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Effects of canyon topographic conditions on ground motion due to harmonic P and SV wave incidences

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ABSTRACT: A numerical model for wave scattering problems due to P and SV wave incidences is outlined in this paper. After introducing the present model, a general parametric study on the displacement patterns along the canyons of different shapes due to harmonic P and SV wave incidences is also performed. The numerical results from this investigation demonstrated that the shape of a canyon may have important effects on the displacement patterns along the canyon and thus a rectangular canyon is not appropriate as a dam site due to its high amplification effects on incident waves.

1. INTRODUCTION

As recent studies (Geli et al., 1988, Wong, 1982, Zhao, 1987) related to surface motion of wave propagation demonstrated, the topographic and geologic features of a canyon have a significant influence on ground motions. This fact might have an important impact on the dynamic response analysis of such large scale structures as dams and bridges because free field motion might have obvious different amplitudes and phases along the abutment on which the structure will be founded. The recent studies (Zhao, 1987) also illustrated that the differences of the amplitudes and phases may affect the dynamic response of a structure dramatically, so that a detailed study on the distributions of free field motions along a natural canyon is needed and this work may have great significance in engineering practice.

Taking into the consideration the topographic and geologic complexities and the features of infinite extension of natural canyons, a numerical model for wave scattering problem in infinite media due to P and SV wave incidences was presented to simulate the near and far field of the canyon. Firstly, the method is outlined in this paper and then several topographic conditions including trapezoidal and V-shaped canyons with different ratios of top width to height, L/H, are considered using P and SV waves propagating from different incident angles. The amplification factors and patterns of displacements along canyon surfaces have been obtained.

2. SIMULATION OF INFINITE MEDIA

In order to analyse dynamic soil-structure interaction problems,. a numerical model for wave scattering problems in infinite media due to SH wave incidences has been presented and the detailed principle and the verification of the model have been provided previously (Zhao et al., 1989). This paper extends mainly the previously developed model to make a general parametric study of the effects of canyon topographic conditions on ground motion due to P and SV wave incidences.

In dealing with the wave propagation problems in infinite media with geometrical irregularities and geologic complexities, a finite and infinite element coupled system has been proven to be very effective (Zhang and Zhao, 1987, Zhao et al., 1989, 1992). The 8-node isoparametric finite element is used in this study and its formulations are well known and need not be repeated. Since the previous dynamic infinite element is used to simulate SH-wave scattering problems and has only one wavenumber to represent the displacement shape function of the element, it is necessary to develop another kind of dynamic infinite element here, in which P-wavenumber and SV-wavenumber are simultaneously used to express the displacement shape function of the element due to the coexistence of both waves in the wave scattering problems along a canyon.

For a 2D dynamic infinite element shown in Fig.-1, since the sides of the element in the infinite direction can be represented by straight lines, only four nodes are sufficient to exactly describe the geometry of the infinite element in the global coordinate system. Therefore, the mapping relationship between the global coordinate system and the local one for this element can be defined as

$$\left.\begin{aligned} x &= \sum_{i=1}^{6} M_i x_i \\ y &= \sum_{i=1}^{6} M_i y_i \end{aligned}\right\} \quad (1)$$

where M_i (i=1,2, ··· 6) is mapping function of infinite element and can be expressed as

$$\left.\begin{aligned} M_1 &= \frac{1}{2}(\xi - 1)(\eta - 1) \\ M_2 &= M_5 = 0 \\ M_3 &= -\frac{1}{2}(\xi - 1)(\eta + 1) \\ M_4 &= \frac{1}{2}\xi(\eta + 1) \\ M_6 &= \frac{1}{2}\xi(\eta - 1) \end{aligned}\right\} \quad (2)$$

It is noted that the reason that M_2 and M_5 are forced to be zero is due to the convenient expression of the coordinate transformation relationship for the infinite element.

