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Ground motion amplification due to underground cavities subjected to incident SV and P in-plane waves

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KEYWORDS
Underground cavity;
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SV wave;
P wave.

Abstract. When a fault crashes, seismic body waves travel away from the source to the ground surface. Seismic wave characteristics change due to source, path and site effects. Site effects consist of surface and subsurface irregularities, such as cavities that can affect the properties of seismic waves. Therefore, in this study, the effects of underground cavities on surface ground motion amplification are investigated for circular and elliptical shapes. Underground cavities are subjected to the vertically propagating SV and P in-plane waves. The effects of dimensionless frequency, depth of cavity, geometry of cavity and also presence of the second cavity are studied in this research. Results show that increasing of dimensionless frequency causes increase in ground motion amplification for both cases of incident SV and P waves. It is also concluded that depth and geometry of cavity can cause very important effects on the ground seismic motion. Presence of second cavity can also aggravate the ground surface seismic motion in addition to the first cavity.

1. Introduction

It is well recognized that ground seismic motion is significantly affected by local site and geology effects. Nowadays, due to development of cities, structures may be constructed near to any types of ground irregularities whether surface or subsurface. Hence, site effects can produce high amplification of the ground seismic motion. To investigate the wave propagation and site effect problems, there are several methods, and many researchers have used them. Scattering of elastic waves by underground cavities can be resolved by numerical or analytical methods. Finite Difference Method (FDM) is a powerful tool to study the elastic wave propagation problems [1]. In this study, implementing the numerical method of finite difference, FLAC^{2D}, the effects of underground cavities on scattering and diffraction of the ground seismic motion are studied, considering dimensionless frequency, depth and geometry of the cavity and distance between two cavities.

Recently, researchers paid attention to the amplification of the seismic ground motion by underground spaces. The earliest research on scattering and diffraction of elastic waves by underground cavities was solved by imagine method for incident SH wave in homogeneous half-space [2]. Lee and Karl [3,4] used an analytical method (i.e., wave function expansion method) to study the diffraction of SV waves by circular, cylindrical cavities. The result of their study was that amplification of the surface displacement can be high and it was affected by depth of underground cavity and dimensionless frequency. Davis et al. [5] used analytical solutions to study the single tunnels in half space for incident in-plane P and SV. They used an approximated model to investigate a case study of 1994 Northridge earthquake. They mentioned that proposed model was applicable to the seismic analysis

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and design of the underground structures. Liang et al. (2003) [6] used analytical method based on the Fourier-Bessel series to solve the response of ground surface motion due to presence of twin tunnels subjected to the plane SV waves and showed that ground motion amplified significantly. Liang et al. [6-9] used wave function expansion method to study wave scattering and diffraction by twin cavities in half-space. Sgarlato et al. [10] studied the influence of underground cavities for evaluation of local seismic response in the urban area of Catania. They used the H/V technique to assess the site response.

Among the researchers which studied effect of underground cavities on ground seismic motion, Chen et al., He et al., Zhu et al., and Liang [11-14] studied scattering and diffraction of the seismic motion in homogenous half space, numerically, using Finite Element Method (FEM) combined with artificial boundaries. Chen et al., He et al. and Zhu et al. [11-13] considered only one cavity and they did not consider interaction effects between two spaces. Liang et al. [15-17] presented analytical solutions for the case of single cavity in poroelastic half-space. Yu and Dravinski [18,19] investigated scattering of a plane harmonic P, SV or Rayleigh wave by a completely embedded corrugated elastic cavity for both half-space and full-space models by using direct boundary integral equation method. Liang et al. [20,21] continued their research considering the amplification of in-plane seismic ground motion by group of cavities in layered half-spaced with dry and saturated poroelastic soil layers implementing boundary element method in frequency and time domains. Alielahi et al. [22] used boundary element method to estimate ground site response by underlined cylindrical cavities subjected to vertically incident of SV and P waves in time domain.

The effects of underground cavities on ground surface motion were studied by some researchers. Most of the previous studies focused on complicated analytical methods and were in frequency domain. However, it is concluded that the effect of dual cavities and the effect of elliptical cavities on ground seismic motion in time domain needs to be investigated. It is due to the progress in the construction of these types of cavities in practice.

2. Description of the problem

Soil is considered as homogenous elastic horizontal layer which is defined by elastic modulus, E, density, ρ and Poisson's ratio, ν. For all cases in numerical modeling, ν, ρ and E are considered constant and are equal to 0.35, 2 ton/m^3 and 1.95 Gpa, respectively. Study of large deformation was not in the scope of this study; therefore, the applied acceleration amplitude is considered low and considering strains in the model the assumption of elastic behavior of soil is acceptable. It should be mentioned that the soil did not experience failure or large strain due to dynamic excitation.

