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Maryam Malekian
Iran University of Science and Technology, Iran

Amirata Taghavi
Iran University of Science and Technology, Iran

Mohammad Hassan Baziar
Iran University of Science and Technology, Iran

Shirin Salemi
SABIR Consulting Company, Iran

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THE EFFECTS OF CANYON TOPOGRAPHY ON DYNAMIC STRESS DISTRIBUTION IN EARTH DAMS

Maryam Malekian
Iran University of Science and Technology
Narmak, Tehran-Iran 16846-13114

Amirata Taghavi
Iran University of Science and Technology
Narmak, Tehran-Iran 16846-13114

Mohammad Hassan Baziar
Iran University of Science and Technology
Narmak, Tehran-Iran 16846-13114

Shirin Salemi
SABIR Consulting Company
Tehran-Iran

ABSTRACT

Limitations of computer storage capacity and high costs have generally restricted the use of numerical methods to two-dimensional dynamic analyses of earth dams. However, differences in canyon topographies in which the earth dams have been built may cause various constraining effects. Comparison between results of plane strain and three-dimensional dynamic analyses may reflect the site effects especially in narrow canyons. Consequently, considering the geometry of canyon, one may choose an appropriate method of dynamic analysis. This paper presents the effect of different canyon geometries on amount and distribution of induced dynamic stresses in plane strain and in three-dimensional analyses. These analyses are executed by FLAC2D and FLAC3D for some sections of earth dams with different length to height ratios. It has been shown that the ratios of plain strain to 3D dynamic shear stresses reach their maximum and minimum values in triangular and rectangular shaped canyons, respectively. With complimentary studies the actual seismic behavior of earth dams could be estimated from plane strain dynamic analyses.

INTRODUCTION

Assessment of the performance and stability of an earth dam during an earthquake often requires a dynamic response analysis in order to determine the accelerations, dynamic stresses, and deformations induced in the dam by the seismic loads. Current methods for determining the seismic stability of an earth dam usually involve a dynamic response analysis of the dam for the maximum earthquake motions likely to affect the structure. One of the available and appropriate tools of performing dynamic analysis is finite difference method. It is worth noting that limitations of computer storage capacity and high costs have generally restricted the use of finite difference method to two-dimensional problems. However, dams constructed in narrow canyons, are three-dimensional in nature. Indeed, the canyon geometry has an indispensable contribution in the nature of earth dams' response. In view of this fact, it is desirable to determine conditions under which three-dimensional behavior is likely to play an important role in the dynamic response of a dam and to evaluate the applicability of two-dimensional analyses for the determination of the dynamic behavior of dams in steep walled canyons. In all of the three-dimensional analyses performed in this study, the peak values of τ_{xy} stresses were found to be very close to peak values of the maximum shear stresses $\tau_{\max}$ at the maximum section of the dams. Therefore, the τ_{xy} stresses are a dominant component of the 3D stress state at all points of that section. $\tau_{\max}$ is defined as half the difference between the major and the minor principal stresses. Therefore, it seems reasonable to perform the comparison between the results of the 3D and 2D analyses of earth dams in terms of the computed peak, τ_{xy} stresses.

In this paper the effects of different canyon geometries-triangular canyons and rectangular canyons- on amount and distribution pattern of induced dynamic stresses are investigated using plane strain and three-dimensional analyses. Some comparisons between two-dimensional and three-dimensional analysis of earth dams have been reported. Hantanaka (1955) and Ambraseys (1960) studied the seismic behavior of a two-dimensional shear wedge located in a rectangular canyon and concluded that for length to height ratios of four or greater, the fundamental longitudinal period of vibration was approximately equal (within 10%) to that of an infinitely long dam.

Makdisi et al. (1982) compared the results obtained from 2D and 3D dynamic analyzes of earth dams located in triangular canyons. They used 100ft (30m) high dams with elastic materials and a constant shear wave velocity of 500fps (153 m/s) and a damping ratio of 0.1 situated in a triangular valley with a width to height ratio of three and subjected to transient ground motions. The computed accelerations at midsection were about 60 to 80% higher in a three-dimensional response analysis than in a plane-strain analysis. On the other hand, computed shear stresses for the same section in the three-dimensional analysis were generally about one half the values computed from plane strain analyses.