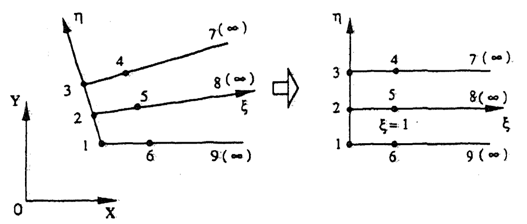

Figure-1 Infinite element

Considering the compatibility condition of displacement on the connected interface between the finite element and infinite element, the displacement field for this 2D dynamic infinite element can be defined as

$$\left.\begin{aligned} u &= \sum_{i=1}^{6} N_i u_i \\ v &= \sum_{i=1}^{6} N_i v_i \end{aligned}\right\} \quad (3)$$

where N_i (i=1, 2, ...,6) are the displacement shape functions of the element and can be expressed as

$$\left.\begin{aligned} N_i &= P_i(\xi)\frac{\eta(\eta - 1)}{2} \quad (i=1,6) \\ N_i &= P_i(\xi)(\eta + 1)(\eta - 1) \quad (i=2,5) \\ N_i &= P_i(\xi)\frac{\eta(\eta + 1)}{2} \quad (i=3,4) \end{aligned}\right\} \quad (4)$$

where $P_i(\xi)$ (i=1,2,...,6) are the wave propagation functions of the element and can be expressed as

$$P(\xi) = e^{-\alpha\xi}(c_1 e^{-i\beta_1\xi} + c_2 e^{-i\beta_2\xi}) \quad (5)$$

where α is a nominal decay coefficient which is used to express the attenuation of wave amplitude due to the dissipation of wave energy in the material and the geometric divergence of the medium; β_i (i=1,2) are two nominal wave numbers in correspondence to S-wave and P-wave in 2D foundations and these nominal wave numbers are used to express the phase characteristics of the wave during propagation in the medium; c_i (i=1,2) are the constants to be determined to match the displacement field of the infinite element with the displacement field of the foundation.

Using the equality condition of the nodal displacements in any infinite side of the element in the ξ direction, these constants can be determined.

From the element described above, it is straightforward to get the mass matrix and stiffness matrix for the 2D dynamic infinite elements as follows

$$\left.\begin{aligned} [M]^e &= \int_0^{\infty}\int_{-1}^{1} [N]^T \rho [N] \, |J| \, d\xi d\eta \\ [K]^e &= \int_0^{\infty}\int_{-1}^{1} [B]^T [D^*] [B] \, |J| \, d\xi d\eta \end{aligned}\right\} \quad (6)$$

where $|J|$ is the Jacobian determinant which can be determined from the mapping relationship of the element in Eqs. (1) and (2). Substituting Eq. (2) and Eq. (4) and related expressions into Eq. (6), the following generalized integral will be encountered in the evaluation of the element mass and stiffness matrices of the infinite element.

$$I = \int_0^{\infty} F(\xi) e^{-(2\alpha + i\beta_j + i\beta_k)\xi} d\xi \quad (j = 1, 2, \; k = 1, 2) \quad (7)$$

This generalized integral can be calculated using numerical integration technique which is discussed in detail elsewhere (Zhao et al., 1989).

3. EFFECTS OF TOPOGRAPHIC CONDITIONS ON GROUND MOTION

The shapes of natural canyons are complex and variable and it is very difficult to include all canyon shapes in a study. For the sake of simplicity, two typical canyon shapes—V-shaped canyons and trapezoidal canyons—are considered in this study. By changing the canyon geometrical parameters, height, H and top width, L, the effects of topographic conditions on ground motions can be analysed.

