismic analysis

3.3. Rayleigh Damping

For a dynamic analysis, the damping in the numerical simulation should reproduce in magnitude and form the energy losses in the natural system, when subjected to a dynamic loading. In soil and rock, natural damping is mainly hysteretic, *i.e.* independent of frequency. Most time-domain wave propagation codes include small strain damping by implementing the original expression proposed by Rayleigh and Lindsay (1945) in which the damping matrix results from the addition of two matrices – one proportional to the mass matrix and the other proportional to the stiffness matrix as shown in Equation 3.1.

$$[\zeta] = \alpha[M] + \beta[K] \qquad (3.1)$$

Where [M] is the mass matrix, [K] is the stiffness matrix and α and β are scalar values selected to obtain given damping value for two control frequencies. Small strain damping calculated using Rayleigh and Lindsay solution is frequency dependent (ζ changes depending on the frequency of the input motion), a result that contradicts most of the available experimental data which show that material damping in soil is frequency independent at very small strain levels within the seismic frequency band of 0.001–10 Hz.

Hudson et al. (2003) incorporated a new formulation (two frequency schemes) of damping matrices for 2D site response analyses. The use of this solution results in a significant reduction in the damping of higher frequencies commonly associated with the use of a Rayleigh damping solution. The use of a two-frequency scheme allows the model to respond to the predominant frequencies of the input motion without experiencing significant over-damping. Hudson et al. (1994) and Park and Hashash (2004) described the application of the full Rayleigh formulation in site response analysis. For soil profiles with constant damping ratio, scalar values of α and β can be computed using two significant natural modes i and j using Equation 3.2:

$$\begin{bmatrix} \zeta_i \\ \zeta_j \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \frac{1}{2\pi f_i} & 2\pi f_i \\ \frac{1}{2\pi f_j} & 2\pi f_j \end{bmatrix} . \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \qquad (3.2)$$

Where ζ_i and ζ_j are the damping ratios for the frequencies f_i and f_j of the system, respectively. For site response analysis the natural frequency of the selected mode is commonly calculated as (Kramer 1996):

$$f_n = (2n-1)\frac{\overline{v}_s}{4H} \tag{3.3}$$

Where n is the mode number and f_n is the natural frequency of the corresponding mode. It is common practice to choose frequencies that correspond to the first mode of the soil column and a higher mode that corresponds to the predominant frequency of the input motion. Kwok et al. (2007) recommended a value equal to five times the natural frequency. Park and Hashash (2004) also give a series of recommendations to determine these two frequencies. Equal values of modal damping ratios are specified at each of the two modes.

4. METHODOLOGY

The main purpose of this section is to analyze site response in small basin filled by sedimentary layers and to discuss the influence of the local geology on site amplification both in time- and frequency-domain. To analyze the seismic response of small basin a model of basin with 1200 m long and 120 m depth is assumed as shown in Figure 2. The model filled with three types of soils, which their mechanical specifications are given in Table 4.1. Six points are chosen along the small basin as schematically shown in Figure 2. They are located at surface of the basin and these points correspond to various basin depths. For parametric investigation on the effects of the edge slope, its slope is assumed to be varied from 25 to 90 degree. Each model is subjected to types of single- and two-components of earthquake motions as shown in Figure 3. In case of two-component, the horizontal and vertical motions are considered to show the cross-coupling effects between different input motions. Based on the element size, the largest frequency that can be captured by the model assigned to be 8 Hz. Furthermore, the input motions are band-pass filtered between 0.1 to 8 Hz. The lower band frequency is assigned to remove the base-line drift of acceleration time histories.

