Structural Behavior of a Coupled Concrete Dam-Reservoir system under Effect of Earthquake loads Using Concrete Damaged Plasticity Model

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Abstract. In this study the effect of dam-reservoir interaction on the dynamic response of gravity dam by assuming the mass concrete is able to be cracked and crushed in tension and compression, respectively is considered. Where the effect of reservoir fluctuation on the dynamic response of concrete dam is investigated. In this study, to simulate the nonlinear behavior of concrete and specifying the position and direction of cracks which is occurred in gravity dam, the concrete damaged plasticity model is used. The results of this study indicate that, the maximum relative displacement in the downstream direction of a dam subjected to an earthquake is occurred when the height of water in the reservoir is at the middle of the dam. In addition, in the case of water level in the reservoir is at the base of dam, the maximum relative displacement of the dam is at the upstream.

1. Introduction

It is indispensable to use mathematics to quantify and understand comprehensively any physical incident such as fluid or structural action, wave propagation, etc. This type of problems can be explained using partial differential equations. The numerical techniques have been developed to resolve the partial differential equations for a computer, and one of the distinguished ones, is the finite element method. For the structural engineering many problems such as fluid-structure interaction can be analysed by this method.

Ardebili and Mirzabozorg (2010) studied the effect of reservoir level fluctuation on nonlinear seismic response of a high concrete arch dam using smeared crack model [1]. They stated that, when the reservoir is impounded, the number of cracked elements and the extension of cracked regions are less than the cases when the reservoir water level is low. Subramani and Ponnuvel studied seismic and stability analysis of gravity dams, where the hydraulic height is considered using Staad PRO [2]. Alora and Gogoi (2013) studied the seismic fracture analysis in concrete gravity dams through MATLAB codes for the statement of crack propagation in concrete gravity dams under static and dynamic loadings.

For the purpose of conducting analysis of the issue under study, verification of the simulation process is necessary to validate the results of the analysis. Therefore, as a first stage in this study, the verification process was revived and the study submitted by Chopra and Chakrabarti (1972) [4] is adopted to validate the numerical modelling of dam subjected to an earthquake using ABAQUS program. In addition, a parametric study on a Koyna dam in conducted to study the structural behaviour of a coupled concrete dam-reservoir system under the effect of earthquake loads using concrete damaged plasticity model.

2. Numerical analysis of concrete dam-reservoir system under the effect of Earthquake

There are many studies on the dynamic behaviour of dams and few have taken into account the effect of changing the water level behind the dam in the design of this type of origin. This requires a description of the behaviour of the dam material under the influence of loads, including dynamic loads. Therefore, the choice of a model for the behaviour of the dam material under the effect of these loads is the most important part of the analysis.
The gravity dams are a structural member can be constructed from concrete material using the weight of the material to resist the horizontal pressure of water in the back of dam. For this type of dam each section of the dam is stable and independent of any other dam section. Koyna dam is an upright gravity structure of concrete. It is about 853.44 m long, 130.0224 m height above the deepest foundation and 85.344 m height above the riverbed. The overflow part of the dam is about 91.44 m long. The dam is erected in 15.24 m wide monoliths. The dam’s overflow and non-overflow sections were designed to attain the following criteria (i) The maximum compressive stresses of concrete is less than the permissible stresses, (ii) the section has no tension and (iii) the factor of shear friction is than permissible values. Additional with the earthquake forces, the reservoir forces are also associated. The height of the water in the reservoir was taken equal to 91.75 m.

The Koyna earthquake was recorded within a monolith near the right bank. The ground motion peak accelerations that recorded at Koyna dam were (0.34 g) for vertical component and (0.49 g) for transverse (horizontal) component.

The horizontal cracks on either the downstream or the upstream face or on the both faces of a number of dam’s monoliths were the generality structural damage to the dam. The essential cracking was in the taller non overflow monoliths on both sides of the spillway section around the level at which the downstream slope face changes abruptly.

The dam-reservoir which is subjected to dynamic load of transverse and vertical components of ground motion is considered as a plane strain problem. The analysis of the problem is performed by using the finite element method. In addition, the effect of variations of water level in the back of the dam on the dynamic response of gravity dam is studied.

