A study on soil–structure interaction analysis in canyon-shaped topographies

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Abstract. In this paper, a coupled finite and infinite element system is used to study the effects of canyon-shaped topography and geotechnical characteristics of the soil on the dynamic response of free surface and of 2-D soil–structure systems under ground motion. A parametric study is carried out for canyon-shaped topographies. It is concluded that topographic conditions may have important effects on the ground motion along the canyon. Geotechnical properties of the soil also have significant amplification effects on the whole system motion, which cannot be neglected for design purposes. Thus, the dynamic response of both free surface and a soil–structure system are primarily affected by surface shapes and geotechnical properties of the soil. Location of the structure is another parameter affecting the whole system response.

Keywords. Finite elements; infinite elements; elastodynamics; topography; site effects; soil–structure interaction.

1. Introduction

The soil–structure interaction is a well-known phenomenon especially in dynamic analysis and design of structures when subjected to various dynamic forces such as earthquakes. In the literature, a large number of studies are presented to emphasize the significance of soil–structure interaction. The soil–structure interaction has considerable influence on the dynamic response of structures especially supported on medium to soft soil conditions. On the other hand, it has been well-understood in the last three decades that the surface shapes and geological features of the soil medium have a significant influence on strong ground motion and dynamic response of structures, especially massive structures such as bridges and dams during seismic events. The effects of topographic irregularities have been repeatedly shown to be detrimental to structures. In the event of a strong earthquake, structures located at the top of hills, ridges or canyons, suffer more considerable damage than those located at the

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base. However, structures standing near the edge of irregular soil surfaces, such as cliffs and canyons, are affected significantly more than those at some distance from the edge. Severe structural damage due to topographic features has been observed in numerous earthquakes: Tokachi-oki (Japan) 1968; San Fernando (USA) 1971; Friuli (Italy) 1976; Miyagiken-oki (Japan) 1978; Irpinia (Italy) 1980; Chile 1985; Eje-Cafetero (Colombia) 1998; Athens (Greece) 1999 and Bingöl (Turkey) 2003. See details in Ohtsuki & Harumi 1983; Ohtsuki *et al* 1984; Celebi 1987; Kawase & Aki 1990; Gazetas *et al* 2002; Assimaki *et al* 2005; Ulusay & Aydan 2005. It has been considered that such severe structural damage is due to the large amplification of seismic waves associated with local topography and surface soil properties (Ohtsuki & Harumi 1983; Ohtsuki *et al* 1984).

There are a large number of analytical and numerical studies which have provided supporting evidence of the significance of topographical effects. The finite difference method is used by Boore (1972) to model site effects for P-SV waves and for an arbitrary shape of topographical feature. Analytical solutions are obtained for SH wave scattering for semi-cylindrical canyons by Trifunac (1973) and for semi-elliptical canyons by Wong & Trifunac (1974). The scattering and diffracting SH wave problems are extended by Wong & Jennings (1975) to arbitrarily-shaped canyons under ground motion by using boundary integral techniques and Fourier transforms. The diffraction of P, SV and Rayleigh waves by a circular canyon and an elliptical canyon is studied by Wong (1979). Effects of topographical and subsurface inhomogeneities are examined by Ohtsuki & Harumi (1983) on seismic SV waves and by Ohtsuki *et al* (1984) on seismic Rayleigh waves by using the hybrid method combining a particle model with finite elements. The effects of canyon topographies and geological conditions on strong ground motion are studied by Chuhan & Chongbin (1988) by using finite and infinite elements. A procedure is presented by Avilés & Pérez-Rocha (1998) for representing the site effects and soil-structure interaction in alluvial valleys by using the one-dimensional (1-D) theory of shear wave propagation. An experimental study carried out in 1993 near Corinth in Greece is presented by LeBrun *et al* (1999) to investigate a scale effect of the dimensions of the hill, by comparing the results of an experiment carried out in 1992 around Sourpi and to compare the observed amplification level with those already reported in the literature. Complex site effects are studied by Chávez-García & Faccioli (2000) to explore how to modify seismic spectra in order to take into account site effects of a two-dimensional (2-D) nature on sine-shaped sedimentary valleys. They concentrated on evaluating the additional amplification that 2-D site effects produced on ground motion. Gazetas *et al* (2002) carried out a case study to determine topography and soil effects in Adámes region during 1999 Parnitha (Athens) Earthquake. Havenith *et al* (2003) examined the effects of various geological factors on the seismic ground motion, such as the presence of surface layers, 2-D and 3-D topography and of a fault zone located at the bottom of the hill. A case-study is carried out by Assimaki *et al* (2005) to illustrate the role of material inhomogeneity, soil-structure interaction and local stratigraphy in altering the energy mechanism at the different topographies. Another case-study is carried out by Stewart & Sholtis (2005) to determine the effects of topography and geological amplification on single-faced slopes. Nguyen & Gatmiri (2007) carried out a parametric study on the 2-D scattering of seismic waves by arbitrary topography by using boundary and finite elements. Gatmiri & Arson (2008) carried out a parametric study to quantify the site effects in 2-D sedimentary valleys by using an optimized 2-D boundary and finite element method.