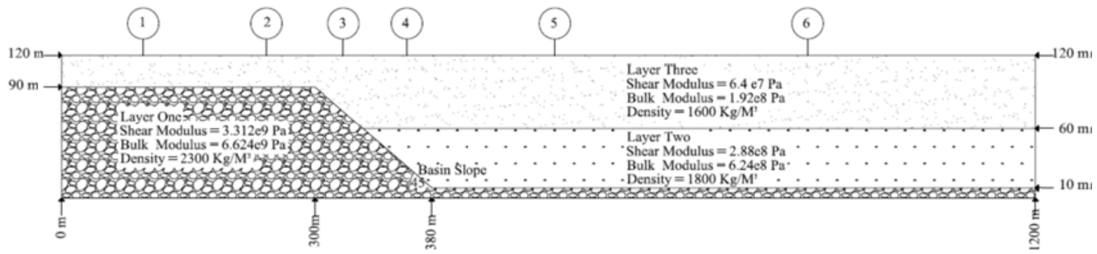

Figure 2. A scheme of assumed small basin model

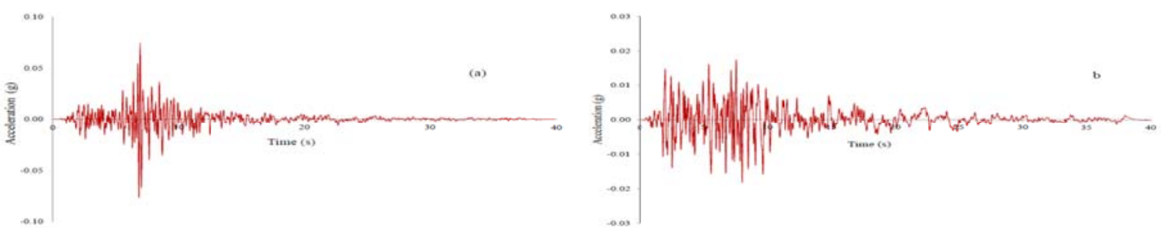

Figure 3. Earthquake ground motion: (a) horizontal component (b) vertical component

Table 4.1. Geotechnical Specification of Soil Layers

Soil Layers	Mass Density (kg/m^3)	Maximum Shear Modulus (Pa)	Bulk Modulus (Pa)	Shear Wave Velocity (m/s)	Poisson's Ratio
Layer one	2300	3.312E9	6.624E9	1200	0.2
Layer Two	1800	2.88E8	6.24E8	400	0.3
Layer Three	1600	6.4E7	1.92E8	200	0.35

5. 2D SITE RESPONSE ANALYSIS OF SMALL BASIN

The surface time histories are estimated for different edge slope using FLAC program at six sites along surface of small basin. Figure 4 shows the estimated time histories at six sites for 45 degree slope. Furthermore, the surface to base spectral ratio is also estimated at these points as shown in Figure 5. A variation of peak ground acceleration can be observed along the basin, especially in the vicinity of basin edge. Meanwhile, from Figure 5, a clear variation in site amplification characteristics both in peak frequency and peak spectral value can be seen. The peak frequency varies from 1.86 to 0.80 Hz from point 1 to 6 (Table 5.1). From points 2 to 5 (in the vicinity of basin edge), instead of one clear peak, two peaks frequencies with varying spectral values can be observed, which are in accordance to those shown by Ghayamghamian (2008).

The same analysis is carried out for the case of two-component (vertical and horizontal) input motions and its results are shown in Figure 6 for calculated spectral ratios of horizontal components of surface to base motions. Furthermore, the peak frequency and peak spectral values at different points are summarized in Table 5.2. The spectral ratios at points 1 and 6 are not changed significantly. Meanwhile, the comparison among peak frequencies and their corresponding amplification values between Tables 5.1 and 5.2 show large differences. This emphasize to the fact that the actual estimation of site response at laterally irregular site need to account for both 2D geometry and filled material, and subjecting the model to all three components of earthquake motion.