For dynamic analysis, incident acceleration waves are considered as SV and P Ricker wavelet with the following equation [23]:

$$a(t) = \left\lfloor 1 - 2b(t - t_0)^2 \right\rfloor \exp \left\lfloor -b(t - t_0)^2 \right\rfloor, \tag{1}$$

where $a(t)$ is dynamic acceleration, $b = (\pi \times f_0)^2$ which f_0 is characteristic frequency and t_0 is the time corresponding to the maximum of $a(t)$. The Ricker wavelet bears some resemblance to an actual seismic wavelet but it actually is second derivative of the error function [24]; however, the explanation of the results of analysis becomes easier using Ricker wavelet. To prevent the artificial wave reflections, it is better to apply the dynamic excitation as the stress history or the force history. Therefore, in this study, the dynamic load is applied to the system as the stress history at the base by applying the quiet boundary at the base of the model and using the free field boundaries at the left and right sides of the mesh [25].

At first, underground cavities are considered as circular and then the effect of elliptical cavities is also studied. Schematic illustration of underground cavities in soil layer is presented in Figure 1. Numerical analyses, by using FLAC^{2D}, are performed to investigate the effects of dimensionless frequency, depth of cavity center, presence of second cavity and geometry of cavity on spatial distribution of peak horizontal and vertical ground accelerations under incident SV and P waves. Results are presented as normalized peak ground accelerations in horizontal and vertical directions. Incident SV produces high amplitude of horizontal acceleration, while incident P causes high amplitude of vertical acceleration. In other words, for incident SV, vertical acceleration and for incident P, horizontal acceleration is parasitic acceleration. Therefore, in case of incident SV, all accelerations are divided by maximum free field horizontal acceleration and in the case of incident P, all accelerations are divided by maximum free field vertical acceleration. In fact, for incident SV, free field motion is only

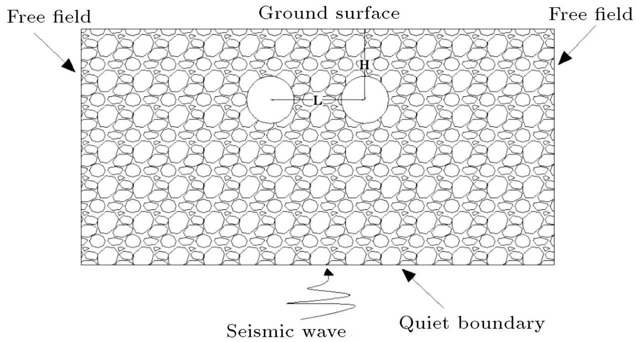

Figure 1. Schematic representation of the model.

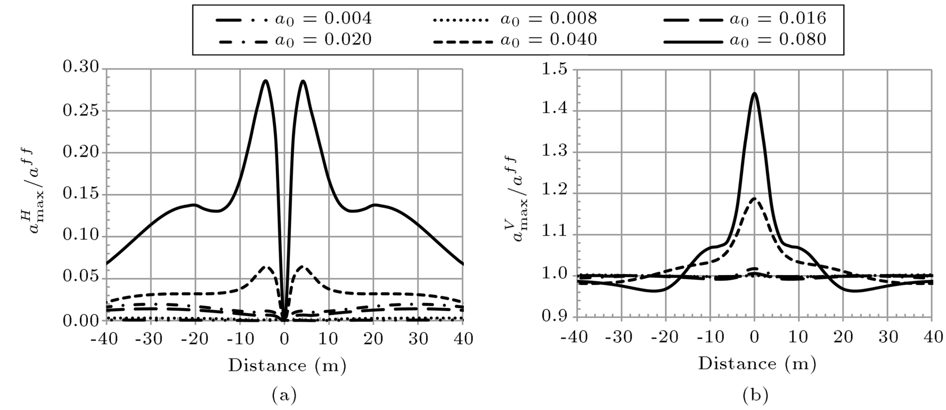

Figure 2. Spatial distribution of normalized peak ground surface acceleration under incident P wave: (a) Horizontal acceleration, and (b) vertical acceleration for various values of dimensionless frequency (circular cavity, $R = 3$ m).