3.1 Free Field Motion along V-shaped Canyons

In this case, a V-shaped canyon with different top width to height ratios L/H(1,3,5) is studied. As shown in Fig.-2, the near field of the canyon is simulated by 8 node isoparametric finite elements, while the far field of the canyon is modelled by dynamic infinite elements. Since the main concern is on the displacement pattern along the canyon, a unit plane harmonic wave with different wave types, different frequencies and different incident angles is selected in the analysis. The horizontal line (Y=0) is chosen as the wave input boundary where the input harmonic wave is transformed into dynamic loads according to elastic wave theory. The angle between the normal of the front of the plane harmonic wave and vertical line is defined as the wave incident angle θ. $\theta = 0$ means that the harmonic wave is vertically propagating into the wave input boundary, while the non-zero θ means that the harmonic wave is obliquely propagating onto the wave input boundary. In order to consider the effects of wave incident direction on ground motion, different values of θ have been selected in the analysis. For all cases, the following parameters are assumed: canyon height H=100m, the elastic modulus of the foundation rock $E = 24\times10^3$MPa, the corresponding Poisson's ratio $\nu = \frac{1}{3}$ and the unit weight $\gamma = 2.4\text{t/m}^3$. In order to investigate the effect of the frequency of the incident wave, the dimensionless frequency a_o is defined as

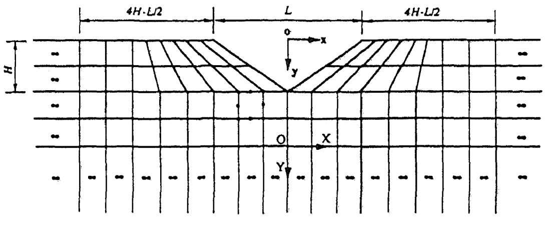

Figure-2 Discretized mesh for a canyon

$$a_o = \frac{\omega H}{\pi C_S} \tag{8}$$

where ω is the circular frequency of the incident harmonic wave; H is the height of the canyon, C_S is the S-wave velocity in the foundation.

Fig.-3 and Fig.-4 show the displacement amplitude distributions along V-shaped canyon due to SV wave incidence with different incident angles. In the case of vertical incident waves (Fig.-3), the symmetry of the displacement pattern along the canyon surface is very good for both SV wave and P wave incidences. Both the maximum value and the pattern of the displacement amplitudes are different for different canyon width to height ratios (L/H), especially for higher frequency wave incidence ($a_o = 1.0$). This fact illustrates that the canyon topographic condition has significant effects on free field motions along the canyon surfaces. The maximum value of displacement amplitude can reach over 3 for both SV wave and P wave vertical incidences. This maximum value appears at the top (x/H=0.5) of the narrower canyon (L/H=1). Even though the input waves are vertical incident waves, all A_U and A_V are not zero for SV and P wave incidences due to the wave mode conversion, and this phenomenon is different from the SH wave incident case (Zhang and Zhao, 1988). In the case of oblique incident waves (Fig.-4), the asymmetry of the displacement amplitude appears and the pattern of free field motion along the canyon surface is also different due to different canyon width to height ratios (L/H). Even though in the case of incident angle $\theta = 15^\circ$ (Fig.-4), the shield effect of the canyon is not obvious in comparison with SH wave incident case (Zhang and Zhao, 1988). This phenomenon can also be attributed to the wave mode conversion in the situation of SV and P wave incidences. Comparing the results obtained from vertical incident wave and the oblique incident wave, it can be concluded that the wave incident angle also affects the free field motion along the canyon surface.

3.2 Free Field Motion along Trapezoidal Canyon

In this situation, a new parameter, L_1, is introduced to express the width of the canyon bottom. The ratio, L_1/L, is selected to describe the exact shape of the canyon. Two extreme values, $L_1/L=0$ and $L_1/L=1$, can represent a V-shaped canyon and a rectangular canyon respectively. L/H=3 is assumed and $L_1/L=0$, 1/3, 1 are selected in this analysis. The wave input boundary and the parameters for the foundation are the same as in the last section. The harmonic waves with different wave modes, different frequencies and different incident angles are also considered as input waves.

