Parametric investigation of valley shape effects on seismic response of concrete gravity dams

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Abstract

The seismic failure of concrete dams is possible in earthquake-prone areas. Their failure can put high risks to life and property. Furthermore, any structural damage to dams will cause negative economic effects. This fact has led to increased attention in dynamic behavior of dams during the last decades. The aim of this study is comparing two and three dimensional seismic response of concrete gravity dams and also necessity of providing more realistic models for considering the effects of cross-stream motions. The effects of dam-reservoir-foundation interaction, nonlinear behavior of mass concrete, the effect different shapes of valley are studied and their effect on nonlinear response and seismic stability of concrete gravity dams are evaluated under two and three-component earthquake records.

Keywords: concrete gravity dam, seismic response, three-dimensional behavior, dam-reservoir-foundation interaction, nonlinear behavior.

1. INTRODUCTION

During last decades, the growing demand for green energy has led to the construction of high concrete dams, which may be located in seismic areas. Seismic safety of concrete dams is one of the most important issues in the field of hydraulic structures, which may disrupt the normal operation of these infrastructures during the seismic event and cause a catastrophic failure that results in loss of life and human property.

Since 1928, after collapse of St. Francis Dam in California, failure of large dams have attracted a lot of attention which have led to extensive research in this field. The investigation of incidents that have occurred since then for various types of dams, emphasizes the importance of this issue. Among the damaged concrete dams during seismic events, the following cases can be mentioned: the Koyna gravity dam with a height of 103 meters in India (1967), the Hsingfengkinag buttress dam with a height of 105 meters in China (1962), the Pacoima arch dam with a height of 113 meters in the United States (1971, 1944), and also the Sefid Rud buttress dam with a height of 106 meters in Iran (1990) [1]. In the past, the seismic analysis of concrete gravity dams was often considered ideally using two-dimensional monoliths and earthquake effects were usually applied by defining a simple seismic coefficient. However, in recent years, attentions have been paid to analyzing of failure of concrete dams in three-dimensional space.

In 1972, Chopra and Chakrabarti conducted the two-dimensional monolith linear analysis of the Koyna dam under the 1967 earthquake [2]. Chopra in 1988 did comprehensive studies on the Pine Flat Dam. In this study, he considered the effects of the reservoir and analyzed the dam under harmonic loading and different earthquake types [3]. In 1985 , A.Rashed and Iwan mentioned the necessity of 3D analysis for the dams seismic design in narrow valleys [4]. In 1997 Paultre and Proulx put the Outardes 3 dam under a forced vibration test. They showed that a three-dimensional model for the dam-reservoir-foundation system, could produce more accurate behavior with consideration of the water compressibility effects. It was also shown that two-dimensional approach can only predict the main frequency of system resonant. According to finite element simulation results, it was found that the 3D behavior of dam is significantly different from ideal two-dimensional behavior of monoliths [5]. Paultre and Azmi in 2002, using the ADAP88 software a finite element computer program, investigated joints behavior and their effect on stability and dynamic response of the Big Tujunga Dam and Outardes 3 Dam [6]. Berets et al. (2012) investigated 3D stability of concrete gravity dams on steep cliff, using finite equilibrium method [7]. Arici et al. in 2014 studied the 3D seismic dam-reservoir-foundation interaction of Andiraz RCC Dam [8]. Wang et al. (2017) studied the Guandi concrete gravity Dam, emphasized on importance of 3D analysis, especially in the presence of transverse earthquake component [9].

The valley shape is one of the important geometric parameters in choosing dam type and determining the ratio of length to height of the dam, this parameter has a significant effect on seismic excitation and its results. The issue that is studied in this paper is the effect of valley shape on seismic stimulation of concrete gravity dams, which is carried out by using dynamic analysis of dam-reservoir- foundation system in frequency domain and time . In the present study, the finite element 3D model of Pine Flat gravity dam has been prepared along with the nonlinear behavior of dam body material, without considering contraction joint. Regarding importance of valley shape, the valley width variations and dam response to all three components of the ground motion is being discussed, and effect of valley width to height ratio are examined as well as the importance of ground motion transverse component along with the horizontal and vertical components. The dam-reservoir-foundation interaction effects are considered in the analysis, and ultimately compared with the results of the 2D model.

