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Seismic Response of U-shaped Canyon in Presence of Underground Cavity Using BEM

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ABSTRACT

The experiences of past earthquakes disclosed considerable effects of underground holes like natural karstic cavities on the seismic ground response. On the other hand, due to the structures such as bridges and dams majority are located in the canyon shaped topographic features, it is essential to study the seismic interaction between them. In this study an attempt is made to study the effect of U-shaped canyon-cavity geometry on strong ground motion. Response analysis was made for the different sizes U-shaped canyon in the presence of different position of underground cavities. The results showed that the response is strongly influenced by size of U-shaped canyon. In order to take these factors into account, U-shaped canyon with different sizes and with different dimensionless period intervals, were assumed. In this paper, the medium is supposed to have a linear elastic constitutive behavior subjected to vertically SV and P propagating incident waves. The result showed that the buried depth of the cavity relative to the roof of the cavity plays a major role in seismic amplification pattern.

Introduction

Exploration on wave scattering and seismic amplification problems of natural or man-made subsurface cavities is important in seismology and earthquake engineering. With rapid development of cities, tunneling under the deep excavation of structures like subway is becoming more common because of the lack of available space for infrastructure. The interaction between newly constructed tunnels and existing surface buildings is an important issue, because it causes strong ground motions, which may cause serious damage to adjacent structures. With regard to development of urban transportation and population growth, using of underground structures and cavities such as subway and tunnels are necessary. On the other hand, it is completely evident that the geometry and topography of sites have a significant effect on the seismic ground response and distribution of damages due to earthquakes. The most of cities, dams and bridges are located on canyon shaped topographic features and between them; U-shaped canyons are popular in nature. Most of existent studies concentrated separately on the seismic behavior of topographic features and buried engineering structures and the study about seismic interaction between topography especially canyons and underground cavities have seldom been published. Many researchers paid great attention to the influence of the subsurface structures on the seismic ground motions by analytical, semi-analytical and numerical methods to deal with topographic effects and wave scattering problems (e.g., Lee et al.1999; Liang et al. 2007). Recently, Liu et al. (2013) presented an analytical solution for scattering of plane harmonic P, SV, SH and Rayleigh waves by a shallow lined circular tunnel in an elastic half-space. The analytical methods are

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restricted to features with simple geometries and SH waves. On the other hand, numerical studies can be used such geometries that can solve real shapes of problems (e.g. seismic interaction between topographic features like U-shaped canyons and cavities). Along with the numerical studies of the issue, one of the most comprehensive numerical studies has been performed by Rodriguez-Castellanos et al. (2006) using 2D indirect boundary element method (IBEM) for P and SV waves. Later, Yiouta-Mitra et al. (2007) conducted a set of dynamic plane strain numerical analyses to evaluate the effect of underground structures on the seismic ground motions. Also, Scattering of harmonic P, SV or SH and Rayleigh waves by 2-D smooth and rough cavity completely embedded in an isotropic half space and full-space using direct boundary integral equation method in the frequency-domain is investigated by (Dravinski and Yu.,2011). Recently, Alielahi et al. (2015) evaluated the seismic response of a linear elastic medium including a buried unlined tunnel subjected to vertically propagating incident SV and P waves using the time-domain boundary element method. They observed that the amplification of the ground surface underlain by a tunnel is increased in long periods. The analytical solution of seismic waves scattering problem by canyon-shaped topography features are complicated. Because of that the most of studies are limited to simple topography shapes and SH incident waves (e.g. Sanchez-Sesma 1985). The series solution of wave functions for 2D scattering and diffraction of plane SH waves induced by a U-shaped canyon are proposed by Gao et al. (2012). They found that a zone of amplification can obviously take place at the bottom of a U-shaped canyon with nearly vertical walls and the results in the frequency domain show that the steepness of the illuminated side canyon wall has a key role in the topographic effects. Based on the numerical solution, Zhao and Valliappan (1993) considered V-shaped, rectangular, and trapezoidal-shaped canyons to SV and P waves with vertical incidence as well as real earthquake input motions were applied to the half space. The effect of the weathered canyon walls was also studied. Likewise, Kamalian et al. (2006, 2007) and Sohrabi-Bidar et al. (2010) solving wave propagation equations in time-domain and investigated the behavior of two and three dimensional canyon features using boundary element methods. Published works were either limited to the simple case of incident SH waves or restricted to some specific values of the geometry ratios and specific dimensionless frequencies. For example, Lee et al. (1999) investigated the scattering of out-of-plane waves of an embedded tunnel cavity beneath circular canyon using a semi-analytical solution. Actually, the U-shaped canyon is a common topographic feature on the Earth's surface (Harbor, 1992; Chiang and Yu, 2006). In this paper, a new shape of canyon are modeled to investigate the seismic response of underground unlined cavity on the surface ground motions.

