INFLUENCE OF UNDERGROUND CAVITY ON THE SEISMICRESPONSE OF U-SHAPED CANYON USING BEM

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ABSTRACT

A 2D scattering and diffraction of plane P and SV waves induced by a U-shaped canyon above underground cavities is proposed herein to account for the topographic effect of such a canyon. Time domain boundary element method(BEM),were performed to study the behaviour of this problem. To show the interaction between U-shaped canyons and underground cavities and their effects on the surface ground motion, a parametric analysis is carried out in very long periodic bands.Influence of various parameters has been investigated. It is shown that site geometry, wave characteristics, and cavity location are the key parameters governing the canyon's response. In this regard, the important parameters considered in this study are: the width of the underground cavities; the cavity depth; radios of cavity and shape of canyon.

INTRODUCTION

Recent destructive earthquakes have shown significant evidences of the effects of surface geology and topography on ground motion characteristics at a site. So, explorating of thewave scattering and seismic amplification problems of natural or artificial subsurface cavities is important in geophysics, seismology and earthquake engineering both in theory and practical application.Also, with rapid development of cities, utilization of underground spaces becomes the very important factor affecting the sustainable development of urban society. When an underground space is excavated, it inevitably causes strong ground motions, which may cause serious damage to adjacent structures. The experiences of pastearthquakes as well as analytical, experimentaland numerical studies have disclosed considerable effects of underground cavities or holes like natural karstic cavities, subway and tunnels on the seismic ground response. 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 (Sanchez-Sesma, 1987; Gazetas and Dakoulas,1992; Aviles and Perez-Rocha, 1998).

Extensive parametrical studies are done to discriminate the topographical and geotechnical effects on seismic ground amplifications in 2D irregular configurations. Also, most of existent studies concentrated separately on the seismic behavior of topographic features and buried engineering structures and studies about seismic interaction between topography especially canyons and underground cavity have seldom been published.

Many researchers paid great attention to the influence of the Earth's surface topography on the earthquake topography by analytical and semi-analytical and numerical methods to deal with topographic effects to analyze seismic wave scattering problems (e.g., Lee and Trifunac, 1979; Lee, 1988; Lee et al., 1999). From analytical and semi-analytical viewpoint, Lee &Trifunac (1979) were the firsts who investigated seismic response of circular tunnels for SH waves in an elastic half-space. Later, extension studies were carried out, Lee and Karl (1993); Liang et al. (2007 a, b). Recently, Liu et al. (2013, 2014) 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. This solution is developed based on the plane complex variable theory and the image technique. The analytical methods are restricted to features with simple geometries wave components. 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 on the effect of underground cavities on seismic ground response has been performed by Rodriguez-Castellanos et al. (2005, 2006). In this study, using 2D indirect boundary element method (IBEM) for P and SV waves, scattering of elastic waves by cracks and underground cavities are studied. Also, 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. Recently, 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, 2010, 2011).

The analytical solution of seismic waves scattering problem by canyon-shaped topography features are complicated and most of studies are limited to simple topography shapes and SH incident waves (Trifunac, 1972; 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 topographic effects.

Based on numerical solution, Zhao and Valliappan (1993) considered V shaped, rectangular, and trapezoidal shaped canyons. Harmonic SV and P waves with vertical incidence as Well as real earthquake input motions were applied to the half space. The effect of 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 investigated the behavior of two and three dimensional canyon features using boundary element methods. Review of the technical literature shows that perfect parametric studies on the seismic behavior of canyons above underground cavities subjected to incident SV and P waves have seldom been published. Published works were either limited to the simple case of incident SH waves or restricted to some specific values of geometry ratios and predominant 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). We herein present a new canyon model to investigate the effect of presence of unlined cavity under U-shaped canyon on surface motions.