2. NUMERICAL MODELING

Numerical modeling of large structures such as dams is a suitable means for performing seismic analysis and evaluating their performance. Solid and fluid interaction is one of the important issues in seismic analysis of structures in the vicinity of liquids such as water reservoirs and concrete dams. Solving the problem of dam interaction with reservoir and foundation is more complicated than other structures due to the behavioral differences between the reservoir water (the fluid) and the constituent materials of the dam body and the foundation (structure) [10]. Assuming the invisicid linear compressible behavior of low-amplitude irrotational motion, the governing equation for the large dam reservoir is explained as follows (wave equation):

$$\nabla^2 P(x,y,z) = \frac{1}{C^2}.\ddot{P}(x,y,z) \qquad (1)$$

In which c is the velocity of the compressive wave in water, P(x,y,z) is the hydrodynamic pressure in addition to the hydrostatic pressure and ∇^2 is the Laplacian operator. In the problem of the dam-reservoir interaction, there is no flow across the interfaces. This assumption is based on the fact that the face of concrete dam is (impervious). This assumption leads to the condition that there is no relative velocity in the direction perpendicular to the (shared) boundary.

The boundary condition of the reservoir bottom divides the hydrodynamic pressure into the vertical acceleration and the acceleration resulting from the interaction between the stored water and the reservoir floor materials. In this modeling, only the interaction will be considered in the vertical direction, this condition is similar to the previous condition, although the coefficient of absorption of the bottom can be considered. At the free surface of the reservoir, the hydrodynamic pressure is zero. In other words, for all nodes located on the reservoir surface, zero pressure is defined as the boundary condition. This assumption also states that there is no surface waves in the reservoir and surface waves are not considered in the modeling.

The far-end boundary at the end of the reservoir in the finite element model of reservoirs with infinite length has been investigated by numerous researchers. Sommerfeld's boundary condition is one of the most common ones, which is based on the assumption of the propagation of plane waves in the fluid at far distance from the dam. This (assumption) is expressed mathematically as follows:

$$\frac{\partial P}{\partial n} = -\frac{1}{C}.\frac{\partial P}{\partial t} \qquad (2)$$

Where n is perpendicular direction to the far-end boundary. This condition introduces a damping to the system, which models the loss of energy from outgoing waves. At the boundaries of the foundation, based on a simplistic assumption, if the propagation effect of the waves is ignored, it is not necessary to define a specific boundary condition for absorption of waves.

3. FINITE ELEMENT FORMULATION OF DAM-RESERVOIR-FOUNDATION SYSTEM

The relationship between hydrodynamic pressure within the reservoir [10], and the vector of applied forces to the dam-reservoir intersection $\{f\}$, is made by a coupling matrix $[Q]$

$$[Q].\{P\} = \{f\} \qquad (3)$$

Using the discretization of reservoir and also considering solids finite element equations, the dam-reservoir interaction is a classical problem involving a second-order differential equation. These equations for dam structure and reservoir are as follows:

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{f_1\} - [M]\{\ddot{U}_g\} + [Q]\{P\} = \{F_1\} + [Q]\{P\} \qquad (4)$$

$$[G]\{\ddot{P}\} + [C']\{\dot{P}\} + [K']\{P\} = \{F\} - \rho[Q]^T\left(\{\ddot{U}\} + \{\ddot{U}_g\}\right) = \{F_2\} - \rho[Q]^T\{\ddot{U}\} \qquad (5)$$