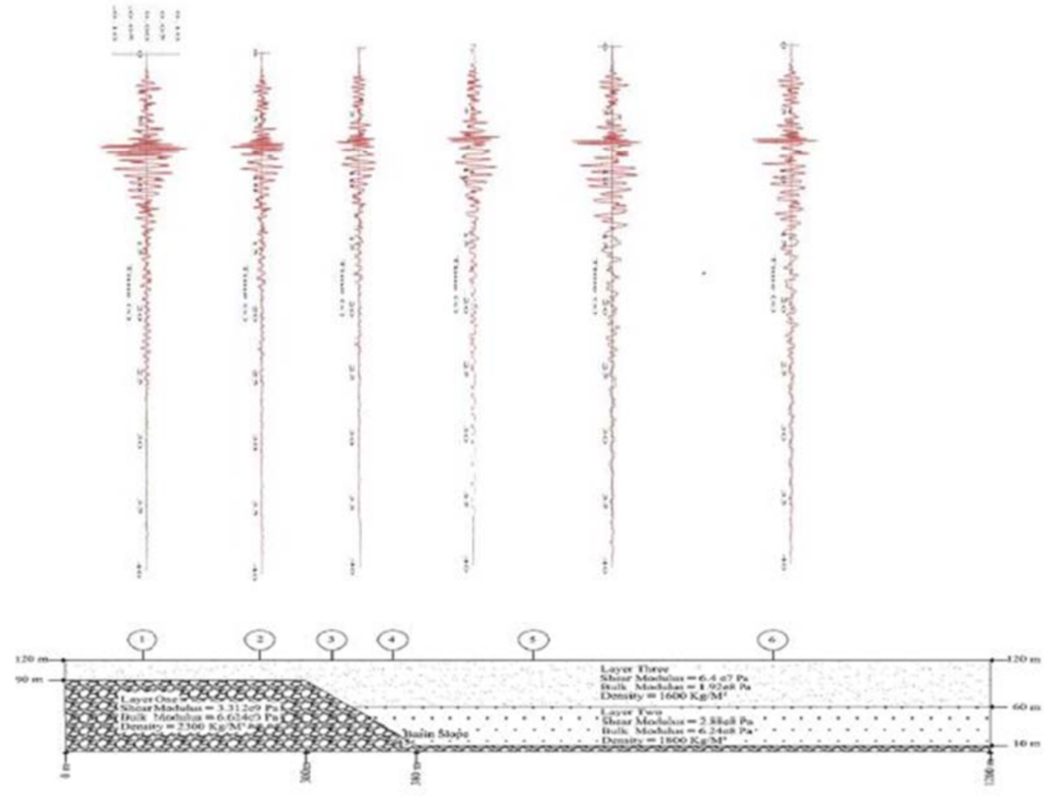

Figure 4. Acceleration time histories at 6 surface points along the basin with 45 degree slope estimated by subjecting the model to the one-component earthquake motion