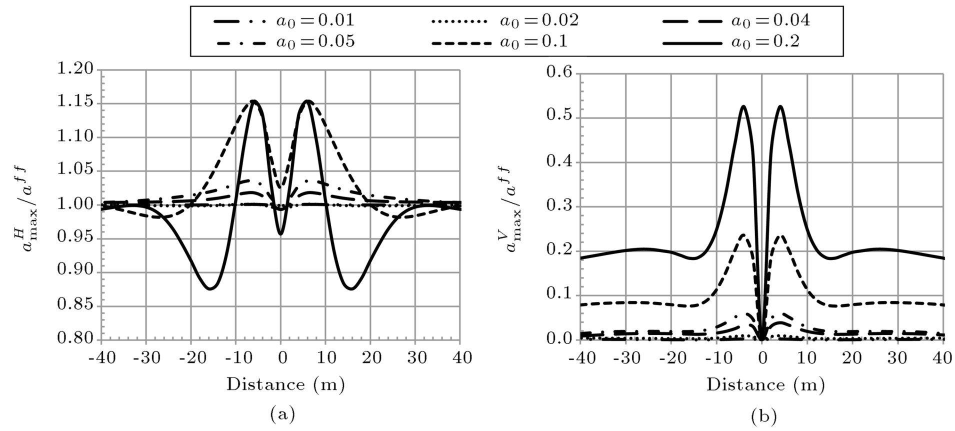

Figure 3. Spatial distribution of normalized peak ground surface acceleration under incident SV wave: (a) Horizontal acceleration, and (b) vertical acceleration for various values of dimensionless frequency (circular cavity, $R = 3$ m).

horizontal and vertical acceleration is negligible, while for incident P free field motion is vertical and horizontal acceleration is negligible. Free field motion is defined as the 1D ground motion which is not affected by any irregularities.

3. Results and discussion

3.1. Effect of frequency of incident motion

To investigate the effect of frequency of incident motion, the dimensionless frequency is defined as follows:

$$a_0 = \frac{2f_0R}{V}, \tag{2}$$

where f_0 is the frequency of input motion, R is the radius of cavity and V is the shear or primary wave velocity in the soil. In this part, cavity is considered circular with radius of 3 m whose center is located at depth of 6 m under the ground surface. Cavity is subjected to vertically propagating SV and P waves. Based on the soil properties, the shear and primary waves velocities are considered 600 m/s and 1340 m/s, respectively. The frequencies of the incident motion are varied as 1, 2, 4, 5, 10, and 20 Hz. The effects of incident motion frequency on spatial distribution of normalized peak ground horizontal and vertical accelerations are illustrated in Figures 2 and 3 for incident SV and P waves, respectively. In these figures, a^{ff}, $a^H_{\max}$ and $a^V_{\max}$ are the free field acceleration, maximum horizontal acceleration, and maximum vertical acceleration, respectively. Distance at the horizontal axis is the distance in horizontal direction from center of the model to the left and right sides at the ground surface.

Same as the other types of ground irregularities such as subsurface and surface topography, dimensionless frequency has a significant effect on acceleration amplification. By increasing of the value of "a_0", peak points of normalized acceleration increase in two directions for two types of incident waves. For incidents of P and SV, effect of a_0, is more significant for high values. These results reveal that for low values of dimensionless frequency, amplification of the ground motion due to presence of the cavity can be neglected. This can be attributed to the long wavelength of the input motion. According to Figures 2 and 3, the

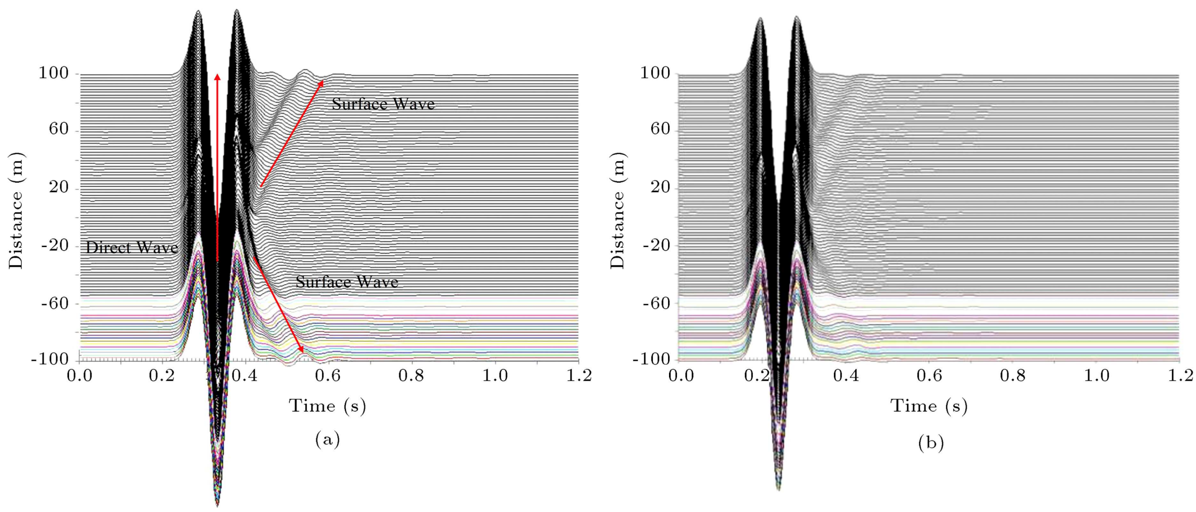

Figure 4. Synthetics seismograms of (a) horizontal acceleration for incident SV, and (b) vertical acceleration for incident P (circular cavity, $R = 3$ m, $f_0 = 10$ Hz).