Parametric Study Methodology

Among the numerical methods, boundary methods can fulfill the radiation condition easily and reduce the dimensions of the problems, but they need discretization of boundaries or numerical integration along boundaries Gao et al. (2012). The main aim of this paper is using of an efficient computer program called SAMBE (Seismic Analysis of Multiple Boundary Element) was developed by Alielahi et al. (2013) based on the time-domain boundary element method. The parametric study was performed by solving the following well known transient boundary integral equation which is governing the dynamic equilibrium of isotropic elastic media:

$$c_{ij}(\xi)u_i(\xi,t) = \int_\Gamma [\int_0^t (U_{ij}^*\,(X,t,\xi,\tau)t_i(X,\tau) - T_{ij}^*(X,t,\xi,\tau)u_i\,(X,\tau))d\tau]d\Gamma + u_j^{inc.}(\xi,t) \qquad (1)$$

Where U_{ij}^* and T_{ij}^* are time-domain displacement and traction fundamental solutions at position X and time t due to a unit point force applied in ξ position and preceding time τ< t, respectively. u_i And t_i are displacement and tractions of boundary element. c_{ij} is the well-known discontinuity term resulting from the singularity of traction fundamental solution kernel. The medium is assumed to have a linear elastic constitutive behavior subjected to vertically propagating incident SV and P waves. The type of vertically propagating waves was assumed as Ricker wavelets with equation as follows:

$$f(t) = A_{max}\,[1 - 2.(\pi.f_p.(t - t_0))^2\,]e^{-(\pi.f_p.(t-t_0))^2} \qquad (2)$$

In which f_p, t_0, t and A_{max} demonstrate the predominant frequency, the appropriate time shift parameter, the total time and the maximum amplitude of the time-history, respectively. In case of SV wave, $f(t)$ designates the horizontal component of the incident motion while the vertical component is zero and in case of P waves, vice versa. Fig.1 shows the geometry and variable parameters of the U-shaped canyon and underground cavity subjected to vertically propagating incident SV and P waves. In this figure, d, a, H, H_0 *and* L are the buried depth of the cavity relative to the roof of the cavity, the cavity radius, the depth of the center of U-shaped canyon, the height of the wall of U-Shaped canyon and the half width of the canyon, respectively. In this study, U-shaped canyon with different h/L, d/L, a/L, H_0/H were assumed. In this regard, the summarizations of the variable parameters are shown in Table1. It is notable that the material behavior of the medium is assumed linear elastic, Poisson ratio, mass density and shear wave velocity of the medium are considered 0.33, 2.0 t/m^3 and 800 m/s, respectively.

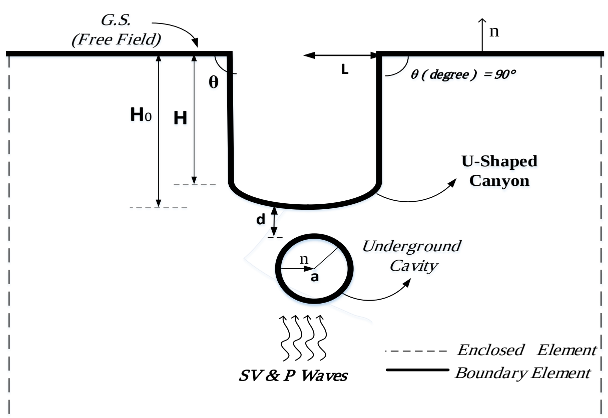

Figure 1. Geometry of U-shaped Canyon with Underground Cavity

Results and Discussion

This section presents the most important results obtained by the parametric studies, which demonstrate the general amplification pattern of 2D U-shaped canyons and show how it is affected by some independent key parameters of wave type and geometry of canyon and underground cavity. All results were presented in dimensionless forms, using the well-known dimensionless period as equation 3, where ω represents the angular frequency of the wave and L and V_s indicate the half width and shear wave velocity of the medium, respectively, which means physically the ratio of the incident's wavelength to the width of the canyon. This wide period interval was apportioned to the following four subintervals: 0.5 to 1.0 (P1), 1.0 to 2.0 (P2), 2.0 to