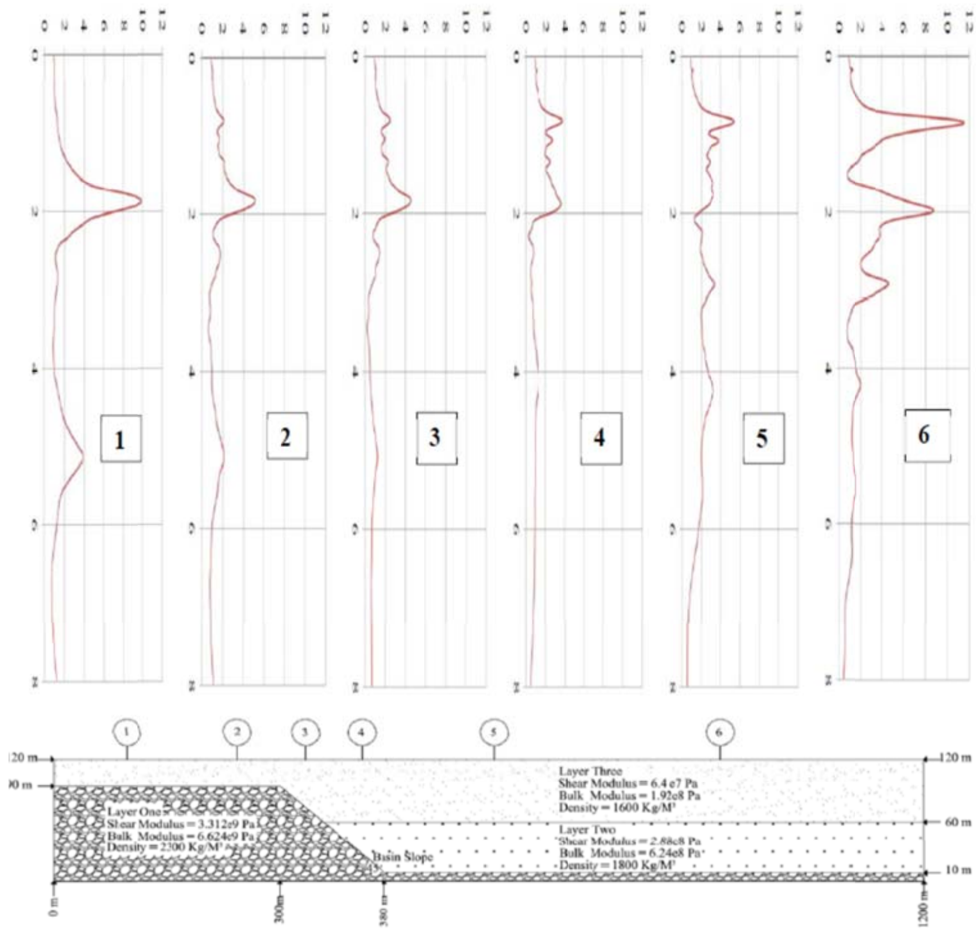

Figure 5. Calculated spectral ratio of surface to base time histories at 6 points along small basin with 45 degree edge slope

From above figures, it can be understood that most changes in site amplification characteristics are occurred in the vicinity of small basin edge. Therefore, we decided to examine the variation of site amplification along small basin for different edge slope. To this end, the 600 points are assumed along the small basin model with edge slope of 25, 60 and 90 degrees. The surface motions are calculated in the same fashion at these points for two cases of one- and two- component input motions. Then, the response spectra of horizontal components for two cases are computed and their variation with frequency and distance are shown in Figures 7 to 9 for 25, 60 and 90 degrees slope edge, respectively.

5. CONCLUSION

In this paper, 2D site response along small basin was investigated using FLAC computer program. The identified site responses clearly showed the effect of lateral irregularity on site amplification characteristics due to coupling of shear waves, which propagate in different site conditions at two sides of basin edge. These shear waves are coupled in the vicinity of small basin edge showing coupled peak frequencies. Furthermore, the results of analysis by subjecting the model to two types of input motion (one- and two- component) showed that the input motions at irregular sites need to be fully taken into account using all three components of input motions. This can be attributed to the cross-coupling among motions in three orthogonal directions, which should be separated from the shear wave coupling effect happen in laterally irregular sites due to site 2D geometry.

Since most changes in site amplification characteristics occurred around small basin edge, the effects of edge slope on site amplification were also investigated. The site response along small basin is calculated for slope edge of 25, 60 and 90 degrees. The results revealed that the site amplification characteristics could be mainly affected in a distance equal to 1.5 times of slope length from the middle of slope edge. Meanwhile, the steep slope largely affects low frequency range than the mild slope.