In the evaluation of the topographic effects, previous studies generally focused to quantify crest/base amplification for free soil surface, but limited papers dealt with the soil-structure interaction associated with local topographic conditions (e.g. Assimaki *et al* 2005;

Avilés & Pérez-Rocha 1998). However, existence and location of a structure on irregular soil surface may also have an effect on dynamic response of the system. Therefore, there is a need for a better understanding of the influence of soil–structure interaction associated with local topographic irregularities on both strong ground motion and dynamic response of structures. Aiming at this goal, a parametric study is carried out in this study to determine the effects of surface shapes and geotechnical properties of the soil on the dynamic response of 2-D soil–structure systems which have different canyon-shaped topographies. A numerical procedure is employed to evaluate whole system response. In the numerical treatment, finite and infinite elements with three wave types (Yerli *et al* 1998) are used. This infinite element type includes three different wave (pressure (P), shear (S) and Rayleigh) character (Yerli *et al* 1998). In the modelling of the structure and near soil region, finite elements are used, while far off soil region is modelled by infinite elements. The soil region is assumed to be homogeneous, isotropic and linear-elastic layer. Because of the damping effect is not under particular interest, it is not taken into account. For the ground motion acceleration data acting horizontally on the soil-rigid base interface, Ricker–Wavelet signal is chosen. A parametric study is carried out to determine the effects of topography and soil properties, on the response of both soil and the structure. The formulation is performed in the Laplace transform domain. Solution in the time domain is obtained by using Durbin's numerical inverse Laplace transform technique (Durbin 1974).

2. Equation of motion in Laplace transform domain

In the 2-D soil–structure interaction analysis under ground motion, formulations are made depending on relative displacements. Equilibrium equations for 2-D problems under ground motion are given by

$$\begin{aligned}\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + f_x - \rho \frac{\partial^2 u}{\partial t^2} &= 0 \\ \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + f_y - \rho \frac{\partial^2 v}{\partial t^2} &= 0,\end{aligned}\quad (1)$$

where u and v are total displacement components and defined as:

$$\begin{aligned}u &= u_r + u_g \\ v &= v_r + v_g.\end{aligned}\quad (2)$$

In equation (2), u_r and v_r are relative displacements and u_g and v_g are displacements due to ground motion. When (2) are substituted in (1), equilibrium equations are obtained as follows:

$$\begin{aligned}\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + f_x - \rho \frac{\partial^2 u_r}{\partial t^2} - \rho a_{gx} &= 0 \quad \left(a_{gx} = \frac{\partial^2 u_g}{\partial t^2} \right) \\ \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + f_y - \rho \frac{\partial^2 v_r}{\partial t^2} - \rho a_{gy} &= 0 \quad \left(a_{gy} = \frac{\partial^2 v_g}{\partial t^2} \right),\end{aligned}\quad (3)$$

where a_{gx} and a_{gy} are horizontal and vertical ground accelerations, respectively. Now, applying Laplace transformation (Yerli *et al* 1998) to (3) and integrating over an element multiplying

by weighting factors, afterwards Galerkin's approach is employed, the governing differential equations are expressed in integral form as:

$$h_e \int_{A_e} \{\delta \bar{\epsilon}\}^T \{\bar{\sigma}\} dA_e + s^2 h_e \int_{A_e} \rho \left\{ \begin{matrix} \delta \bar{u}_r \\ \delta \bar{v}_r \end{matrix} \right\}^T \left\{ \begin{matrix} \bar{u}_r \\ \bar{v}_r \end{matrix} \right\} dA_e = h_e \int_{A_e} \left\{ \begin{matrix} \delta \bar{u}_r \\ \delta \bar{v}_r \end{matrix} \right\}^T \left\{ \begin{matrix} \bar{f}_x \\ \bar{f}_y \end{matrix} \right\} dA_e \\ + h_e \int_S \left\{ \begin{matrix} \delta \bar{u}_r \\ \delta \bar{v}_r \end{matrix} \right\}^T \left\{ \begin{matrix} \bar{t}_x \\ \bar{t}_y \end{matrix} \right\} dS - h_e \int_{A_e} \rho \left\{ \begin{matrix} \delta \bar{u}_r \\ \delta \bar{v}_r \end{matrix} \right\}^T \left\{ \begin{matrix} \bar{a}_{gx} \\ \bar{a}_{gy} \end{matrix} \right\} dA_e, \quad (4)$$

where h_e is element thickness, ρ is mass density and s is Laplace transform parameter. Overbar represents the Laplace transform of related quantity. Equation (4) is the usual virtual work principle in the Laplace transform domain. In the numerical treatment, by using finite element approximation, the system equations of motion in the Laplace transform domain are obtained as:

$$([\bar{K}] + s^2[\bar{M}])\{\bar{U}\} = \{\bar{P}\}, \quad (5)$$

in which $[\bar{K}]$ and $[\bar{M}]$ are system stiffness and mass matrices, respectively; $\{\bar{P}\}$ is system load vector and $\{\bar{U}\}$ is system displacement vector that contains all the nodal displacements. These matrices can be obtained by combining the element sub-matrices of the form:

$$[\bar{K}]_e = h_e \iint_{A_e} [\bar{B}]^T [D] [\bar{B}] dA_e \\ [\bar{M}]_e = h_e \iint_{A_e} \rho [\bar{N}]^T [\bar{N}] dA_e \\ [\bar{P}]_e = -h_e \iint_{A_e} \rho [\bar{N}]^T \left\{ \begin{matrix} \bar{a}_{gx} \\ \bar{a}_{gy} \end{matrix} \right\} dA_e. \quad (6)$$

In the presence of viscous damping in the material, the material constants in material matrix $[D]$ are to be multiplied by $(1 + \zeta s)$. Here, ζ is damping coefficient.

3. Formulations of finite and infinite elements

In dealing with the interaction problems with geometrical irregularities and different geological properties, a coupling system of finite and infinite elements has proved to be an effective procedure (Chuhan & Chongbin 1987, 1988). In this study, a standard eight-node isoparametric, quadratic plane element is used as the finite element. Figure 1 shows the eight-node isoparametric, quadratic finite element. The chosen finite element formulations are well-known. Therefore, the formulations need not be discussed in detail, only interpolation functions (Reddy 1993) are given as:

$$N_i = \frac{1}{4}(1 + \xi \xi_i)(1 + \eta \eta_i)(\xi \xi_i + \eta \eta_i - 1) \quad (\text{corner nodes}) \\ N_i = \frac{1}{2}(1 - \xi^2)(1 + \eta \eta_i) \quad (\text{side nodes, } \xi_i = 0) \\ N_i = \frac{1}{2}(1 + \xi \xi_i)(1 - \eta^2) \quad (\text{side nodes, } \eta_i = 0). \quad (7)$$

Figure 1. Eight-node isoparametric finite element.

For the discretization of the far off soil region, infinite elements that include three different wave types (P, S and Rayleigh waves) have been used. Figure 2 shows infinite element with three wave types. The shape functions of dynamic infinite elements are constructed by using a wave-propagation function that represents the amplitude attenuation and phase delay in the direction extending to infinity. The mapping functions of the infinite elements (Chuhan & Chongbin 1987) are given as:

$$\begin{aligned} M_1 &= \frac{1}{2}(\xi - 1)(\eta - 1) \\ M_2 &= 0 \\ M_3 &= \frac{1}{2}(1 - \xi)(\eta + 1) \\ M_4 &= \frac{1}{2}\xi(1 - \eta) \\ M_5 &= \frac{1}{2}\xi(1 + \eta). \end{aligned} \quad (8)$$

In the Laplace transform domain, the horizontal ($\bar{u}$) and vertical ($\bar{v}$) displacement fields of

Figure 2. Infinite element with three wave types.