PARAMETRIC STUDY METHODOLOGY

Numerical methods used for the seismic analysis of the multi-dimensional sites are divided into three main categories: domain methods such as finite element methods, boundary methods such as boundary element methods, and hybrid methods combining domain and boundary 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 (2012) and Alielahi et al. (2013) based on 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:

$$(\alpha^2-\beta^2)u_{j,ij}(x,t)+\beta^2u_{j,ij}(x,t)+b_i(x,t)-\ddot{u}_i(x,t)=0 \quad (1)$$

Where u_i indicates the displacement vector and b_i denotes body force vector. α and β are the compression and shear wave velocities of the body, respectively. They are obtained using $\beta^2=(\lambda+2\mu)/\rho$ and $\alpha^2=\mu/\rho$ in which, λ and μ are Lame coefficients and ρ is mass density.

In this regard, the medium is assumed to have a linear elastic constitutive behavior subjected to vertically propagating incident SV and P waves. In this paper more ratios those affect amplification pattern of U-Shaped canyon, assumed. The type of vertically propagating waves was assumed as Ricker wavelets with equation as follows:

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

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. Figure 1 shows the geometry and variable parameters of the U-shaped canyon and underground cavity subjected to vertically propagating incident SV &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 order to take these factors into account, U-shaped canyon with different h/L, d/L, a/L, H_0/H were assumed.

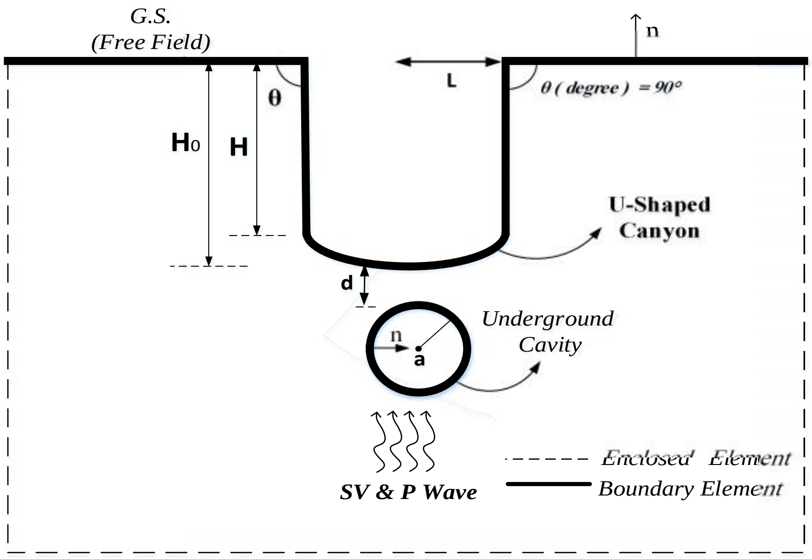

Figure 1. Schematic Geometry of U-Shaped Canyon with Underground Cavity

Table 1 summarizes the variable parameters in these parametric studies.

Table1.Variable parameters for parametric studies

Dimensionless Parameters	Variable Parameters
WR=a/L	0.25,0.5,1
DR=d/L	0.25,0.5,1.0, 1.5,2.0
SR=H/L	0.3,0.5,1
HR=H_0/H	1.2

Figure 2 and 3 demonstrates general perspectives of the scattering and diffraction of waves in 2D U-Shaped canyon (DR=0.25 & SR=0.5) subjected to an incident SV and P waves, respectively.