Where [M], [C], and [K] respectively are the mass, damping and dam structure stiffness matrices, and [G], [C`] and [K`], respectively are the mass, damping and reservoir stiffness matrices. $\{f_1\}$ is body forces and hydrostatic vector, [6] and [2], respectively are the displacements vector and hydrodynamic pressures vector. $\{\ddot{U}_g\}$ is the ground motion acceleration vector and ρ is the fluid density. The dot represents the variable time derivative. In formulation of the dam-reservoir-foundation finite element system, with the assumption of massless foundation, [K], [M] and [C] matrices comprise the subset of matrixes that is composed of the dam and the foundation structures. In this case, the dam and foundation are considered as a unit, interacting with the water of the reservoir.

4. CASE STUDY

The case study in this is Pine Flat gravity dam. The dam consists of 36 monoliths with the width of 15 m and a 12-m width monolith. The crest length is 550 m and the highest monolith is 122 m. The geometric characteristics of 2D section of the dam with its foundation and the reservoir are shown in Fig. 1. The downstream 3D view of the dam and the main geometric parameters are shown in Fig. 2. As it can be seen, the valley lateral sides () are considered at angle of 45 ° and the main parameter studied is the width of the valley at the river level (B). H represents the highest dam monolith height with the value of 122m.

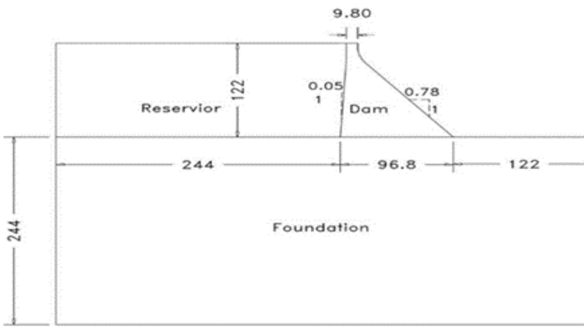

Figure 1. geometric characteristics of 2D Pine Flat dam section

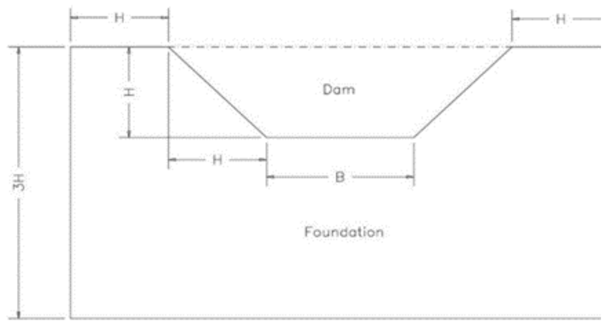

Figure 2. The downstream view of the dam

The concrete material of the dam body with nonlinear behavior has been modeled by using concrete damage plasticity approach. The elastic behavior of concrete is: density of 2400 Kg/m^3, initial Young's modulus of 30 GPA and Poisson's Ratio of 0.2. For nonlinear behavior of concrete, only tensile failure is considered and the behavior of the concrete has been assumed linear in compression. Concrete stress-strain behavior in nonlinear state with the corresponding values of tensile failure has been shown in Fig. 3 [11].

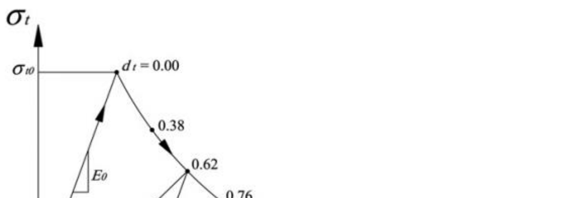

Figure 3. stress-strain relation for the nonlinear concrete

The post-yielding behavior is modeled in a softening form by decreasing the concrete elasticity modulus with a tensile load failure variable dt. The tensile failure variable is a function of nonlinear strains and its variation is shown in Fig. 3. The tensile yield of concrete is assumed as 2.9 Mpa. The reservoir water is considered as full and has been modeled by the density of 1000 Kg/m^3 and the bulk modulus of 2.07 GPa. In the case of gravity dams which are constructed on competent abutments, the finite element model of mass-less foundation can adequately/ model the rock. In this study, massless foundation with Young's modulus of 30 GPa and Poisson's