the infinite element can be written as:

$$\bar{u} = \sum_{i=1}^7 \bar{N}_i \bar{u}_i \quad \bar{v} = \sum_{i=1}^7 \bar{N}_i \bar{v}_i, \quad (9)$$

where $\bar{N}_i$: displacement shape functions of the infinite element, and they can be expressed as:

$$\begin{aligned} \bar{N}_1(\xi, \eta, s) &= \bar{P}_1(\xi, s) \left[\frac{1}{2} \eta(\eta - 1) \right] \\ \bar{N}_2(\xi, \eta, s) &= \bar{P}_2(\xi, s) (1 - \eta^2) \\ \bar{N}_3(\xi, \eta, s) &= \bar{P}_3(\xi, s) \left[\frac{1}{2} \eta(\eta + 1) \right] \\ \bar{N}_k(\xi, \eta, s) &= \bar{P}_k(\xi, s) \left[\frac{1}{2} (1 - \eta) \right] \quad k = 4, 6 \\ \bar{N}_k(\xi, \eta, s) &= \bar{P}_k(\xi, s) \left[\frac{1}{2} (1 + \eta) \right] \quad k = 5, 7, \end{aligned} \quad (10)$$

where $P_k(\xi, s)$ is the wave-propagation function. Based on the derivation for the harmonic infinite elements given by Chuhan & Chongbin (1987), the wave-propagation functions can be approximately represented by the superposition of plane waves. Thus, their general form in the Laplace transform domain is expressed by Yerli *et al* (1998) as:

$$P_k(\xi, s) = ae^{-(\alpha+\beta_1)\xi} + be^{-(\alpha+\beta_2)\xi} + ce^{-(\alpha+\beta_3)\xi} \quad \beta_k = \frac{s}{c_k} L, \quad (11)$$

where α : decay parameter; c_k : wave velocities and a, b, c are undetermined constants. To determine the constants a, b and c , detailed formulations are given in Yerli *et al* (1998) by using (9).

Calculation of the infinite element stiffness and mass matrices is performed numerically. For the finite direction, the usual Gauss–Legendre integration technique is used. But infinite integrals are evaluated by using Newton–Cotes numerical integration scheme (Bettess & Zienkiewicz 1977).

4. Parametric studies

The effects of topographic irregularities and soil properties on the dynamic response of the 2-D soil–structure systems which have canyon-shaped are evaluated under ground motion. Diverse shapes of soil–structure systems are studied. A schematic representation of the numerical models is shown in figure 3. Here, T_0 is the reference soil–structure system which has a regular surface shape. Other topographic shapes are considered as $L_1/L = 0$ (Triangle), $L_1/L = 0.25$ (Trapezium), $L_1/L = 0.50$ (Trapezium), $L_1/L = 0.75$ (Trapezium) and $L_1/L = 1$ (Rectangle), where L_1 and L represent half-width at the base of the canyon and half-width at the surface of the canyon, respectively. However, three different height-width ratios are considered, i.e. $H/L = 0.25$, $H/L = 0.50$ and $H/L = 1$, where H represents height of the canyon. In the soil–structure systems, the structure is modelled as a solid block

Figure 3. The soil–structure systems with different topographies.

with mass density $\rho_{\text{str}} = 2400 \text{ kg/m}^3$, Poisson's ratio $\nu = 0.20$ and modulus of elasticity $E_{\text{str}} = 30000 \text{ MPa}$, accounting for the macroscopic properties of the structural system. The height of the structure is 12 m. for all simulations, corresponding to a 4-story building with 3 m mean story-to-story spacing. It is noted that in all simulations, no relative displacement is allowed at the soil–structure interface. The soil region is assumed as homogeneous, isotropic and linear-elastic material. Reference soil properties are assumed as mass density $\rho_s = 2000 \text{ kg/m}^3$, Poisson's ratio $\nu = 0.35$ and modulus of elasticity $E_s = 200 \text{ MPa}$. In the literature, it is reported that the modulus of elasticity of the soil types are generally between 50 and 250 MPa (Bowles 1988). Four different soil types are taken into account, i.e. $G1/G = 1$, $G2/G = 2$, $G3/G = 4$ and $G4/G = 10$, where G represents shear modulus of the soil types. On the other hand, the material properties are not crucial because only a comparative study has been carried out to determine the effect of topographical irregularities and soil properties on the whole soil–structure system response relative to those of the soil–structure system with no slope ($T0$).