4.17 (P3) and 4.17 to 8.33 (P4), for incident waves with short, medium, long and very long periods, respectively. Alielahi et al.(2015) showed that the maximum amplification will occur in incident waves with greater wavelengths. Accordingly, the effect of underground cavity on amplification pattern of U-shaped canyons are presented in the very long periodic bands (4.17<P<8.33) because of the paper briefing. It should be noted that displacements of each canyon point with respect to the free-field without the cavity is defined as the amplification coefficient. For simplicity the well-known concept of average horizontal spectral amplification (AHSA) defined by Borcherdt et al. (1994) is followed in this parametric study. Furthermore, for each point on the ground surface, the average amplification in all mentioned periodic intervals is intended by numerical integration of the spectral amplification with respect to the period. Amplification patterns of canyon are shown in -3L to 3L interval to express the canyon amplification patterns, correctly. In following sections in the case of SV and P incident waves the horizontal and vertical and components of ground motion are named as direct components, respectively. Amplification curves were calculated by dividing Fourier amplitude of the horizontal component of the motion.

$$P = \frac{\pi V_s}{\omega L} = \frac{\lambda}{2L} \quad (3)$$

Table1.Variable parameters for parametric studies

Dimensionless Parameters	Variable Parameters
WR=a/L (Cavity radius to half-width of canyon ratio)	0.25,0.5,1
DR=d/L(Cavity depth ratio)	0.25,0.5,1.0, 1.5,2.0
SR=H/L(Shape ratio of the canyon)	0.3,0.5,1
HR=H_0/H(Canyon Concavity ratio)	1.2

Influence of Shape Ratio Effect (SR)

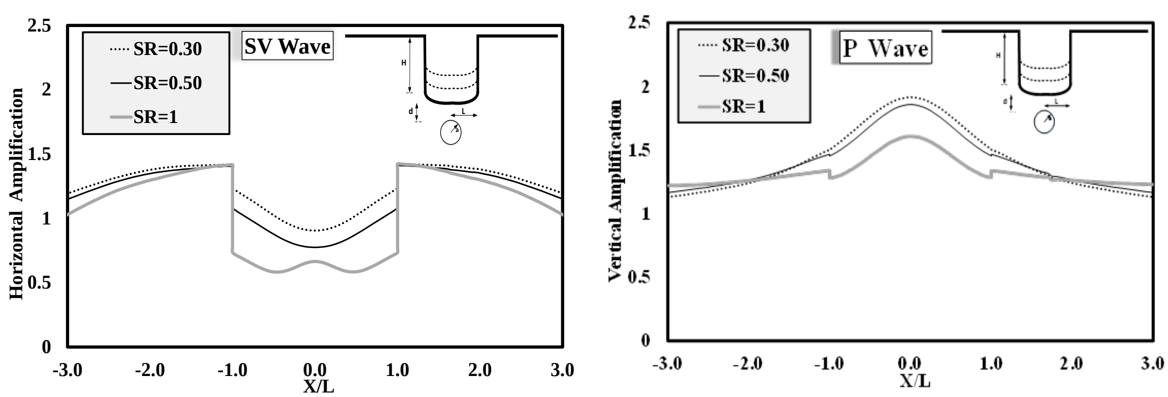

Figure 3. Shape ratio effect on amplification curves of 2D U-shaped canyon subjected to incident SV and P waves.

Figure 3 compare amplification curves of 2D U- shaped canyons with different shape ratios above the underground cavity subjected to incident SV and P waves, respectively. In general, the amplification or de-amplification pattern of the U-shaped canyon which located on the underground cavity decreases with the shape ratio. For the case of SV wave, the higher amplification and de-amplification occurs in the corner and center zone of the canyon, respectively. While the propagation of P waves creates the higher seismic amplification in the center zone of the canyon. Accordingly, the edges of U-shaped canyon and center of it are most important in the case of SV and P waves, respectively.

Influence of Cavity Radius Ratio (WR)

In this section, we compare the effect of increasing or decreasing the radius amplitudes of underground cavity on the amplification pattern of U-shaped canyon. Figure 4, categorizes the amplification patterns of direct component for 2D U-shaped canyon subjected to vertically incident SV and P waves, respectively. With a glance on curves, increasing the cavity radius toward the canyon width will cause more amplification in comparison with the case without cavity. It is resulted that, in the case of SV wave with increasing of WR, direct component of amplification increases in the edges of canyon. Conversely in the case of P wave, amplification increases in the center of canyon. It is evident that the identical wave trapped zones (Lee et al, 1999) between the cavity roof and bottom of the canyon increase because of the bigger cavities. This phenomenon causes more amplification on the canyon surface. The difference between P and SV waves is that direct amplifications of P wave are greater than SV wave.