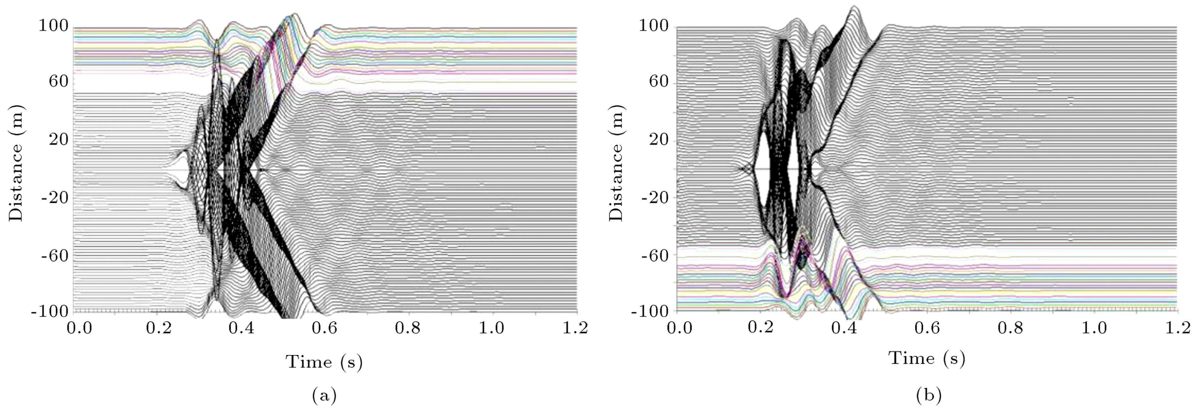

Figure 5. Synthetic seismograms of (a) vertical acceleration for incident SV, and (b) horizontal acceleration for incident P (circular cavity, $R = 3$ m, $f_0 = 10$ Hz).

presence of the cavity causes high spatial variations of the ground motion in vicinity of cavity.

Synthetic seismograms are results of modeling the seismic response of an input motion at the ground surface. Synthetic seismograms of horizontal and vertical accelerations for both SV and P in-plane waves are shown in Figures 4 and 5. Generation of surface waves can be seen in these figures, which is more complicated and obvious in the parasitic accelerations (vertical in case of incident SV, horizontal in case of incident P). Figures 4 and 5 confirm that the presence of the cavity causes more significant variations of ground surface acceleration and production of surface waves.

3.2. Effect of the depth of cavity

To investigate the effect of the depth of cavity, h/R ratio is used as depth ratio, where h is the depth of cavity center and R is the radius of circular cavity. Effects of depth ratio on spatial distribution of normalized peak ground horizontal and vertical accelerations for both incidents SV and P waves are illustrated in Figures 6 and 7.

By increasing the depth of cavity center, the effect of cavity on ground surface motion reduces and for higher value of h/R (i.e. $h/R > 6$) the effect of cavity can be neglected. The similar results were reported by Alielahi et al. [22]. There is a reverse relationship between the emplacement depth and ground amplification in both directions for incident SV and P. In other words, surface cavities have an important effect on aggravation of the ground surface motion. This effect is more clear for $h/R < 4$. Similar results were reported by Lee and Karl (1992) for incident SV [3]. Another result of the presented research shows in the case of incident P, horizontal parasitic acceleration is very low and the effect of depth is not very significant.

3.3. Effect of two cavities

The effect of presence of second cavity in addition to the first one is also investigated. Second cavity is located at different horizontal distances from the first

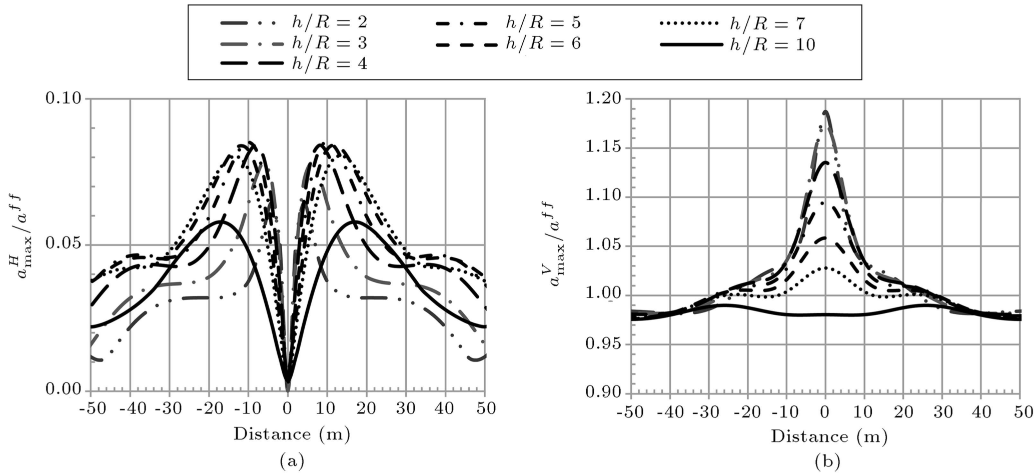

Figure 6. Spatial distribution of normalized peak ground surface acceleration under incident P wave: (a) Horizontal acceleration, and (b) vertical acceleration for various values of depth ratio (circular cavity, $R = 3$ m, $f_0 = 10$ Hz).