For the ground motion acceleration data acting horizontally on the soil-rigid base interface, Ricker–Wavelet signal is chosen. The input signal is shown in figure 4. Its equation in time is given as

$$f(t) = A_0(1 - 2a^2)e^{-a^2}, \quad (12)$$

Figure 4. Ricker–Wavelet signal.

Figure 5. Typical finite-infinite element discretization of the soil-structure systems.

where $a = (t - t_s)/t_0$; t_s is the time at which the maximum occurs; A_0 is the amplitude and is fixed to 1, t_0 corresponds to the dominant period of the wavelet. In this study, t_0 was set to $1/\pi$, which corresponds to a dominant frequency of the wavelet near 1 Hz. The time lag t_s was taken equal to $3t_0$ ($t_s = 3/\pi$) as in Estorff *et al* (1990).

In the parametric studies, a numerical procedure is employed to evaluate whole system response. In the numerical treatment, finite and infinite elements are used. For the discretization of the structure and the near soil region, standard eight-node isoparametric, quadratic plane finite elements are used. In the discretization of the far off soil region, infinite elements that include three different wave types (P, S and Rayleigh waves) with a decay parameter are used. Some of the previous studies have shown that the effects of decay rates of different waves in the infinite elements are not sensitive in the numerical analysis (Chuhan & Chongbin 1987). Horizontal and vertical extensions of the finite element boundaries which have an effect on the accuracy of the results are discussed by Chuhan & Chongbin (1988). Typical finite-infinite element discretization of the systems is shown in figure 5. For the finite and infinite elements presented earlier, a computer program coded in FORTRAN90 programming language is prepared. The efficiency and accuracy of the program code were published by Düzgün (2007). The solutions are obtained in the Laplace domain. Then using Durbin's numerical inverse Laplace transform technique (Durbin 1974), solutions are transformed into time domain.

In the analysis, relative horizontal displacements are computed at the top and bottom of the structure (points A and B) and upper and bottom edge of the slope (points C and D). Special attention is paid to evaluate the amplification of waves by the local soil properties and the amplification due to the topographical irregularities. Interest is focused on parameters determining dynamic behaviour of the soil-structure system under ground motion: free surface response, influence of canyon-shape and depth, location of the structure and soil properties. In this way, effects of these parameters on the system response are evaluated by comparing with those of the soil-structure system with no slope (T_0). Displacements are calculated at every 0.04 s. Maximal values of displacements, calculated in the time interval [0 s; 5.12 s] are considered. It should be noted that the results obtained from the parametric studies are relative quantities.

5. Results and discussion

The effects of surface shapes and geotechnical properties of the soil on dynamic response of both free soil surface and the soil–structure systems are parametrically evaluated. In the literature, it is reported that topographical effects are mainly caused by wave focusing in

Figure 6. Influence of surface shape on horizontal displacements (a) for $H/L = 0.25$, (b) for $H/L = 0.5$ and (c) for $H/L = 1$.

surface irregularities and interference between incident and reflected plane waves with surface waves (Gazetas *et al* 2002). The amplification mechanism due to topographic irregularities is reported in Gazetas *et al* (2002) that the wave field affecting the surface motions consists of: (a) the vertically propagating incident SV wave; (b) waves reflecting at the horizontal ground surface and at the sloping surface of the cliff; (c) waves transmitted through, and reflected at layer interfaces, and (d) diffracted waves. Diffracted waves include: (i) SP waves that are

Figure 7. (Continued).

Figure 7. Influence of canyon height on horizontal displacements (a) for triangle, (b) for trapezium ($L1/L = 0.25$), (c) for trapezium ($L1/L = 0.5$), (d) for trapezium ($L1/L = 0.75$) and (e) for rectangle.

generated at the cliff surface due to the critical or near-critical incidence of the vertical SV waves. Such waves propagate upward along the sloping surface and interfere with direct SV waves; (ii) Rayleigh waves generated at the crest of the hill. The interference between these various types of direct and diffracted waves generates an increased motion near the crest and rapidly varying motion along the horizontal ground surface. However, amplification is also affected by geological properties (Chuhan & Chongbin 1988; Gatmiri & Arson 2008). It is also reported by Nguyen & Gatmiri (2007) and Gatmiri & Arson (2008) that surface shape and depth are very effective on whole system motion. The results are obtained in this study correspond with those of the literature. The results show that surface shapes of a soil stratum have a significant influence on dynamic response of both free soil surface and the soil–structure systems. Geotechnical properties of soil and location of the structure also have effect on the system behaviour. The results also show that structures located at the top of irregular topographies suffer considerable damage than those located at the base. Moreover, structures standing near the edge of irregular topographies are affected more than those at some distance from the edge, in the event of a ground motion. It is reported that the points near the edge of irregular soil surfaces are more critically affected than those at some distance from the edges (Assimaki *et al* 2005; Stewart & Sholtis 2005). Detailed results are shown below.