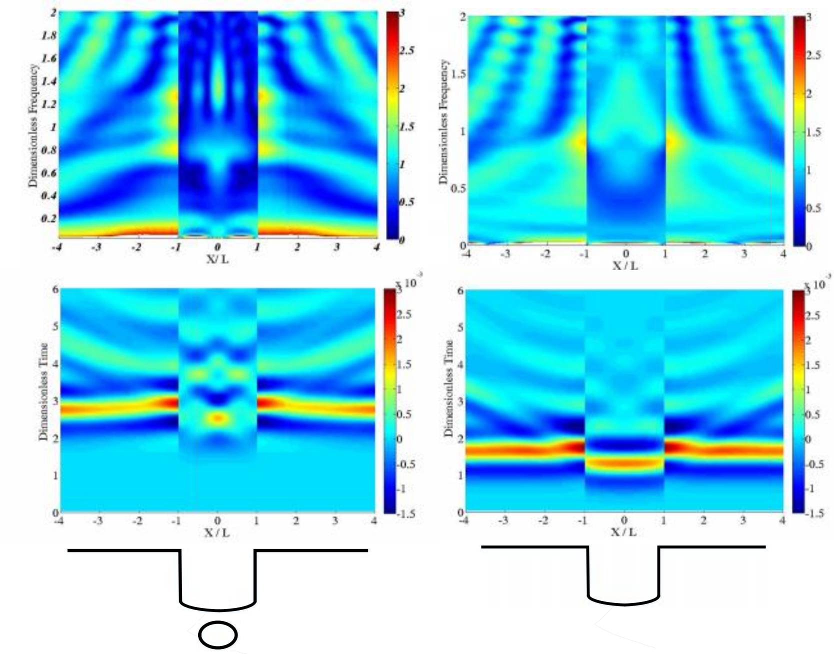

Figure 2. Amplification pattern of 2D U-Shaped canyon with circular cavity subjected to SV wave

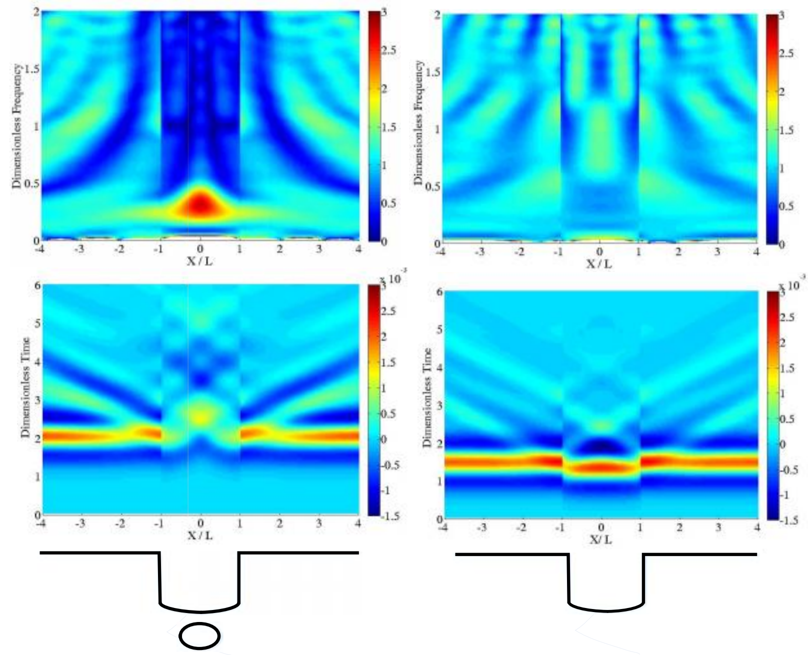

Figure 3. Amplification pattern of 2D U-Shaped canyon with circular cavity subjected to P wave

PARAMETRIC ANALYSIS RESULTS

This section presents the most important results obtained by the parametric study, 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 $P=\frac{\pi V_S}{\omega L}=\frac{\lambda}{2L}$, 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. Because of existent literature for example

Alielahi(2012)showed that important effects were occurred especially in very long periods (P4) and also for brevity, the effect of underground cavity on amplification pattern of U-shaped canyons in very long periodic bands (4.17< P <8.33) are detailed. It should be noted that displacements of each canyon point with respect to the free field without the cavity is defined as the amplification.

Amplification patterns of canyon are shown in -3L to 3L interval to express canyon amplification patterns, correctly. In following sections in the case of SV & P incident waves the horizontal and vertical and components of ground motion are named as direct components, respectively.