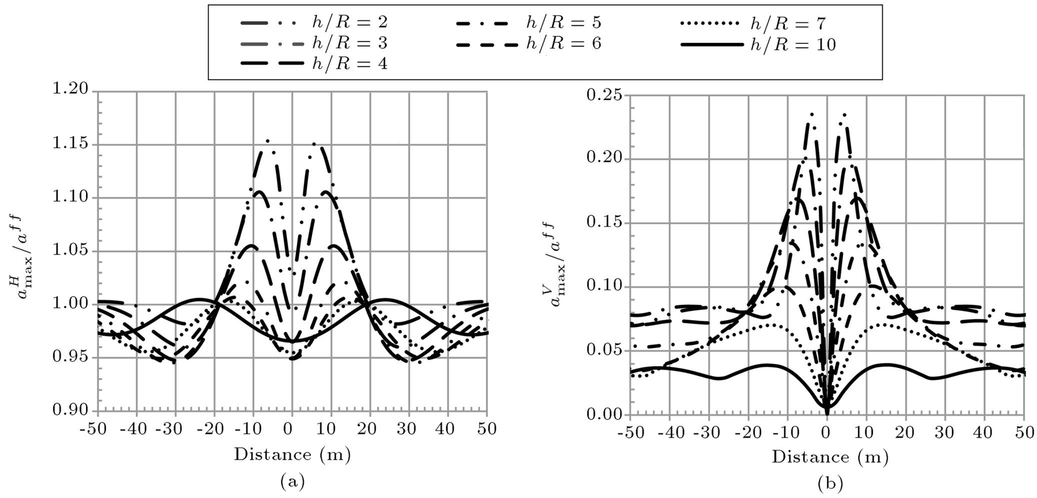

Figure 7. Spatial distribution of normalized peak ground surface acceleration under incident SV wave: (a) Horizontal acceleration, and (b) vertical acceleration for various values of depth ratio (circular cavity, $R = 3$ m, $f_0 = 10$ Hz).

one. The L/R ratio is used where L is the horizontal distance between two circular cavities centers and R is the circle radius (see Figure 1). The effects of values of L/R on spatial distribution of horizontal and vertical accelerations are illustrated in Figures 8 and 9 for two types of incident motion. It is noted that $L/R = 0$ corresponds to one cavity.

As can be seen in Figure 8 (incident P), presence of the second cavity aggravates the acceleration in two directions significantly. However, increasing the distance between two cavities causes reduction of acceleration aggravation in horizontal and vertical directions. In other words, decreasing the value of L/R induces each of two cavities and aggravates the effect of another cavity. In the case of incident SV (Figure 9), there are no direct trends in spatial variations of normalized peak ground accelerations in two directions. Increasing of the distance between two cavities until $L/R = 5$ will cause two cavities aggravate the response of each other and as L/R increases, the amplification of horizontal accelerations increases. Then, increasing the L/R to more than 5 will cause reduction of cavities effect on each other to reduce. Same as horizontal direction, there is no direct trend for variation of vertical acceleration with L/R. In this case, however, as L/R increases until $L/R = 5$, the amplification of vertical accelerations decreases. Then increasing the L/R to more than 5 will cause increasing of amplification. Generally, it can be seen in all figures that peak points of curves for cases with two cavities have higher values with respect to case of one cavity. It can be deduced that adding the second cavity produces more critical condition in aggravation of the ground seismic motion.

3.4. Effect of cavity geometry

The effect of cavity shape is also investigated in this study. The elliptical cavities with various aspect