Fig.-5 and Fig.-6 show the displacement amplitude distributions along V-shaped ($L_1/L=0$), trapezoidal ($L_1/L=1/3$) and rectangular ($L_1/L=1$) canyons due to SV and P wave vertical incidences with different frequencies. Moreover, SV and P wave oblique incidences with different incident angles are also calculated in this study and the related results are not provided here for the sake of saving space. In the case of a trapezoidal canyon, the canyon shape may affect the pattern of the displacement amplitudes along the canyon surface dramatically, especially for the rectangular canyon which gives the different pattern of ground motion from the V-shaped and trapezoidal canyons because of the rapid change of the canyon bank. The maximum value, which can reach 5 in the case of SV wave incidence (Fig.-5) and 3.4 in the case of P wave incidence (Fig.-6), is observed at the top of the rectangular canyon. This fact illustrates that the rectangular canyon results in greater amplification of ground motion than V-shaped and trapezoidal canyons. Thus, the rapid change of the canyon bank should be considered carefully in the structure aseismic analysis because it may induce extreme value of the free field motion and thus affect the response of the structure. On the other hand, it appears that the V-shaped and

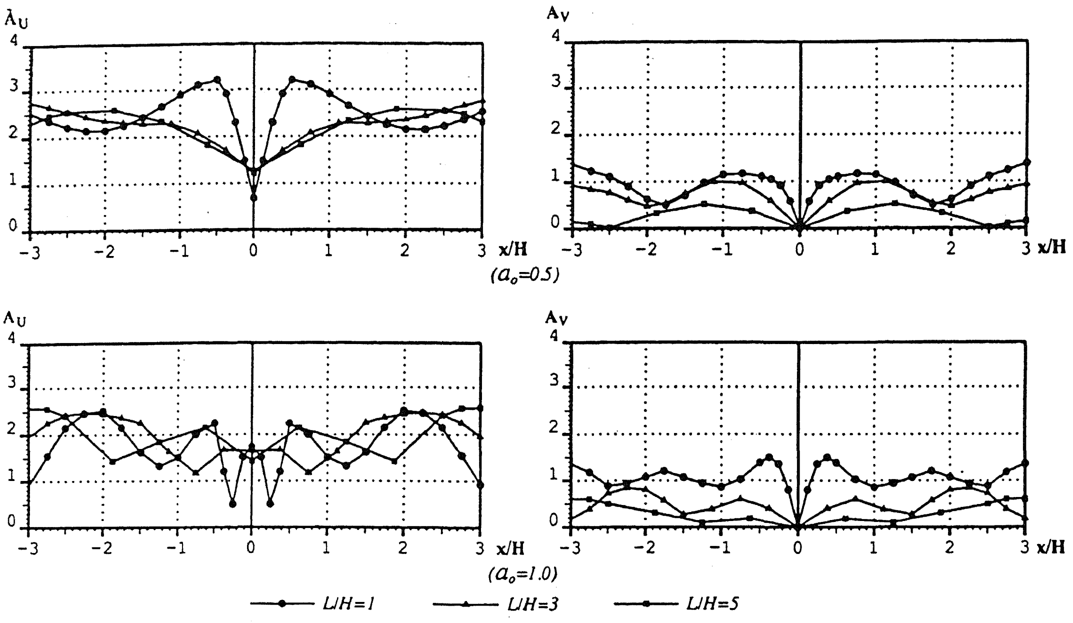

Figure-3 Distributions of displacement amplitudes along V-shaped canyons due to SV-wave incidence (θ = 0)