SHAPE RATIO EFFECT (SR)

Figure 4 shows the effect of shape ratios. In general, in the case of SV wave edges of canyons are most important from center and in the case of P wave it' vice versa. Maximum response values on the canyon surface are obtained in the case with nearest distance between the cavity roof and canyon slopes, that in the case of SV and P waves, it occurs in edge and center of 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 slopes. Similar results were indicated by (Lee et al., 1999, 2002 and Rodriguez-Castellanos et al., 2005, 2006). Some diffracted waves are more easily "trapped" between the ground surface and the roof of the underground cavity resulting in a standing wave pattern, there. As can be seen, maximum amplification occurs in edges the amplification or de-amplification potential of the canyon increases with the shape ratio.

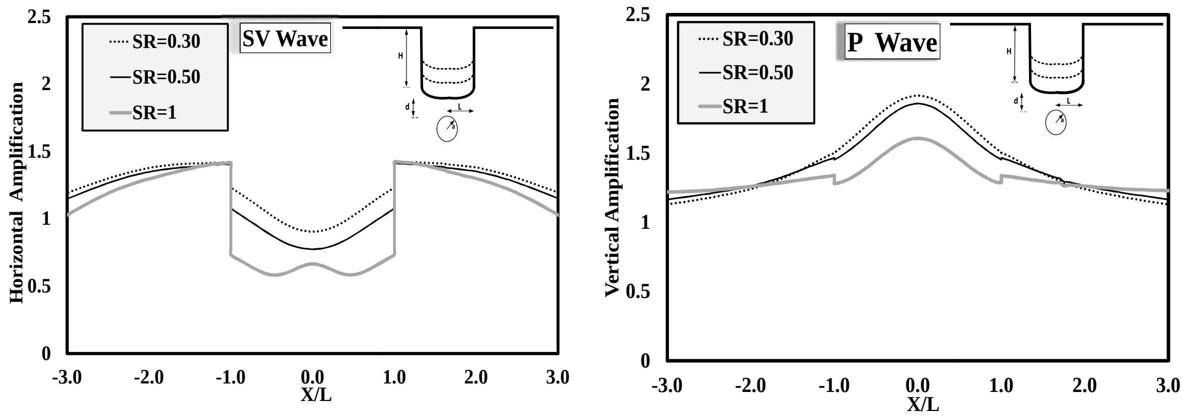

Figure 4. Shape ratio effect on averaged amplification curves of 2D U-shaped canyon subjected to vertically propagating incident SV & P waves

CAVITY RADIUS RATIO (WR) EFFECT

In this section, we compare the effect of increasing or decreasing the radius amplitudes of underground cavity on amplification pattern of U-shaped canyon. In this regard, two incident waves (SV & P waves) were investigated. Figure 5, categorizes the amplification patterns of direct component of 2D U-shaped canyon subjected to vertically incident SV & P waves respectively. With a glance on curves, increasing the cavity radius 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, $Hrz\,amplification$ in edges of canyon increase and there is a fair amount equal in the center of canyon but in the case of P wave, $Vrt\,amplification$, in the center of canyon, increases. Because of the shallow cavities create more identical wave trapped zones (Lee et al.,1999) between the cavity roof and bottom of the canyon. This phenomenon causes more amplification on the canyon surface. The only difference between P and SV waves is that direct amplifications of P wavearegreater than SV wave. As can be seen, the higher amplification potential occurs in the center zone of the canyon in P waves and in the edges of canyon in SV wave.