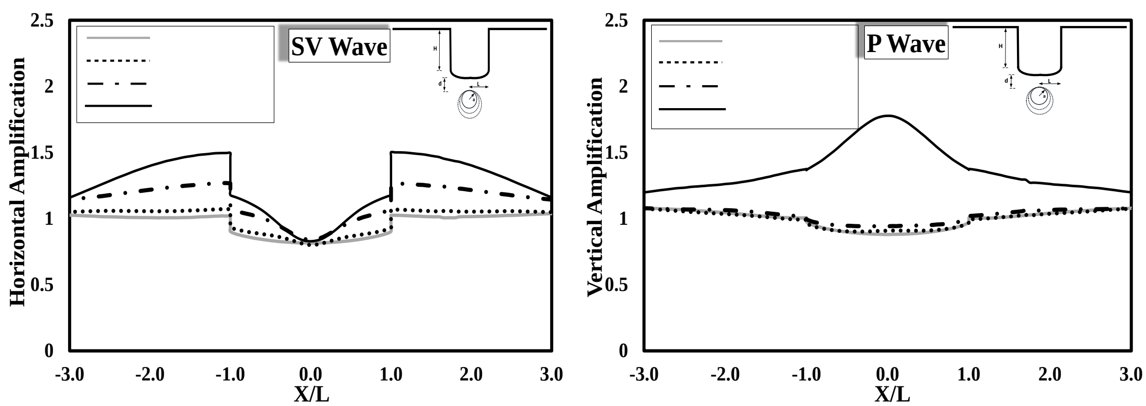

Figure 4. Cavity radius ratio (WR) effect on amplification curves of 2D U-shaped canyon subjected to incident SV and P waves.

Influence of Cavity Depth Ratio (DR)

Figure 5 shows the effect of the cavity depth ratio on the seismic amplification of the U-shaped canyon for incident SV and P waves in very long periodic bands. In these analyses, the shape ratio (SR) and cavity radius ratio (WR) are selected 0.5 and 1, respectively. Moreover, five depth ratios of the cavity are considered in this study. The shallow cavity effects are visible like amplification in the direct component for all points along the canyon. The present study indicates that the distance between the crest of the cavity and the bottom of the canyon plays an important role in the seismic response of the canyon. For SV waves, approaching cavity to the bottom of the canyon, the seismic behavior of the canyon is changed from de-amplification to amplification. In other words, a greater amplification is visible with decreasing DR ratio. Also, wave responses of deeper cavities (for DR>1.50) on the canyon surface are similar to the response of the canyon without cavity, especially in the edges of canyon. Also, in the case of P wave, with increasing the depth ratio, amplification of the center of canyon decreases. In general, Maximum response values on the canyon surface are obtained in the case with nearest distance between the cavity roof and canyon walls, that in the case of SV and P waves, it occurs in edges and center of the canyon, respectively. This non-negligible amplification is occurred due to trapped diffracted waves and several interactions between upper face of the cavity section and canyon walls. Similar results were indicated by (Lee et al. 1999 and Rodriguez- Castellanos et al. 2006).

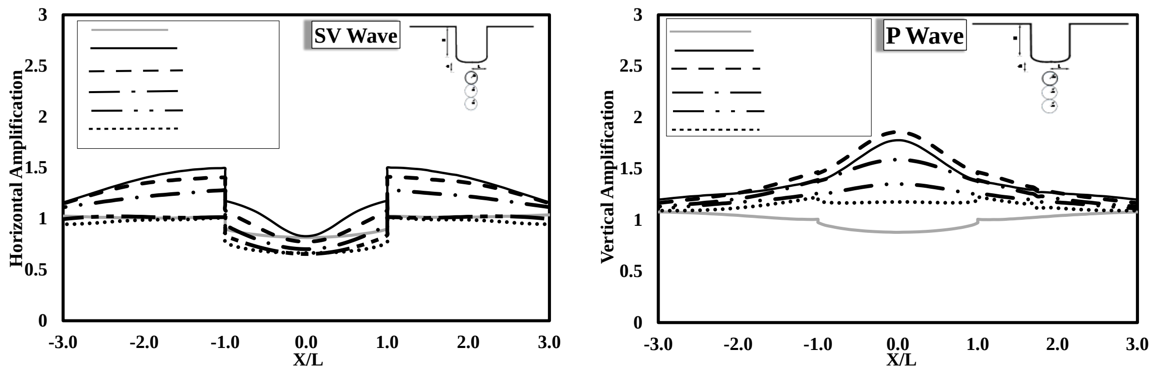

Figure 5. Cavity depth ratio (DR) effect on amplification curves of 2D U-shaped canyon subjected to incident SV and P waves.