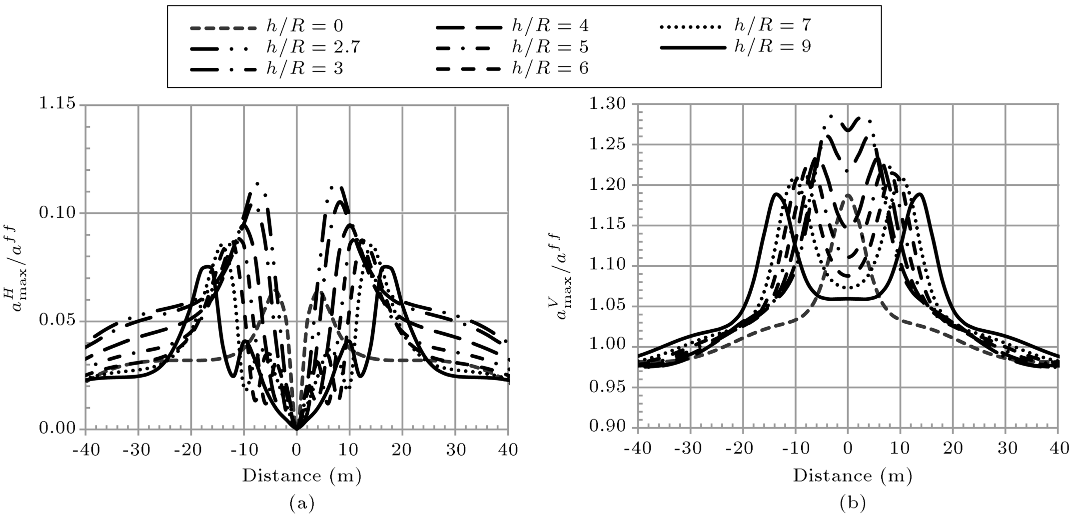

Figure 8. Spatial distribution of normalized peak ground surface acceleration under incident P wave: (a) Horizontal acceleration, and (b) vertical acceleration for various distances between two cavities (circular cavity, $R = 3$ m, $f_0 = 10$ Hz).

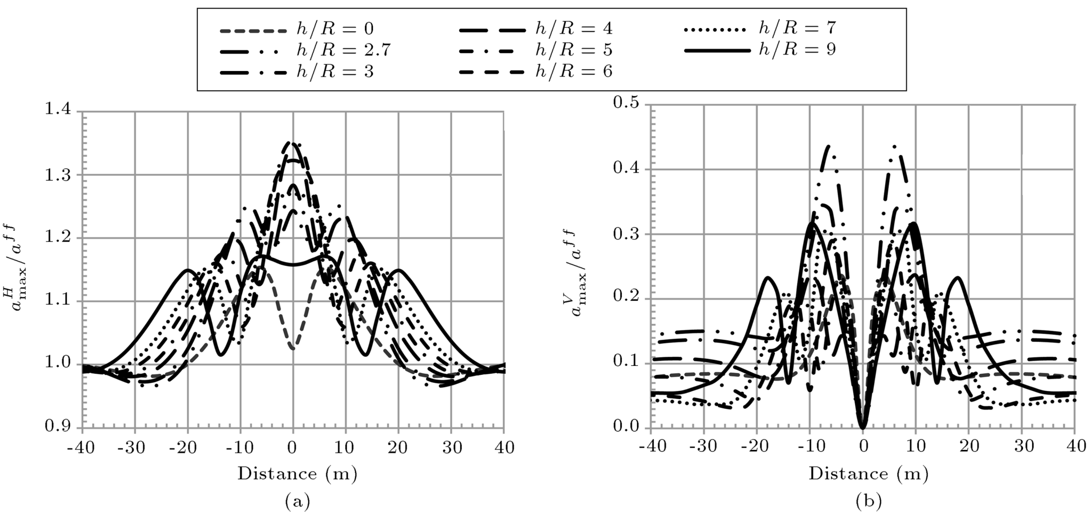

Figure 9. Spatial distribution of normalized peak ground surface acceleration under incident SV wave: (a) Horizontal acceleration, and (b) vertical acceleration for various distances between two cavities (circular cavity, $R = 3$ m, $f_0 = 10$ Hz).

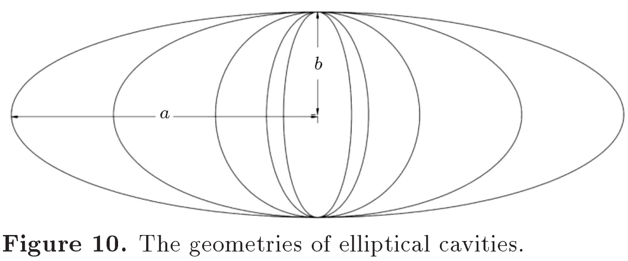

Figure 10. The geometries of elliptical cavities.

ratios are examined to understand the effect of cavity shape (Figure 10). Spatial distribution of normalized peak ground horizontal and vertical accelerations for incident P and SV waves are presented in Figures 11 and 12, respectively. It is noted that a/b in these figures is the ratio of horizontal to vertical dimension of the cavity (see Figure 10) and $a/b = 1$ corresponds to circular cavity. Geometry of cavity has an important role on amplification of seismic motion. Considering elliptical cavity, increasing the ratio of horizontal to the vertical dimension (a/b) will increase the amplification of the ground surface motion significantly for two cases of incident waves and two directions which shows amplification has a direct relationship with the ratio of a/b and the aggravation of the motion is more important for $a/b = 2$ and 3. In the case of incident P, amplification of vertical acceleration reaches to 2.14, which is a significant value. In the case of incident SV, in addition to high amplification of horizontal acceleration, the aggravation of the vertical acceleration is also considerable and its value reaches horizontal acceleration of the free field.