Ratio of 0.33 has been used. In this research, six 3D finite element models of the dam-reservoir-foundation with the ratio of valley width (B) to dam height (H) are investigated as follows: $\frac{B}{H} = \frac{1}{3}, \frac{2}{3}, 1, \frac{4}{3}, \frac{5}{3}, 2$

Fig. 4 shows the finite element model of the dam-reservoir-foundation system in 2D mode and Fig. 5 shows 3D model with B / H ratio of 1. It should be noted that Pine Flat dam is actually located in valley with B / H ratio of 2.5. It has been tried to use approximately same mesh density in all models. The finite element mesh has been sufficiently refined to simulate the nonlinear behavior of the dam body.

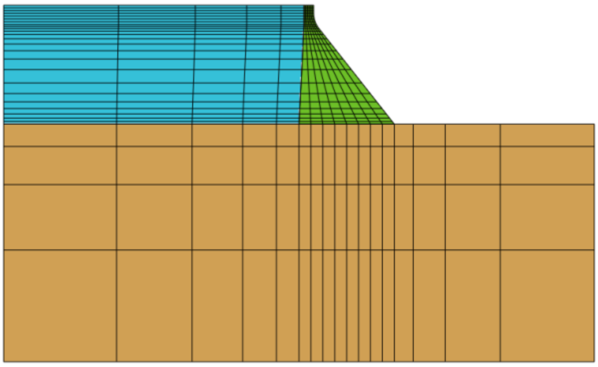

Figure 4. 2D Finite element model

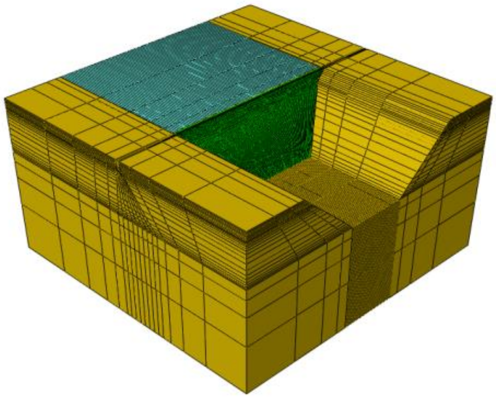

Figure 5. 3D Finite element model

4.1. SEISMIC LOADING

The loading consists of two static and dynamic steps. In this modeling, static loading includes the dam body weight and the full reservoir hydrostatic load. Typical foundation weight is not applied during static analyses, after the static loading, the seismic loading of the model begins. This seismic loading is the recorded accelerogram during the Kern County earthquake at Taft Station on July 21, 1952. Dynamic analysis of the Pine Flat dam is done by considering the separate and also simultaneous influence of horizontal components (in the stream direction), vertical and transverse (perpendicular to the stream). In Fig. 6, horizontal, vertical, and transverse records are shown, respectively.

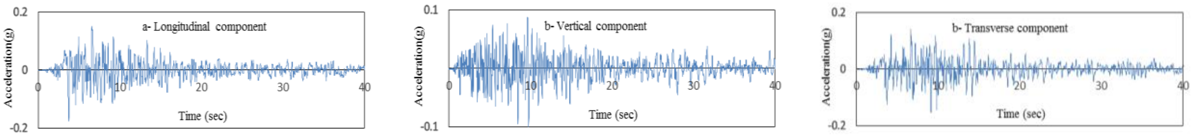

Figure 6. Kern County earthquake record

4.2. DAMAGE INDEX

In order to show damaged areas in the models, and to compare the imposed damages, a failure index is defined as follows:

$$DI = \frac{\sum D_e . V_e}{\sum V_e} \tag{6}$$

in which D_e is the tensile damage of the element e and V_e is the element volume. This index, which is the weighted average of the damage imposed to the dam body, can be calculated on the entire dam body or locally on damage prone areas such as neck of the dam, its heel or lateral abutment areas. The locations for computing this index have been shown in Figs.7, 8 and are explained as follows:

1- Right abutment in 3D models
2- Left abutment in 3D models
3- The neck of the dam from 102-meter level (downstream kink) to 114-meter level (curved end in upstream).
4- Dam heel, in 2D and 3D models

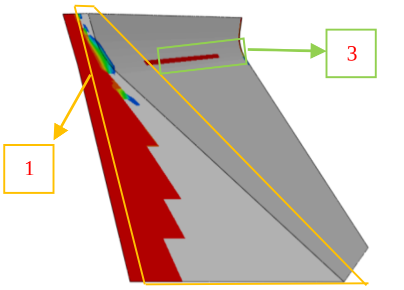

Figure 7. Downstream view

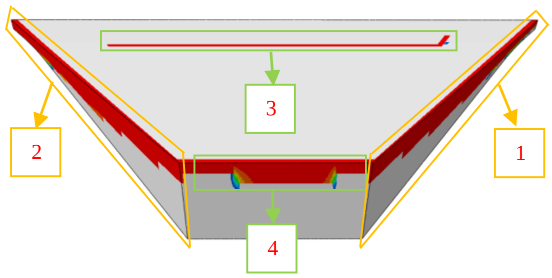

Figure 8. Upstream view

5. Results and Discussion

5.1. Dam's Crest Displacement

The maximum relative absolute displacement of the dam crest middle point under three components of the earthquake has been shown separately and simultaneously for all 3D and 2D models in Fig. 9. x, y, and z is respectively horizontal, vertical, and transverse records.

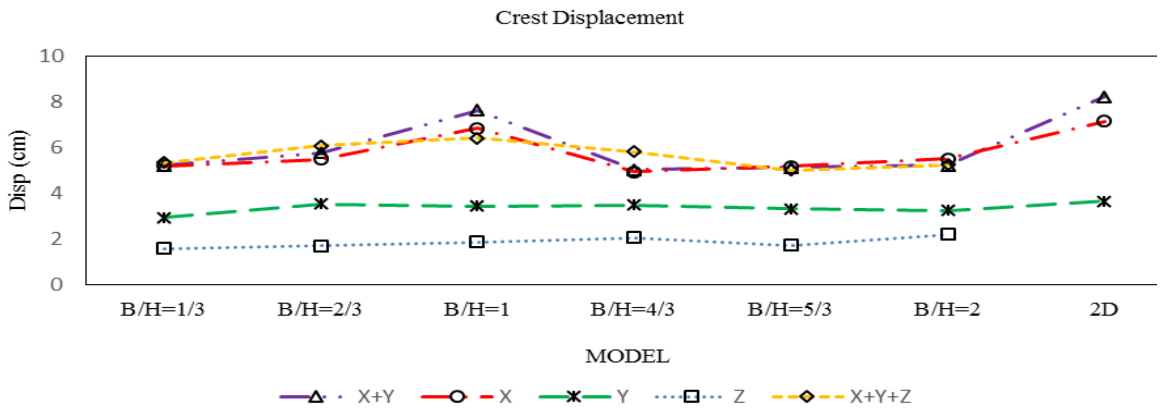

Figure 9. Crest Displacement

It should be noted that in the 2D model only two longitudinal and vertical earthquake components are applied. The minimum displacement is observed in applying transverse component, and the application of vertical component only causes the least relative displacement. As shown in Fig. 9, the greatest relative displacement of the crest is related to the records containing horizontal component, although the addition of transverse and vertical components may sometimes reduce the relative displacement. The two-dimensional model shows more displacements in comparison with most 3D models. In general, there is no definite conclusion of (B / H) ratio effect on the dam seismic response due to the natural frequencies change of system and, consequently, the amounts of spectral intensity (according to the earthquake record) by changing the (B / H) ratio.