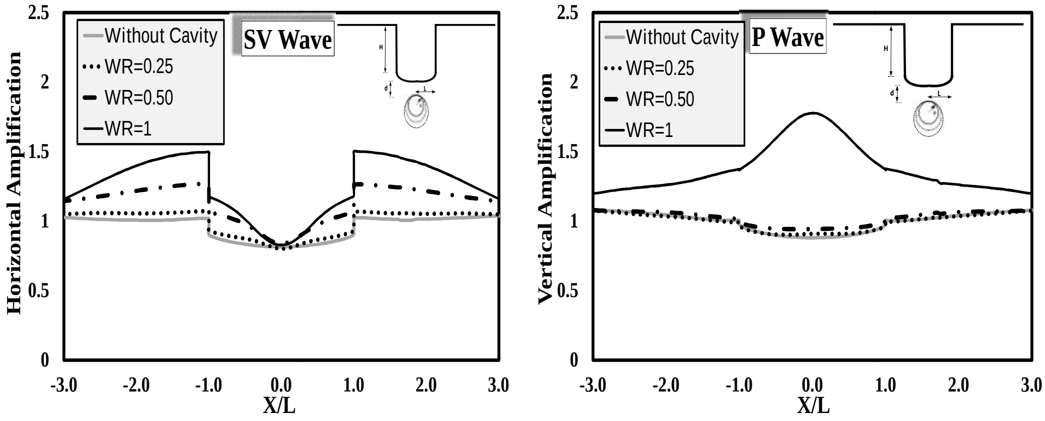

Figure5. Cavity radius ratio (WR) effect on averaged amplification curves of 2D U-shaped canyon subjected to vertically propagating incident SV & P wave

CAVITY DEPTH RATIO (DR) EFFECT

Figure 6show the effect of cavity depth ratio on the seismic amplification of the U-shaped canyon for incident SV and P waves in very long periodic bands. The shape ratio (SR) and cavity radius ratio (WR) were 0.5 and 1, respectively and five depth ratios and a 2D case were considered in this section. Direct components of amplification for both SV and P waves are shown in these figures. The seismic response of the site due to the canyon-cavity generally appears in the form of a seismic de-amplification (in the case of SV wave) in comparison to the canyon without cavity. Shallow cavity effects are visible like amplification in the direct component for all points along the canyon.

Yiouta-Mitra et al. (2007) and the present study indicate 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 wave, 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 considered 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.

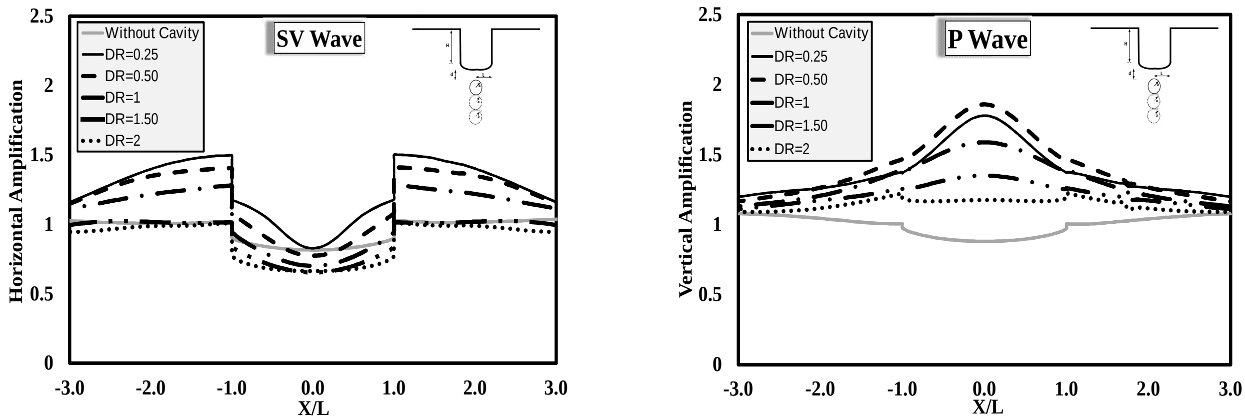

Figure 6. Cavity depth ratio (DR) effect on averaged amplification curves of 2D U-shaped canyon subjected to vertically propagating incident SV & P waves