The synthetic seismograms of the accelerations in horizontal and vertical directions for both incident

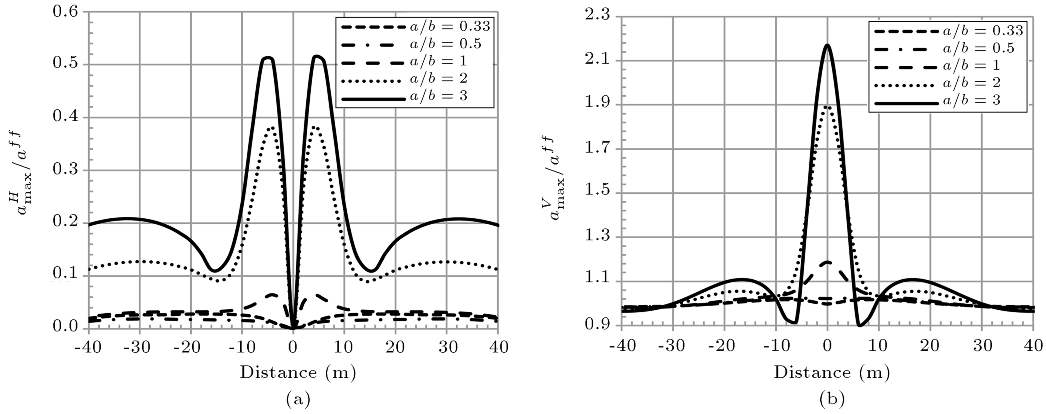

Figure 11. Spatial distribution of normalized peak ground surface acceleration under incident P wave: (a) Horizontal acceleration, and (b) vertical acceleration for various values of cavity aspect ratio ($f_0 = 10$ Hz).

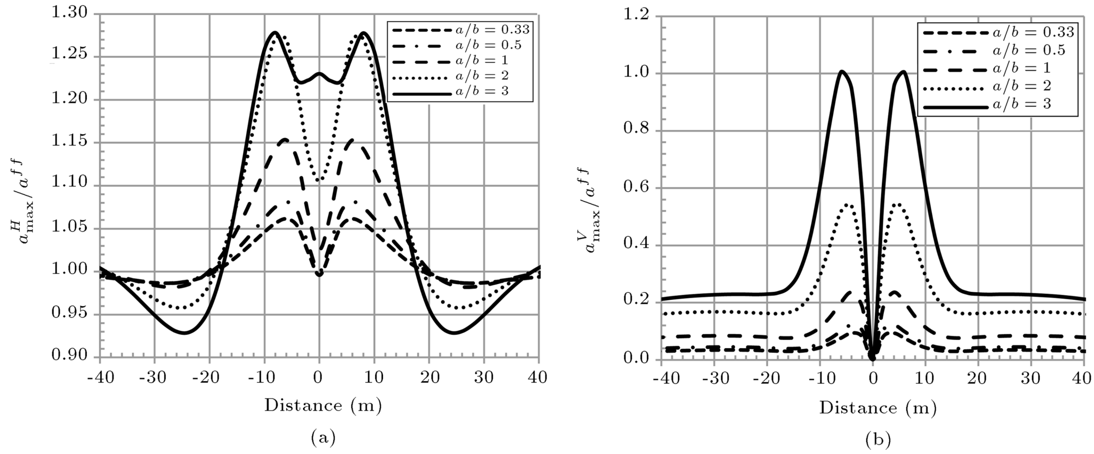

Figure 12. Spatial distribution of normalized peak ground surface acceleration under incident SV wave: (a) Horizontal acceleration, and (b) vertical acceleration for various values of cavity aspect ratio ($f_0 = 10$ Hz).