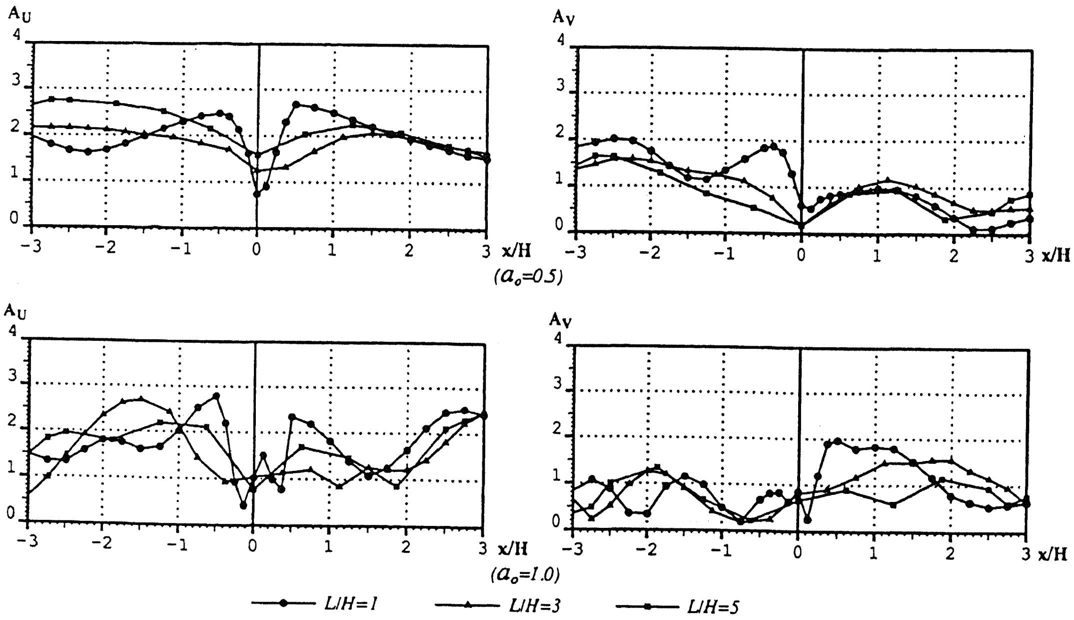

Figure-4 Distributions of displacement amplitudes along V-shaped canyons due to SV-wave incidence (θ = 15°)

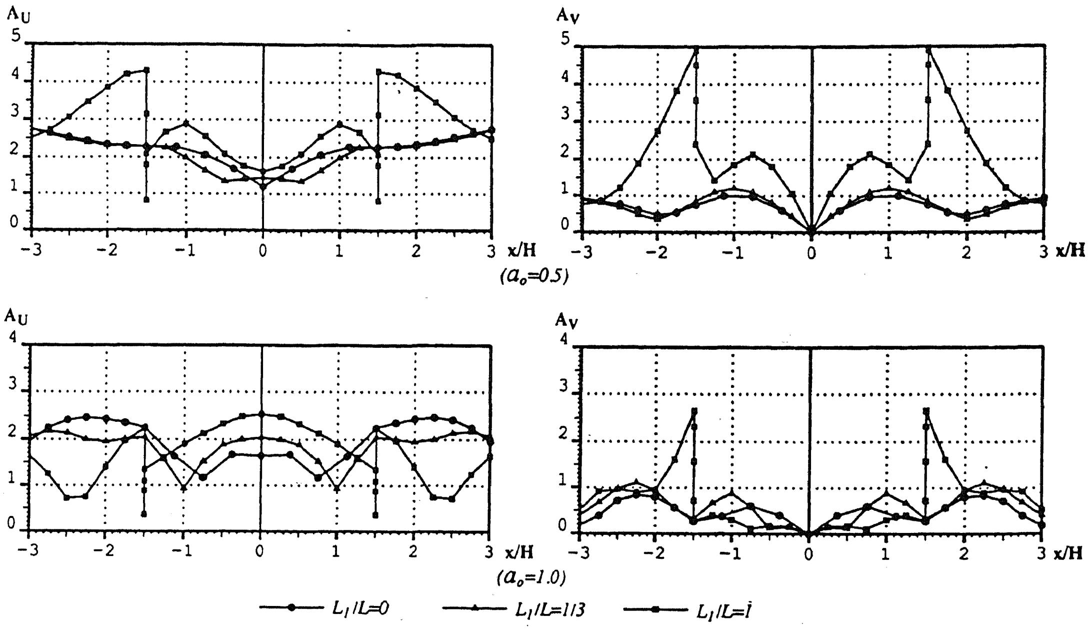

Figure-5 Distributions of displacement amplitudes along different shaped canyons due to SV-wave incidence (θ = 0)