Figure 8. (Continued).

Figure 8. Influence of surface shape and location of the structure on horizontal displacements for $H/L = 0.25$.

Figures 6–7 illustrate free surface motion of different canyon-shapes with three ratios $H/L = 0.25, 0.50$ and 1 (the height H varies while the half-width L remains constant). Here, U_x and U_{xT0} represent horizontal displacements of other canyon-shapes and of the reference system ($T0$) without structure, respectively. According to the results, horizontal displacements are strongly affected by surface shapes. Horizontal motions tend to be attenuated at the canyon center and slightly amplified at the upper edges. Horizontal displacements decrease inside the canyon, but increase at the upper edge of the canyon depend on $L1/L$ ratio and height of the canyon. Horizontal displacements, however, decrease when the x/L ratio increases, and gets closer to those of the reference system ($T0$) without structure. For the same dimensions, the triangular canyon-shape is the least affected while the rectangular canyon-shape is the most affected. The site effects are also reinforced by height of the canyon. It is shown that the deeper canyon has the more amplification effect at the edges and the more attenuation effect is seen inside the canyon. These results agree well with the literature (Nguyen & Gatmiri 2007; Gatmiri & Arson 2008). When H/L ratio gets increases: (i) the horizontal displacements inside the canyon decrease and reach local minimum, (ii) close to the edges, horizontal displacements increase, but the distance from the centre of the canyon, the horizontal displacements decrease and are almost become equal to those of the reference system ($T0$) without structure.

It is shown that surface shapes of the soil layer also have an effect on dynamic response of whole system, depending on the location of the structure on the soil layer. The results are summarized in figures 8–11 for different surface shapes and for different H/L ratios. Here, horizontal axis represents location of the structure. According to the results, location of the structure is one of the parameters affecting dynamic response of the soil–structure system. In the reference system ($T0$), location of the structure has a minor effect on the system behaviour but in the other systems (Triangle; $L1/L = 0.25$; $L1/L = 0.50$; $L1/L = 0.75$ and Rectangle), location of the structure has more effect on the whole system response. When location of the structure gets closer to upper edge of the canyon, the amplification of horizontal displacements at the upper and bottom sides of the structure (points A and B) and the upper edge of the canyon (point C) increase, but at the bottom edge of the canyon (point D) is

Figure 9. (Continued).

Figure 9. Influence of surface shape and location of the structure on horizontal displacements for $H/L = 0.50$.

slightly influenced, and so, horizontal displacements reach a local maximum near upper side of the canyon. On the other hand, when the structure is located inside the canyon, smaller horizontal displacements are computed than those of the upper side of the canyon. In this case, location of the structure has a minor effect on the system behaviour. The most effect is seen when the structure is located close to the upper edge of the canyon. These results support the documented observations from destructive seismic events reported in the literature (Ohtsuki & Harumi 1983; Ohtsuki *et al* 1984; Celebi 1987; Kawase & Aki 1990; Gazetas *et al* 2002; Assimaki *et al* 2005; Ulusay & Aydan 2005). However, surface shape of a soil stratum is another parameter affecting the system response. Site effects are reinforced by surface shapes. According to the results obtained from the parametric studies, the overall trends of amplification and attenuation are strongly dependent on the surface geometry. Horizontal displacements decrease inside the canyon, but increase at the upper edges of the canyon depending on $L1/L$ ratio and height of the canyon. Horizontal displacements, however, decrease when the x/L ratio increased. When $L1/L$ ratio gets greater: (i) an amplification occurs at the upper and bottom sides of the structure (points A and B) and at the upper edge of the canyon (point C) in the case of $x/L > 1$, while an attenuation occurs at the points A, B and C in the case of $x/L < 1$, (ii) horizontal displacements at the bottom edge of the canyon (point D) decrease. The site effects are also reinforced by height of the canyon. When H/L ratio gets increases: (i) the horizontal displacements of the points A, B, C and D inside the canyon decrease, (ii) close to the upper edges, horizontal displacements of the point A, B and C increase, but the distance from the centre of the canyon horizontal displacements decrease, (iii) the horizontal displacements of the point D at the upper side of the canyon systematically decrease. It is shown that for stiffer slopes, the amplification at the upper side and attenuation at the bottom side of the slope are accentuated. Displacement amplifications get stronger as the slope become steeper.