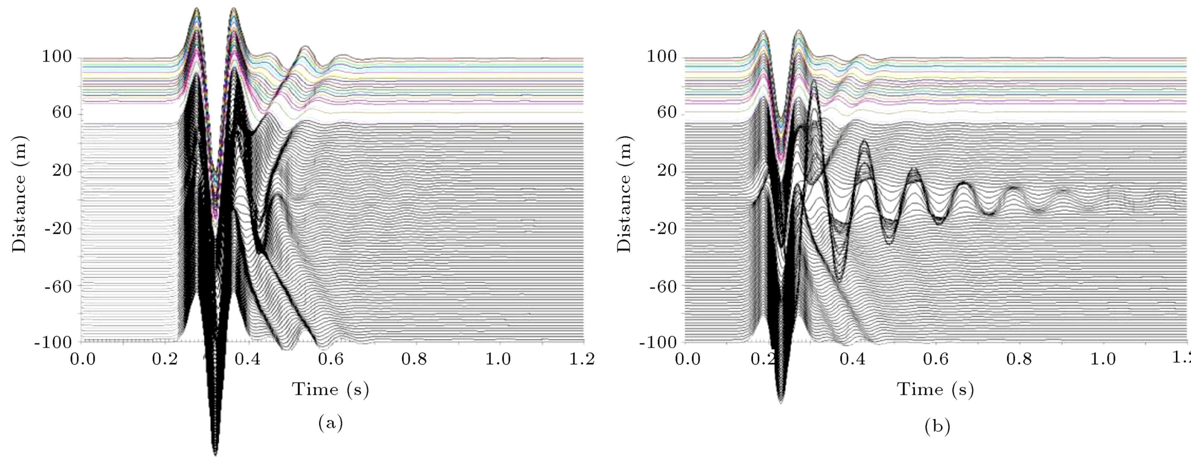

Figure 13. Synthetic seismograms of (a) horizontal acceleration for incident SV, and (b) vertical acceleration for incident P (elliptical cavity, $a/b = 3$, $f_0 = 10$ Hz).

SV and P waves are illustrated in Figures 13 and 14. These figures show the generation of the surface waves due to elliptical underground cavities ($a/b = 3$). It can be deduced that presence of the cavity with more elliptical shape causes more significant changes in seismic waves and production of surface waves. In comparison of circular cavity (Figures 4 and 5), the elliptical cavity with $a/b = 3$ (Figures 13 and 14) produces more complicated surface waves with higher amplitude.

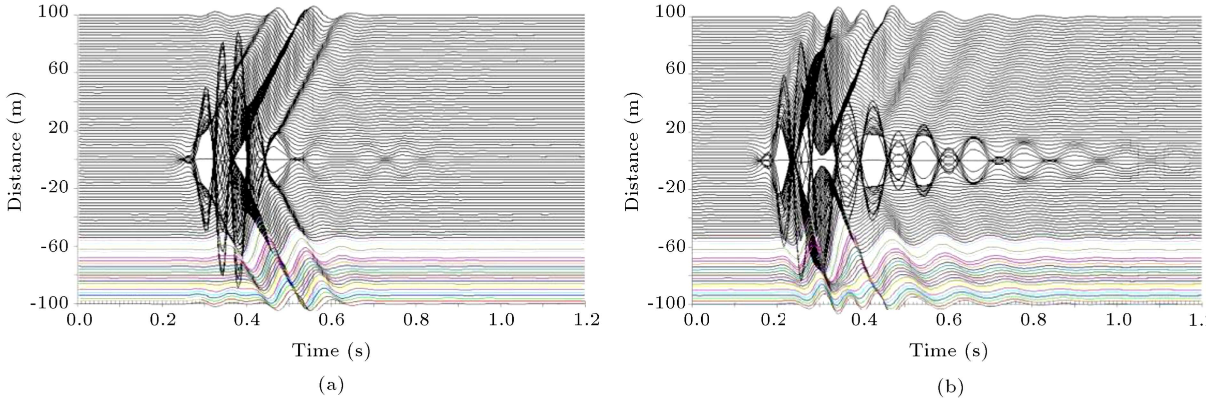

Figure 14. Synthetic seismograms of (a) vertical acceleration for incident SV, and (b) horizontal acceleration for incident P (elliptical cavity, $a/b = 3$, $f_0 = 10$ Hz).

4. Conclusions

Implementing the numerical method of finite difference, the effect of underground cavities on ground seismic motion are investigated considering dimensionless frequency, depth and geometry of cavity, and cavities distance. The main conclusions which were obtained in this study are as follows:

- The presence of the underground cavity can produce high spatial variations and destructive aggravations of ground seismic motion. Also underground cavity can produce high amplitude of surface motion which causes complicated wave field.
- Dimensionless frequency has an important effect on amplification of the ground motion due to underground cavity. For high values of dimensionless frequency, aggravations of acceleration for incident P and SV in-plane waves are significant in vertical and horizontal directions. However, for low values this effect can be ignored.
- The depth of cavity is also important in altering the ground motion. For surface cavity, aggravation of the acceleration is more important, but for very deep emplacement, the effect of cavity can be neglected.
- The presence of the second cavity in addition to first one causes more significant aggravation and higher amplification of the ground motion with respect to one cavity only. In this case, for incident P, decreasing the cavities distance causes an aggravation in their effect on each other. For incident SV, increasing the distance between two cavities, until $L/R = 5$, will cause two cavities to aggravate the response of each other; as L/R increases, the amplification of horizontal acceleration increases. Increasing the L/R more than 5 will cause the reduction of cavities to affect each other.
- Elliptical cavities produce different responses in comparison to circular cavity and the increase of the ratio of horizontal to vertical dimension of cavity will cause the increase of the ground motion amplification in vertical and horizontal directions very significantly for both incident P and SV in-plane waves.
- Finally, it is mentioned that an earthquake with high value of predominant frequency caused less destructive effects than earthquakes with low frequencies due to little amount of earthquake energy. However, presence of the topographic irregularities can aggravate the motion for high frequencies of incident motion, and this range of frequency could be important in such conditions. Topographic irregularities also change the frequency content of input motion.

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