Mejia et al. (1983) presented a comparison between the results of three-dimensional and two-dimensional dynamic analyses of two dams with different canyon geometries. That is, two dams located in triangular canyons with widely different valley wall slope had been used for comparison. Those dams correspond to the Oroville dam (Length/Height=7) and a hypothetical dam with the same main section as Oroville but in narrower canyon (L/H=2). It was found that a plane strain analysis of the maximum section of Oroville dam give values for the shear stresses that are within 20% of those computed from a three-dimensional analysis of the dam.

Baziar et al. (2004, 2006, 2009) and Heidari (2004) studied the acceleration amplification in three-dimensional and two-dimensional dynamic analysis of earth Dams. They found that the difference in computed amplification in 2D and 3D dynamic analysis is within 15% for dams located in long valleys. Moreover, in dams with length to height ratio of smaller than 4, amplification computed from plane strain analysis is about half of three-dimensional analysis. They also concluded that by reducing length to height ratio, L/H, the acceleration amplification increases; that is, for dams situated in narrow canyons, plane strain analysis is not reasonable.

ANALYSES PERFORMED

The most important factors influencing the dynamic response of an earth dam to seismic loading are: the geometry of the dam, the dynamic properties of the dam materials, and the nature of the input motions. In particular, canyon geometry is the most important factor that determines whether a dam behaves as a two-dimensional or a three-dimensional structure. Accordingly, ten dams located in triangular and rectangular shaped canyons have been used for the comparisons presented in this study. These hypothetical dams have the same main cross section and material property with Alborz earth dam situated in a trapezoidal shaped canyon in Mazandaran-Iran and has a crest length to height ratio (shape ratio), L/H, of about 10 (Heidari, 2004). The studied dams have the shape ratio of 2, 4, 6, 8, and 10. Dams located in triangular canyons had also equal slopes. For the sake of comparison and reduction of the number of two-dimensional analyses, the cross section of Alborz dam is used in 2D analysis.

Input Motions

Ricker wave accelerogram were used in the analyses. The acceleration time history of Ricker wave is shown in Figure 1.

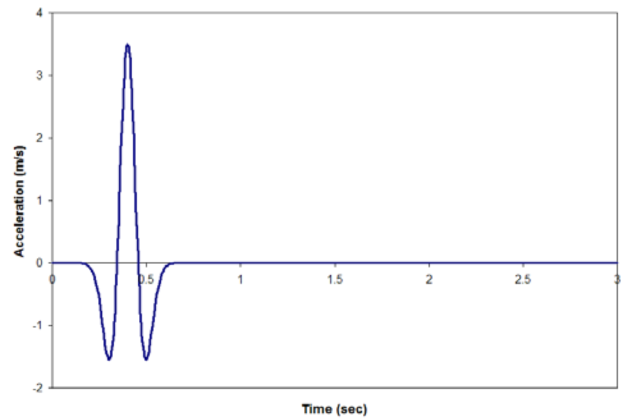

Fig. 1. The acceleration time history of Ricker wave

Finite Difference Models

FLAC2D and FLAC3D, the commercial finite difference codes, were used for two-dimensional and three-dimensional analyses of chosen ten structures, respectively. Figure 2 shows the model used for the two-dimensional dynamic analyses. Figures 3 and 4 present the model utilized for three-dimensional dynamic analyses of dams located in triangular and rectangular shaped canyons, respectively. Nodal points are fixed in the z-direction and are free to move in the x and y directions. Material of embankments behaves according to Mohr-coulomb plasticity model and foundation and valleys material behaves according to isotropic elastic model. For modeling purpose, first the valley and foundation are modeled and permitted to subside, then velocity and displacement in all direction are assumed zero. In order to obtain real conditions and estimate authentic displacements, dam is modeled in 20 stages. The equivalent linear method was also used to account for the nonlinear behavior of the dam materials.

There are few aspects that should be considered when preparing a FLAC dynamic model: (1) dynamic loading and boundary conditions, and (2) the amount of mechanical damping. Dynamic loading used in this study is explained in the previous section. Furthermore, Rayleigh damping of 1% is used to provide material damping. It is worth noting that the boundaries of the numerical model should be placed at sufficient distances to minimize wave reflections and achieve free-field conditions. For soils with high material damping, this condition can be obtained with a relatively small distance. However, when the material damping is low, the required distance may lead to an impractical model. An alternative procedure is to enforce the free-field motion in such a way that boundaries retain their non-reflecting properties –i.e., outward wave originating from the structure are properly absorbed. A technique of this type was developed for FLAC, involving the execution of free-field calculations in parallel with main analysis. Figure 5 shows free-field conditions in boundaries of model.