Geotechnical properties of the soil also have an effect on the whole system motion. In order to determine the effect of the geotechnical properties of the soil on the dynamic response of both free soil surface and the soil–structure systems, four different soil types are studied, i.e. $G1/G = 1$, $G2/G = 2$, $G3/G = 4$ and $G4/G = 10$, where G represents shear modulus of

Figure 10. (Continued).

Figure 10. Influence of surface shape and location of the structure on horizontal displacements for $H/L = 1$.

Figure 11. (Continued).

Figure 11. Influence of canyon height and location of the structure on horizontal displacements (for rectangle).

the soil types. Figures 12–13 illustrate the effect of the soil properties on the dynamic response of the free surface and of the soil–structure systems, respectively. To explain briefly, only one soil–structure system which has $H/L = 0.50$ is taken into account. The results show that horizontal motion of the systems is also affected by the geotechnical properties of the soil. According to the results, as the ratio $G\#/G$ increases, i.e. the soil gets stiffer, maximal values of the horizontal displacements decrease. This fact indicates that, the greater amplification can be expected as the soil gets looser. The soft soils significantly aggravate the amplification. From these results, it can be concluded that soil–structure interaction on stiff soils can filter the horizontal motion.

6. Conclusion

Effects of topography and soil properties on dynamic response of both free surface and soil–structure system are evaluated. A parametric study is carried out for canyon-shaped

topographies to characterize topographical effects by coupling finite and infinite elements with three wave types. Special attention is paid to evaluate the amplification of waves by the local soil properties and the amplification due to the topographical irregularities. Interest is focused on parameters determining dynamic behaviour of the soil–structure system under

Figure 12. (Continued).

Figure 12. Effects of soil properties on horizontal displacements of the free surface.

ground motion: free surface response, influence of canyon-shape and depth, location of the structure and soil properties. The effects of these parameters on the system response are evaluated by comparing with those of the soil–structure system which has regular surface shape ($T0$). According to the results, there is no doubt that local topographic conditions play an important role on ground motion and should be explicitly considered in the design

purpose. Geotechnical properties and location of the structure also play a role on the system behaviour. It is concluded that: (i) ground motion is generally amplified at the upper edges of canyons, but it is systematically attenuated at the canyon center. (ii) The effects of the surface shapes are strongly dependent on the ratios $L1/L$ and H/L . Displacement amplifications get stronger as the slope become steeper. (iii) Location of the structure has also effect on the whole system response. When location of the structure gets closer to upper edge of the canyon, the

Figure 13. (Continued).

Figure 13. Effects of soil properties on horizontal displacements of the soil–structure system (for rectangle).

amplification of displacements increase. In this case, horizontal displacements reach a local maximum near upper sides of the canyon, but when the structure is located at inside the canyon, location of the structure has a minor effect on the system behaviour. Therefore, in the event of a ground motion, structures located at the top of irregular topographies, can suffer more damage than those located at the base, moreover, structures standing near the edge of irregular topographies can affect more than those at some distance from the edge. (iv) Geotechnical properties of the soil are also effective on the displacement amplification. Soft soil layers significantly aggravate the amplitude of the motion, which cannot be neglected for design purposes, but as the soil become stiffer, the amplification decreases. (v) Weak motion data can be used as a guide in studies, but they are inadequate to describe topographical effects associated with real seismic events. (vi) Soil–structure interaction on stiff soil regions filter the horizontal motion.

There are a number of different parameters affecting the system motion, such as exciting frequency, different landscape parameters, inclination angle, effect of damping, etc. for different shaped canyons. Hence, the 2-D model used in this study may not be quite appropriate for some real cases. Nevertheless, the results obtained in this study correspond with those in the literature. Moreover, since the effects of canyon-shape and width to height ratios on dynamic response of a soil–structure system are studied, the results could give an insight into or understanding of topographical effects of the canyons.

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