Engineering Application

Table 2. Horizontal Amplification (SV Wave)

POSITION	WR	DR	SR 0.3	SR 0.5	SR 1
			4.17<Dimensionless Period<8.33		
Edge of Canyon	0.25	0.25	1.0	1.1	1.3
		0.5	1.0	1.1	1.3
		1	1.0	1.1	1.3
		1.5	1.0	1.1	1.3
		2	1.0	1.1	1.3
	0.5	0.25	1.2	1.3	1.4
		0.5	1.2	1.3	1.4
		1	1.2	1.2	1.4
		1.5	1.1	1.1	1.3
		2	1.0	1.1	1.2
	1	0.25	1.5	1.5	1.5
		0.5	1.4	1.4	1.4
		1	1.2	1.3	1.2
		1.5	1.1	1.0	1.2
		2	0.9	1.0	1.2
	Without cavity		1.0	1.0	1.3

Building codes and seismic microzonation guidelines need to emphasize that the effect of underground cavities and tunnels should be considered in the seismic design of the structures with high natural periods, especially in the case of shallow cavities. Introducing simple preliminary ideas for modification of the standard design spectra for structures to be located on the canyons by underground structures such as metro stations, underground parking stations, subway tunnels and cavities is the purpose of this research. The results encourage a step forward for site response analysis and microzonation of topographical areas by distinguishing the amplification patterns of a U-shaped canyon and free field half-space. Results of this paper can be used in building codes and seismic microzonation guidelines. Tables 2 and 3 represented horizontal and vertical amplification values of shear (SV) and compression (P) waves at the corner (X/L= -1) and center (X/L= 0) of the U-shaped canyon above circular cavities relative to the free field reference site are calculated, respectively

Table 3. Vertical Amplification (P Wave)

POSITION	WR	DR	SR 0.3	SR 0.5	SR 1
			4.17<Dimensionless Period<8.33		
Center of Canyon	0.25	0.25	0.9	0.9	0.8
		0.5	0.9	0.9	0.8
		1	0.9	0.9	0.8
		1.5	1.0	0.9	0.8
		2	1.0	0.9	0.8
	0.5	0.25	1.0	0.9	1.3
		0.5	1.0	1.0	0.9
		1	1.1	1.0	0.9
		1.5	1.1	1.1	0.9
		2	1.1	1.0	0.9
	1	0.25	1.8	1.8	1.9
		0.5	1.9	1.9	1.6
		1	1.7	1.6	1.4
		1.5	1.5	1.3	1.1
		2	1.3	1.2	1.0
	Without cavity		0.9	0.9	0.8

Summary and Conclusions

Clear representations of the amplification pattern of 2D U-shaped canyon above cavity subjected to vertically propagating SV and P waves were obtained by extensive numerical parametric analysis using the time-domain boundary element method. The amplification potential of the canyon was strongly influenced by shape ratio of the canyon, depth and radius of the cavity. Also, it is shown that:

- Increasing the cavity radius, WR, will cause amplification in comparison to the case without cavity. This is more pronounced at the corner and center of the canyon for SV and P waves, respectively.
- Decreasing the canyon SR, intensifies the amplification pattern of all points along it in the presence of the shallow cavity.
- In case of canyon with a shallow embedded underground cavity, the amplification values of SV and P waves increase significantly. On the other hand, increasing the depth of the cavity (DR), the effect of the cavity on the seismic response of the canyon is decreased or becomes insignificant. The distance between the bottom of the canyon and the upper surface of the cavity is a very important parameter. Decreasing of this distance may trap scattered waves and a more amplification will occur.

- Generally, wave scattering and amplification in the case of compression waves is much more significant than the shear waves, in very long period bands. The maximum amplification occurs in center and corner of the canyon surface in case of P and SV waves, respectively.

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