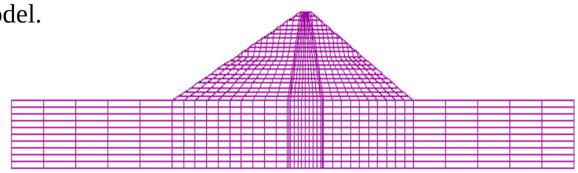

Fig. 2. Two-dimensional FD model of the main section of earth dam

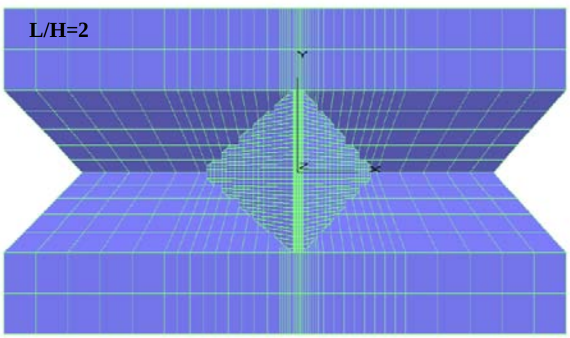

Fig. 3. Three-dimensional FD model of earth dam with length to height ratio of two located in triangular canyon

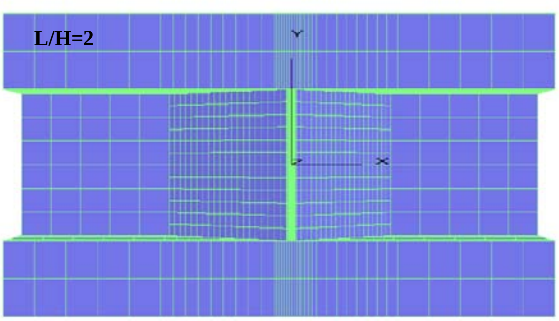

Fig. 4. Three-dimensional FD model of earth dam with length to height ratio of two located in rectangular canyon

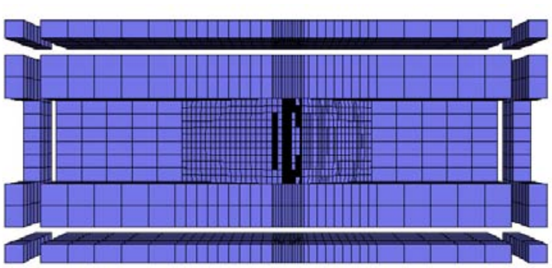

Fig. 5. Free-field boundaries in a FLAC3D FD model

SHEAR STRESS COMPONENTS

The most appropriate parameters to perform the comparisons between the results of 3D and 2D analyses of earth dams are the crest accelerations and dynamic stresses induced in the dams by the earthquake motions. Due to the tensorial nature of the stress state at a point, the comparison between dynamic stresses is not straightforward. Accordingly, one stress component has been selected to perform the comparisons presented herein. In Figure 6 different components of shear stresses are presented for the main section of a dam with length to height of 6 located in triangular canyon. It can be seen that in the main section, xz shear stresses (which correspond to xy shear stresses in two dimensional analyses) are larger than other component. The maximum value of τ_{xz} also happens near the base of the dam. This figure illustrates that the peak values of τ_{xz} are very close to the peak values of the maximum shear stresses $\tau_{\max}$. Therefore, τ_{xz} is the predominant component in determining the three dimensional stress states of the points located in the main section.