ENGINEERINGAPPLICATION

Building codes and seismic microzonation guidelines need to emphasize that the effect of underground tunnels should be considered in the seismic design of the structures with high natural periods, especially in the case of shallow tunnels. Introducing simple preliminary ideas for modification of the standard design spectra for structures to be located on 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. the necessity of making tunnels and subways in urban areas, especially for public transportation purposes, has increased as the tunnel construction is the certain solution to overcome traffic problems in populated cities. Hence, 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 2.Horizontal spectral amplification (SV Wave)Table 3.Vertical spectral amplification (P Wave)

POSITION	WR	DR	SR		
			0.3	0.5	1
			The dimensionless period ranges are 4.17<P4<8.33		
			P4	P4	P4
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

POSITION	WR	DR	SR		
			0.3	0.5	1
			The dimensionless period ranges are 4.17<P4<8.33		
			P4	P4	P4
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

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 the length of the incident wave, shape ratio and, location of cavity. It was shown that the ground motion was de-amplified along the canyon. At the edges of the canyon and in the half-space, the ground motion was slightly amplified. The de-amplification potential of the canyon generally increased as the shape ratio increased, but the rate of increase depended on the wavelength and varied across the canyon. Also, it is shown that:

- 2D U-shaped canyon interaction with an underground cavity can significantly affect the seismic ground response against incident P and SV waves by a seismic amplification or de-amplification. Generally, wave scattering and amplification in the case of compression waves is much more significant than the shear waves, in very long period bands.
- Seismic interactions between the canyon and cavity are strongly affected by the geometric dimension and position with respect to each other in a way that a small geometric change may lead to the response amplification or de-amplification.
- Increasing the cavity radius, WR,will cause amplification in comparison to the case without cavity. This is morepronounced 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. Greater amplifications are observed in this case for P waves in comparison to SV waves.
- The maximum amplification occurs in center and corner of the canyon surface in case of P and SV waves, respectively.

REFERENCES

Alielahi H, Kamalian M, AsgariMarnani J, Jafari M K andPanji M (2013) Applying a Time-domain Boundary Element Method for Study of Seismic Ground Response in the Vicinity of Embedded Cylindrical Cavity, *International Journal of Civil Engineering*, 11(1):45-54

Alielahi H (2012) Using Time-Domain BEM for Evaluating Seismic Interaction between Underground Cavities and Topographic Structures, Ph.D. Dissertation, Science and Research Branch, Islamic Azad University, Tehran, Iran

Aviles J and Perez-Rocha LE (1998) Site effects and soil structure interaction in the valley of 604 Mexico, Soil Dynamics and Earthquake Engineering 17: 29-39

Chiang CS and Yu HS (2006) Morphotectonics and incision of the Kaoping submarine canyon, SW Taiwan orogenic wedge, *Geomorphology*, 80, 199–213

Dravinski M and Yu CH (2010) Peak surface motion due to scattering of a plane harmonic SH wave by a randomly corrugated scatterer, *Journal of Seismology*, 14:653–664

Dravinski M and Yu CH (2011) Peak surface motion due to scattering of plane harmonic P, SV, or Rayleigh waves by rough cavity embedded in an elastic half-space, *Journal of Seismology*, 15: 131–145

Gazetas G andDakoulas P (1992) Seismic analysis and design of rock fill dams: state-of-the-art, 602, *Soil Dynamics and Earthquake Engineering*, 11: 27-61 603

Gao Y, Zhang N, Li D, Liu H, Cai Y and Wu Y (2012) Effects of Topographic Amplification Induced by a U-Shaped Canyon on Seismic Waves, *Bulletin of the Seismological Society of America*, 4: 1748–1763

Harbor JM (1992)Numerical modeling of the development of U-shaped valleys by glacial erosion, *Geol. Soc. Am. Bull*. 104, 1364–1375

Kamalian M, Jafari MK, Sohrabi-Bidar A, Razmkhah A andGatmiri B (2006) Time-Domain Two Dimensional Site Response Analysis of Non-Homogeneous Topographic Structures by A Hybrid FE / BE Method, *Soil Dyn. Earthquake Eng*., 26(8): 753-765