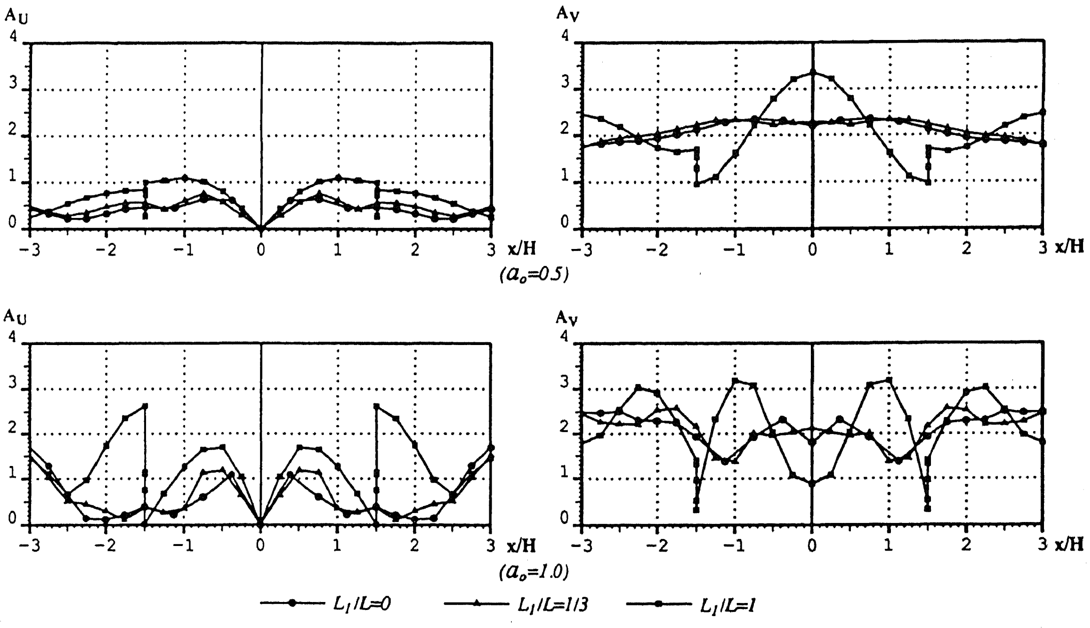

Figure-6 Distributions of displacement amplitudes along different shaped canyons due to P-wave incidence (θ = 0) trapezoidal canyons result in the roughly same overall trend of the ground motion although some difference may exist between them. Again, the symmetry and asymmetry of the free field motion distribution were observed for vertical and oblique incident waves. Since the canyon shape (L_1/L) and the top width to height ratio (L/H) of real situations are basically within the range studied, the above results might give an insight into and understanding of the topographic effects on ground motions. However, the fact that different amplification of different shaped canyons exists suggests that the 2D model used in the analysis may not be quite appropriate for real cases if the topographic irregularities along the longitudinal direction of the canyon are significant. In this case, a 3D model is needed for further study.

The fact that the topography of the canyon may affect the ground motion of the canyon illustrated that in the process of selecting a dam site, a comprehensive study related to the requirements on the economy and the safety of the dam should be made, from the viewpoint of structure aseismic design. Generally, a rectangular canyon is not appropriate to be a dam site due to its high amplification effect on incident waves.

4. CONCLUSIONS

The shape of a canyon has important effects on the displacement patterns along the canyon. Since the rectangular canyon results in greater amplification of ground motion than V-shaped and trapezoidal canyons, it is recommended that the rapid change of the canyon bank be considered carefully in the structure aseismic analysis because it may induce extreme value of the free field motion and thus affect the response of the structure. From the viewpoint of structural aseismic design, a comprehensive study related to the requirements on the economy and the safety of the dam should be made to select a dam site and generally, a rectangular canyon is not appropriate to be a dam site due to its high amplification effects on incident waves.

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