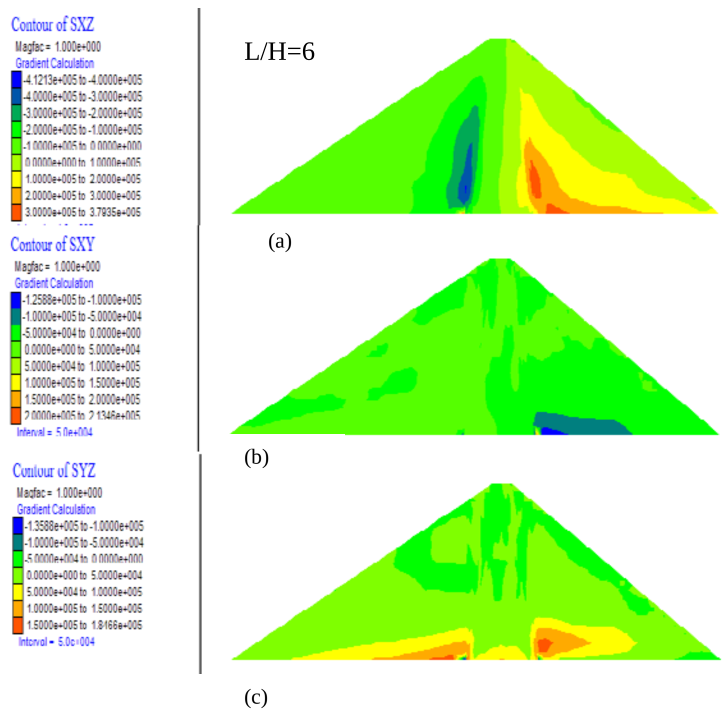

Fig. 6. Components of shear stress in main section of dam with L/H=6; (a) τ_{xz} (b) τ_{xy} (c) τ_{yz}

Furthermore, it has been shown by several case studies that where two-dimensional conditions prevail, the use of the shear stress on horizontal planes, τ_{xy}, as the parameter that controls the generation of pore pressures and deformations of dam materials, results in satisfactory assessment of the seismic stability of earth dams. Hence, it seem reasonable to perform the comparison between the results of the 3D and 2D analyses of earth dams in terms of the computed peak, τ_{xy}, stresses.

COMPARISON OF RESULTS

Maximum Section

Static and dynamic analyses are performed for the selected dams consequently. Figures 7 and 8 depict the dynamic shear stress distribution for a dam with L/H=2.0 located in triangular and rectangular shaped canyons, respectively. In addition, Figure 9 shows distribution of shear stress in two-dimensional analysis.

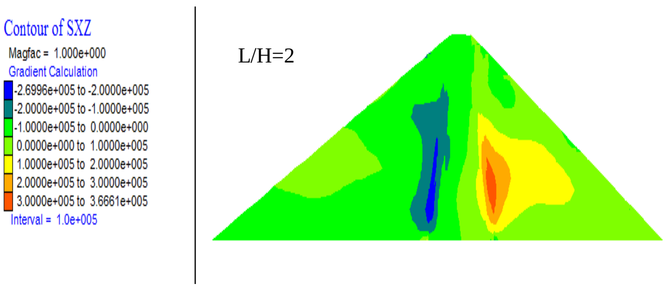

Fig. 7. Shear stress distribution in the maximum section of dam with length to height ratio of two located in triangular canyon

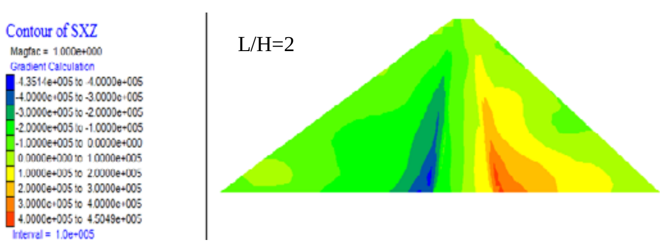

Fig. 8. Shear stress distribution in the maximum section of dam with length to height ratio of two located in rectangular canyon

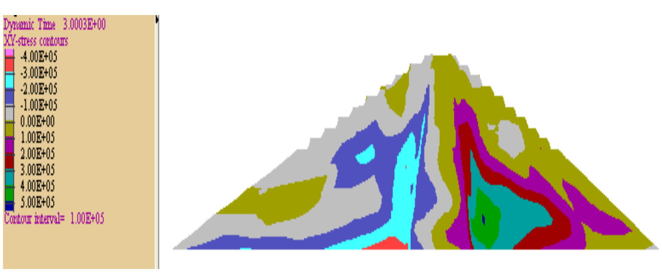

Fig. 9. Shear stress distribution in the maximum section of dam-two dimensional analysis

It can be said that the maximum shear stresses happen near the base of dam. Probably, it is due to change in martial properties in this region.

The ratio of peak τ_{xy} stress obtained from 2D and 3D models, τ_{xy2D}/τ_{xy3D}, were computed for the maximum section of ten dams with the shape ratio of 2, 4, 6, 8, and 10 located in triangular as well as rectangular canyons. Figure 10 depicts the alteration of τ_{xy2D}/τ_{xy3D} with respect to shape ratio. It can be seen that, for sections situated in triangular canyons the plane strain analysis gives considerably higher stresses compared with the three-dimensional analysis. In addition, the stresses obtained from 2D analysis for dams with shape ratio of 2 and 10, are within 36% and 12% higher than 3D analysis, respectively. Besides, for sections situated in rectangular canyons the plane strain analysis gives slightly higher stresses in comparison with three-dimensional analysis. That is, the stresses obtained from 2D analysis for dam with length to height ratio of 2 and 10 are within 11% and 4% higher than 3D analysis, respectively. An increase in shape ratio will bring about increase in shear stress ratio. The results also show that differences between two-dimensional and three-dimensional analysis in dams situated in triangular canyons is higher than the dams located in rectangular canyons.