5.2. Damage Index

The calculated damage index in the highest monolith of the 3D models, which is located in the middle of the model, is compared with the 2D model in two areas of the neck and heel of the dam in Figs. 8, 9. The index has been calculated separately and the results of applying the three earthquake components is shown simultaneously and separately in Fig. 10. Final tensile damage at the middle monolith for three models of (B / H) = 1/3, 1, 2 and the 2D model under the Kern County earthquake record is compared in Fig. 11. As can be seen, the lowest damage value is for the model (B / H) = 2. By increasing the (B / H) ratio, the amount of damage in the dam neck region decreases. This damage, especially under the longitudinal component, can only reach over 20%. In general, there is no damage in the neck region of the 2D model. About the dam heel, the addition of transverse and vertical components to the longitudinal component sometimes increases and (sometimes) reduces the imposed damage. But in contrast to the dam neck, the damage which is applied to the dam heel in the two-dimensional model is more than the 3D model. Therefore, it can be concluded that considering the 2D model results in far-fetched and non-conservative results, especially in the case of damage in dam neck region

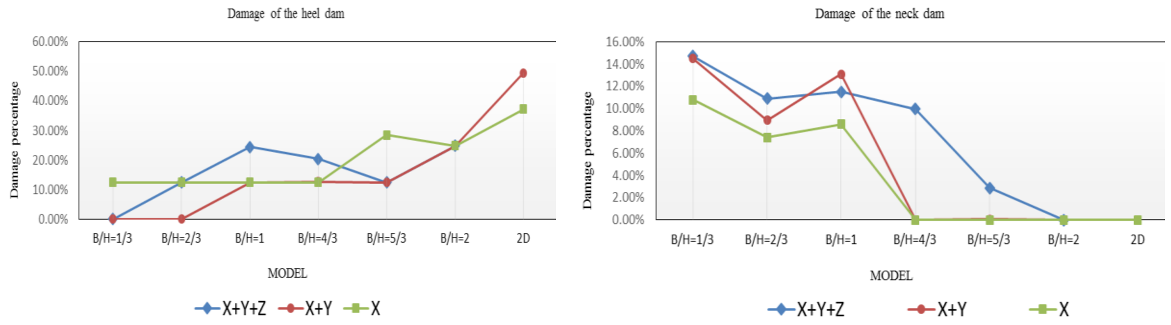

Figure 10. Comparison of the damage in the 2D and 3D models

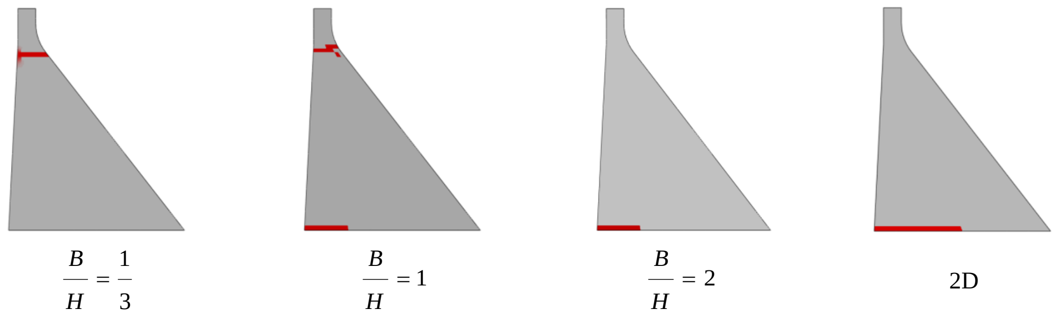

Figure 11. Tensile damage in the highest monolith of 3D and 2D models

In the following, we investigate the damage index in four areas shown in Fig. 8, in which only the 3D models were compared and the results has been presented in Fig. 12. As can be seen, the earthquake transverse component that is ignored in the 2D analysis, causes increase in the applied damage to the right and left lateral supports and also the dam neck in all 3D model. However, the damages that are applied to the dam heel are more likely to be governed by the earthquake longitudinal component.