Kamalian M, Gatmiri B, Sohrabi-Bidar A andKhalaj A (2007) Amplification Pattern of 2D Semi-Sine-Shaped valleys Subjected to Vertically Propagating Incident Waves,*CommunNumer Meth Engng*, 23:871–887

Lee VW, Manoogian ME and Chen S (2002) Antiplane SH-deformations near a surface rigid foundation above a subsurface rigid circular tunnel,*Earthquake Engineering and Engineering Vibration*, 1(1): 27-35

Lee VW, Chen S and Hsu IR (1999) Antiplane diffraction from canyon above a subsurface unlined tunnel, *ASCE Journal of Engineering Mechanic*, 25(6): 668-675

Lee VW and Karl J (1993) Diffraction of SV waves by underground, circular, cylindrical cavities, *International Journal of Soil Dynamics and Earthquake Engineering*, 11(8): 445-456

Lee VW (1988) Three-Dimensional Diffraction of Elastic Waves by a Spherical Cavity in an Elastic Half Space, I: Closed form solutions, *Soil Dynamics and Earthquake Engineering*, 7(3): 149-161

Lee VW andTrifunac MD (1979) Response of Tunnels to Incident SH-Waves, *Journal of the Engineering Mechanics Division*, 105(4): 643-659

Liang J, Ba Z and Lee VW (2007, a) Scattering of plane P waves around a cavity in poroelastic half space (i): analytical solution, *Journal of Earthquake Engineering and Engineering Vibration*, 27(1): 1–6

Liang J, Ba Z and Lee VW (2007, b) Scattering of plane P waves around a cavity in poroelastic half space (ii): numerical results,*Journal of Earthquake Engineering and Engineering Vibration*, 27(2): 1–11

Liu Q, Zhao M and Wang L (2013) Scattering of plane P, SV or Rayleigh waves by a shallow lined tunnel in an elastic half space,*Soil Dynamics and Earthquake Engineering*; 49: 52–63

Liu Q, Zhao M and Zhang C (2014) Antiplane scattering of SH waves by a circular cavity in an exponentially graded half space,*International Journal of Engineering Science*, 78: 61–72

Rodrıguez-Castellanos A, Luzo´nb F and Sanchez-Sesma FJ (2005) Diffraction of Seismic Waves in an Elastic, Cracked Halfplane Using a Boundary Integral Formulation,*Soil Dynamics and Earthquake Engineering,* 25: 827–837

Rodrıguez-Castellanos A, Sanchez-Sesma FJ, Luzon F and Martin R (2006) Multiple Scattering of Elastic Waves by Subsurface Fractures and Cavities,*Bulletin of the Seismological Society of America*, 96(4A):1359–1374

Sanchez-Sesma FJ (1985) Diffraction of Elastic SH Waves by Wedges, *Bull Seism Soc Am*, 75(5): 1435-1446

Sanchez-Sesma FJ (1987) Site effects on strong ground motion,*Soil Dynamics and Earthquake Engineering,* 6(2):124-132

Sohrabi-Bidar A, Kamalian M andJafari M K (2010) Seismic response of 3-D Gaussian-shaped canyons to vertically propagating incident waves,*Geophysical Journal International* 183:1429–1442

Trifunac M D (1972) Scattering of Plane SH Waves by a Semi-Cylindrical Canyon,*Earth Eng and StrucDyn*, 1:267-281

Yiouta-Mitra P, Kouretzis G, Bouckovalas G andSofianos A (2007) Effect of Underground Structures in Earthquake Resistant Design of Surface Structures, *Dynamic Response and Soil Properties, Geo- Denver: New Peaks in Geotechnics*

Zhao C andValliappan S (1993) Incident P and SV Wave Scattering Effects under Different Canyon Topographic and Geological Conditions,*Int J NumAnaly Methods in Geomechanics*, 17(2): 73- 94