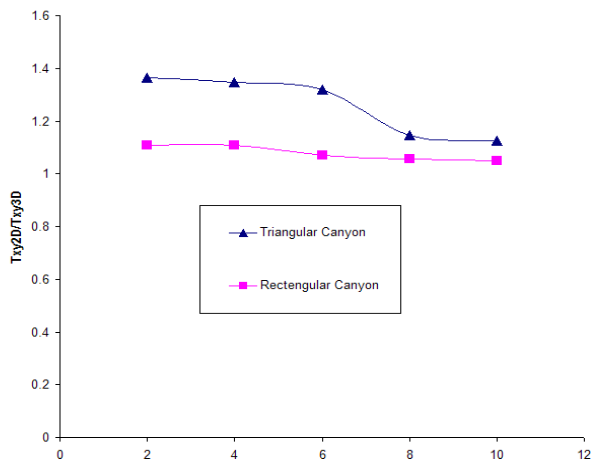

Fig. 10. The alterations of τ_{xy2D}/τ_{xy3D} with respect to shape ratio

Quarter Section

It is sometimes desirable to study the seismic behavior of the quarter section in the dynamic analysis of earth dams. In order to study the effects of three-dimensional behavior, the quarter section dynamic shear stresses of six dams situated in triangular and rectangular shaped canyons have been compared with 2D analyses results. Figure 11 shows the 2D FD model of quarter section.

Considering the shape ratios of 2, 6, and 10, the methodology of the previous section is used in this section. Figures 12, 13, and 14 present the variation of τ_{xy2D}/τ_{xy3D} ratio with respect to x/L (the ratio of distance from main section to half-length of dam).

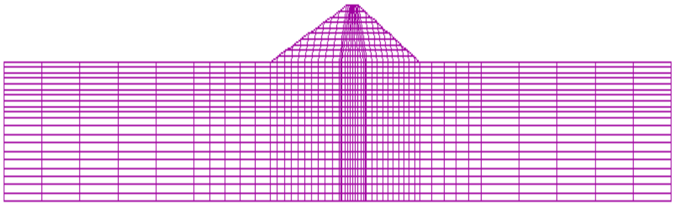

Fig. 11. Two-dimensional model of earth dam- quarter section

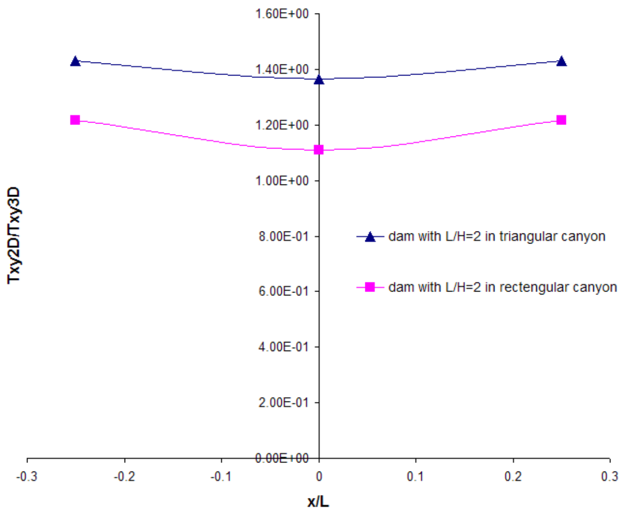

Fig. 12. Variation of τ_{xy2D}/τ_{xy3D} ratio in the longitudinal direction for dam with L/H=2

These figures show that for earth dams with length to height ratio of 2, 6, and 10 located in a triangular shaped canyon, τ_{xy2D} in x/L=0.25 is 43%, 62%, and 54% higher than τ_{xy3D}, respectively. τ_{xy2D} is also 22%, 13%, and 5% higher than τ_{xy3D} for the mentioned dams located in a rectangular shaped canyons canyon.