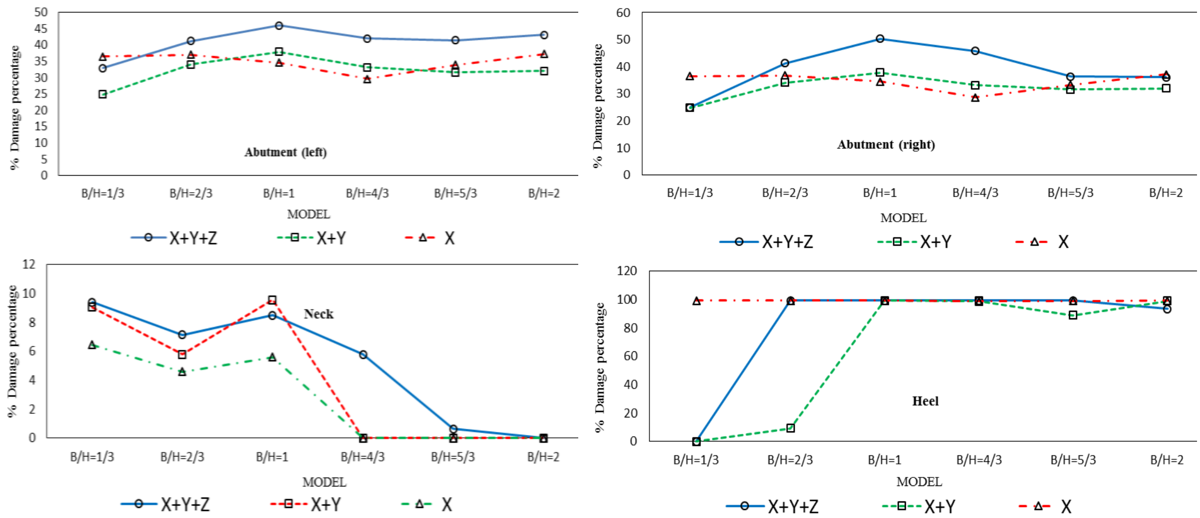

Figure 12. Comparison of the damage in 3D model

6. CONCLUSIONS

This study showsthat increasing the width of valley at the river level and, consequently, increasing the length of dam cause:

1. The lowest relative absolute displacement of the dam crest middle point is related to the only application of the transverse component and then only with the application of the vertical component.
2. The maximum crest relative displacement is related to the records, containing the horizontal component, although the addition of lateral and vertical components may sometimes reduce the relative displacement of the dam crest.
3. In comparison with the most of 3D models, the 2D models concluded more relative crest displacement which indicates that the 2D model results are unrealistic.
4. Evaluation of ultimate tensile damage in the highest monolith of 3D models for comparison with the two-dimensional model under the Kern County earthquake record indicates reduction in the dam neck region damage by increasing valley width to model B/H= 2 and by further increase in valley width, the damage amount has remarkable increase, specially under longitudinal component. In two-dimensional model, the damage is only related to dam heel and generally is more than the three-dimensional models.
5. Comparison of just three-dimensional models shows that the earthquake transversal component is ignored in the 2D analysis and leads to increase of applied damage to the right and left side supports and also the dam neck in all 3D models, and applied damage to the dam heel is governed by the longitudinal component of the earthquake.
6. Totally, in comparison of 3D models, the maximum amount of tensile damage is concentrated in the abutments, and by increasing the valley width, the dam neck damage decreased.

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