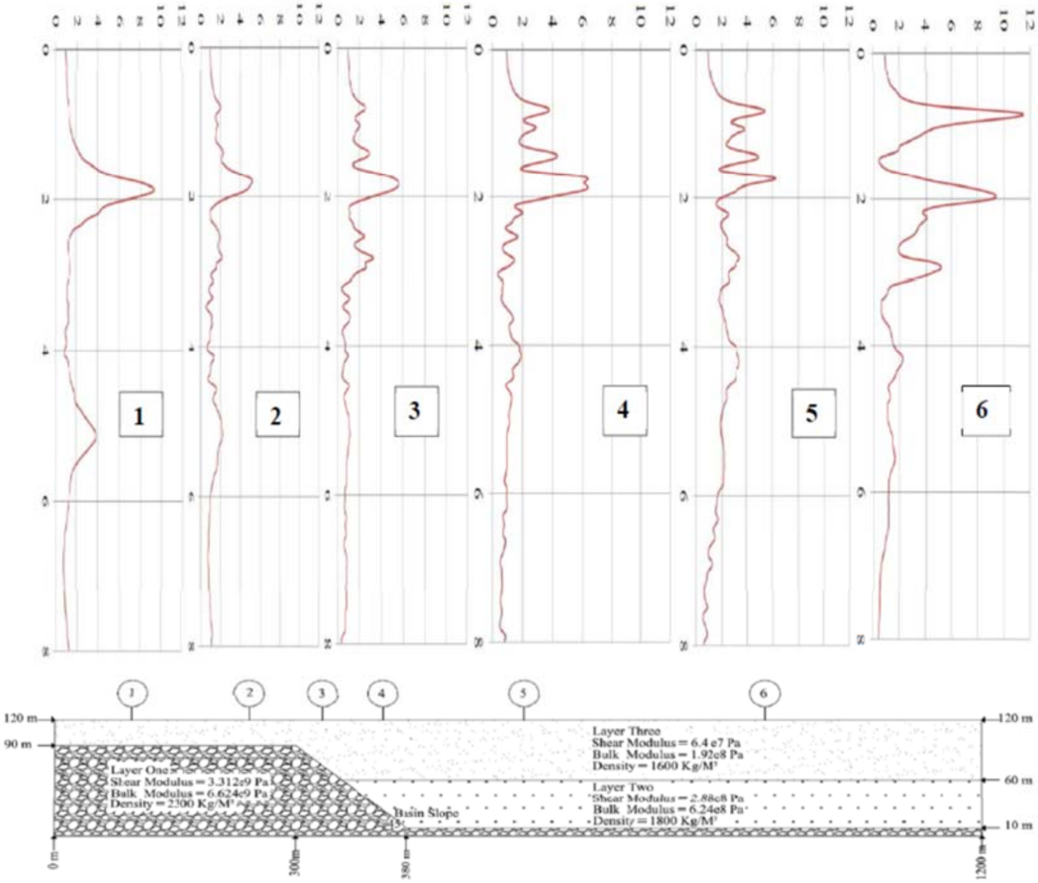

Figure 6. Calculated spectral ratio of surface to base time histories of horizontal components at 6 points along small basin with 45 degree edge slope by subjecting the model to two-component input motion

Table 5.1 The peak frequencies and spectral values at six points along basin for one-component motion

Points	Distance (m)	Peak Spectral Ratio	Corresponding Frequency (Hz)
Point 1	150	9.83	1.86
Point 2	280	5.1	1.80
Point 3	310	4.4	0.78 and 1.8
Point 4	360	3.75	0.8 and 1.83
Point 5	400	5.3	0.8 and 1.07
Point 6	900	11.5	0.8

Table 5.2 The peak frequencies and spectral values at six points along basin for two-component motion

Points	Distance (m)	Peak Spectral Ratio	Corresponding Frequency (Hz)
Point 1	150	9.21	1.86
Point 2	280	5.21	1.78
Point 3	310	5.46	1.39 and1.78
Point 4	360	6.33	0.8, 1.41 and1.86
Point 5	400	6.26	0.8, 1.41 and 1.73
Point 6	900	11.5	0.83

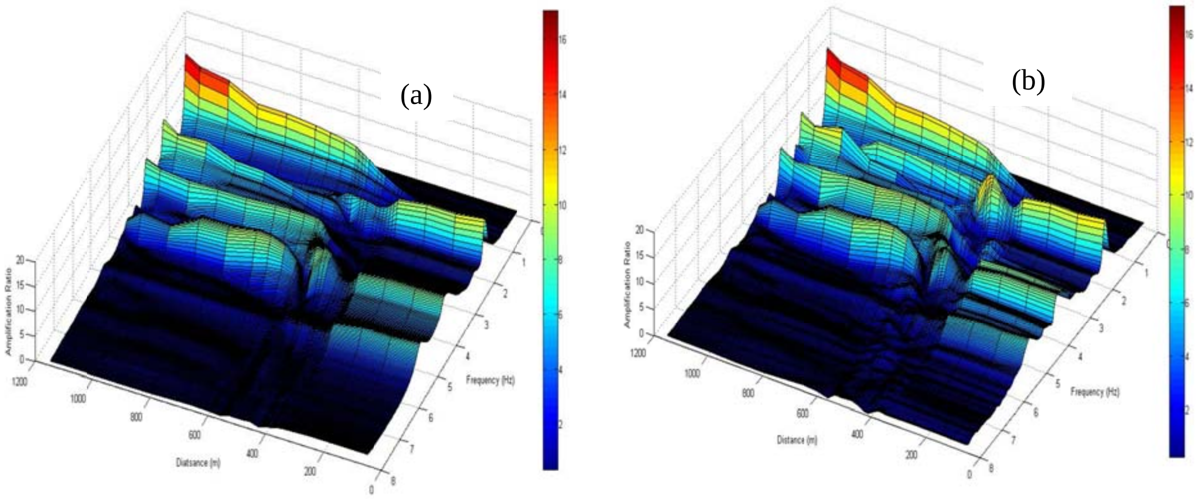

Figure 7. Site responses along small basin at different frequencies and distances for a slope edge of 25 degree subjected to (a) one-component (b) two-component of earthquake motions