Regarding the results, in the main section the differences between shear stresses obtained from 2D and 3D analysis is lower than the quarter section. In addition, in the quarter section the canyon shape plays a more important role in altering the τ_{xy2D}/τ_{xy3D} ratio than the main section. That is, in the main section the differences between induced dynamic shear stresses due to the canyon shape effect is lower than the quarter section.

The maximum difference between shear stress computed from 2D and 3D analysis for dams located in triangular canyons are greater than 40% and on the other hand this difference for dams located in rectangular canyons is about 13%.

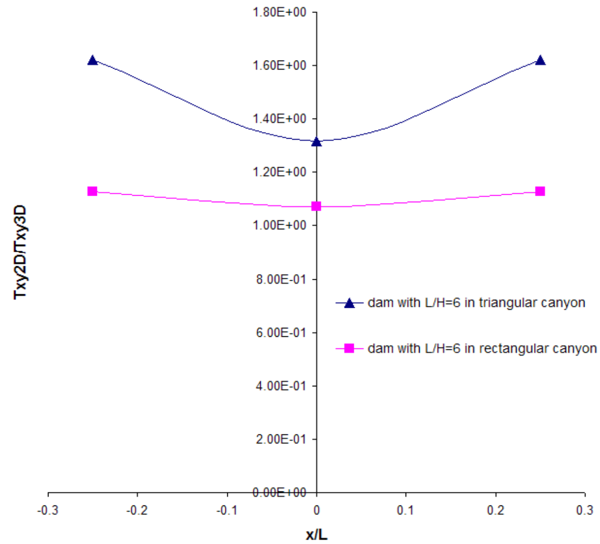

Fig. 13. Variation of τ_{xy2D}/τ_{xy3D} ratio in the longitudinal direction for dam with L/H=6

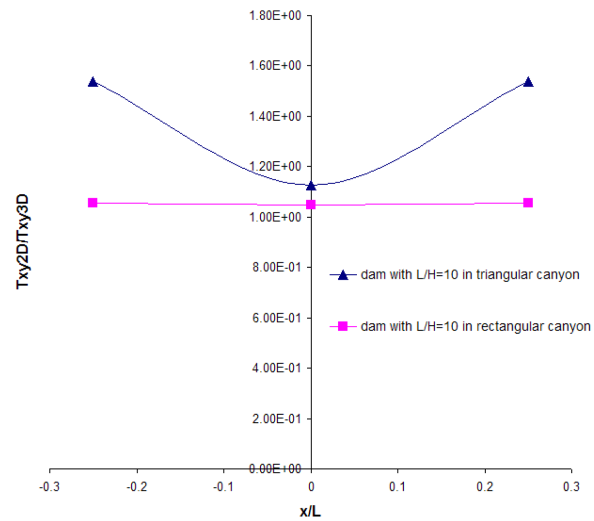

Fig. 14. Variation of τ_{xy2D}/τ_{xy3D} ratio in the longitudinal direction for dam with L/H=10

Mejia et al (1983) also reported a 40% difference in shear stress obtained from the 2D and 3D analysis for the quarter section of a dam with length to height ratio of 7.

CONCLUSIONS

In this paper, an attempt has been made to investigate the effect of canyon topography on the dynamic response of embankments. FLAC3D and FLAC2D were used to study the response of earth dams located in triangular and rectangular canyons.

The maximum shear stresses for several lengths to height ratios of embankment dams were compared with plane strain solutions for comparable sections. It was found that in the main section the shear stresses for dams located in triangular canyons with length to height ratio as high as 2 were about 36% larger than those computed from three dimensional analyses. However, if a similar dam was situated in rectangular canyon, differences will be reduced to 11%. In the quarter section of a dam with a length to height ratio of two located in triangular canyon, the computed 2D shear stress were about 43% larger than those of the 3D analysis. On the other hand, the computed shear stress ratio for the same section of the same dam located in rectangular canyon is reduced to 22%.

In addition, it was found out that dynamic response of dams situated in rectangular canyon have more two-dimensional nature than dams located in triangular canyons.

To sum up, the dynamic response of embankment dams may be affected significantly by the topography of the canyons. In narrow canyons, the plane strain assumption was found inadequate in predicting the response, instead a three dimensional analysis similar to that described previously should be used to account properly for the effects of the canyon walls on the response of the dam. As more dams and embankments, are being built in narrow triangular canyon such three-dimensional analyses can be expected to provide a useful and more accurate tool for evaluating the response of these dams under earthquake loading conditions.

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