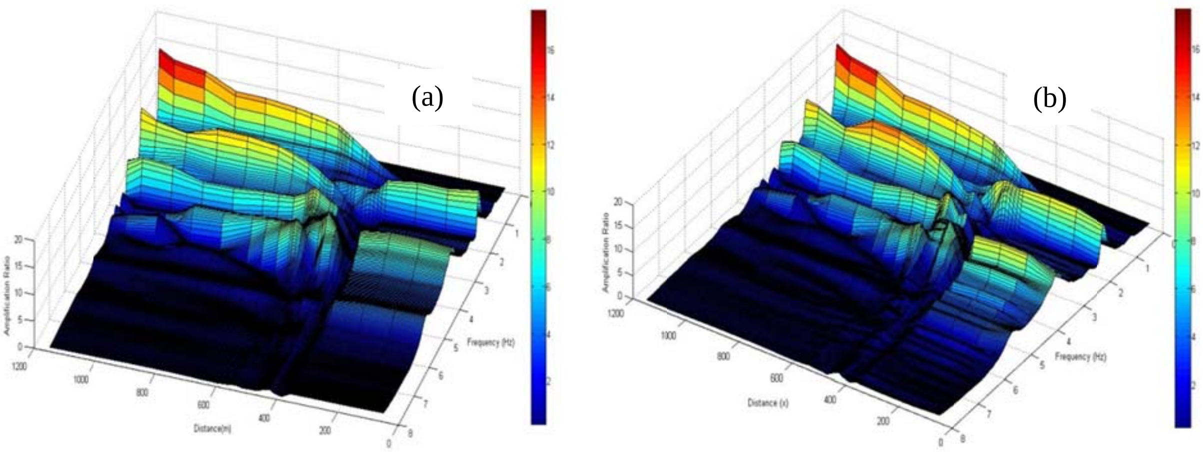

Figure 8. Site responses along small basin at different frequencies and distances for a slope edge of 60 degree subjected to (a) one-component (b) two-component of earthquake motions

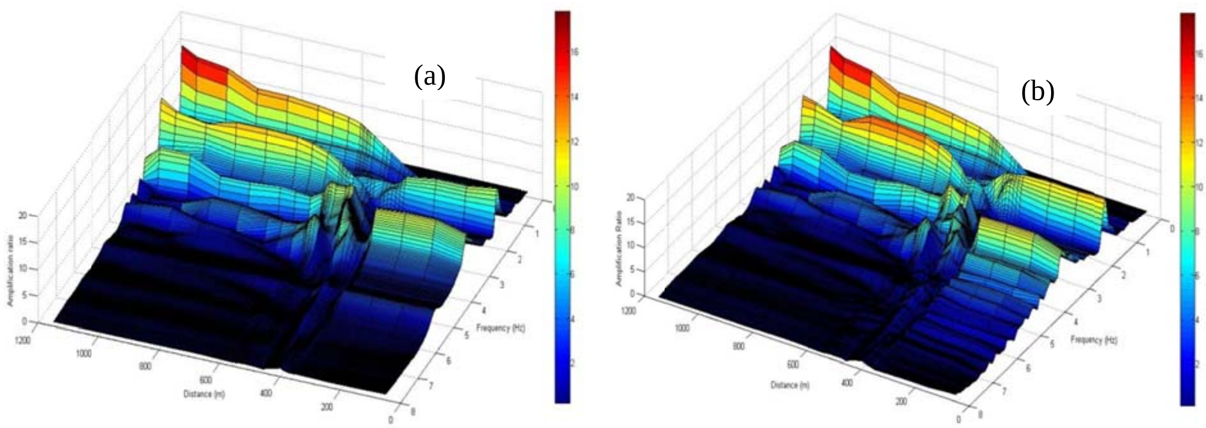

Figure 9. Site responses along small basin at different frequencies and distances for a slope edge of 90 degree subjected to (a) one-component (b) two-component of earthquake motions

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