2.1 Numerical modelling of Koyna dam under the effect of earthquake loads

Structural analysis of large structures whose stability depends on the weight of starch such as dams should include an analysis of the behavior of the dam material, and this is about the way that the behavior of material is modelled. The failure of such dams, especially when they are exposed to earthquakes, is the result of a breakdown in the structure of the dam, which leads to cracks. The study of the location and direction of the occurrence of these cracks should be taken into consideration in the design. The section of dam under consideration is shown in Figure 1.

Figure 1: The section of Koyna dam
The properties of the concrete for the dam used in the analysis are the damping coefficients (α) is zero and β is 0.005432, mass density of concrete is 2643 Kg/m³, Young’s modulus is 31026407.805 kN/m², and Poisson’s ratio (0.2). The concrete damage plasticity model is used to simulate the nonlinear behavior of the concrete material. The model is a plasticity-based, damage for concrete. There are several types of failures that occur in structures. In the case of the structure that depends on the weight of the facility such as dams, there are two important types of failure mechanism must be taken into account. In this model, the failure mechanisms of tensile cracking and compressive crushing of the concrete material is assumed. The evolution of the yield (or failure) surface is controlled by two hardening variables, $\varepsilon^{plh}$ and $\varepsilon^{plc}$ as a tensile and compressive equivalent plastic strains, respectively which are linked to failure mechanisms under tension and compression loading, respectively. The properties of concrete damage plasticity model are shown in Table 1.

| Properties                                    | Value  |
|----------------------------------------------|--------|
| Dilation angle, $\psi'$                      | 36.31  |
| Eccentricity                                 | 0.1    |
| Ratio of initial equiaxial compressive yield stress to the initial uniaxial compressive yield stress | 1.16   |
| Ratio of second stress invariant on the tensile meridian to that on the compressive meridian | 2/3    |
| Compressive initial yield stress, $\sigma_{co}$ (kN/m²) | 13000  |
| Compressive ultimate stress, $\sigma_{cu}$ (kN/m²) | 24100  |
| Tensile failure stress, $\sigma_{to}$ (kN/m²)  | 2900   |

The default of the viscosity parameter is considered zero. A number of assumptions are made for the properties of material. The tensile strength is estimated to be 10% of the ultimate compressive strength ($\sigma_{cu} = 24100$ kN/m²) which is multiplied by a dynamic amplification factor of 1.2 to account for rate effects. Thus, in this case, the tensile strength, $\sigma_{to} = 2900$ kN/m². The behavior of tensile post failure is given in terms of a fracture energy cracking criterion, where the stress/displacement curve is specified instead of a stress-strain curve as shown in Figure 2 (a). In addition, tensile damage, $dt$ is specified as a function of cracking displacement by using the post cracking damage displacement curve as shown in Figure 2 (b). The stiffness degradation damage caused by compressive failure (crushing) of the concrete, dc is assumed to be zero.
Figure 2: The tensile properties of concrete.

The time-acceleration history of earthquake in transverse (horizontal) and vertical direction are shown in Figures 3 and 4, respectively.

Figure (3): The transverse (horizontal) component of Koyna earthquake.

Figure (4): The vertical component of Koyna earthquake.

For simplicity the problem, the interaction between the dam and the soil is neglected and therefore, the boundary condition at the dam base is considered as a fixed boundary.
The analysis is performed in steps. Three steps are used to represent the loads that are applied on Koyna dam. These steps are the self-weight of dam which is entered in the first step. In the second step, the hydrostatic pressure with various water levels is entered (see, Figure 5), and the earthquake load is applied in the third step. The procedure of analysis is dynamic implicit. In analysis of structure under the effect of self-weight, the boundary condition is applied at the bottom of dam, so that the displacement is fixed in x and y-direction. In step of dynamic analysis, there is freedom of movement in these directions mentioned above. In addition, a prescribed acceleration of earthquake is applied as a boundary condition in x and y-direction.

![Figure 5: Simulation of the hydrostatic pressure load.](image)

The type of element used to discretize the model is CPE4R which is implemented in Abaqus program. The problem is considered as a plane strain state, because the position of the loading does not vary along the trend.

The relative horizontal displacement of Koyna dam at two nodes is considered due to the transverse (horizontal) and vertical components of Koyna earthquake. The first node is at the downstream crest of Koyna dam and the second node is in the abrupt change of the downstream slope of Koyna dam.

2.2. The results of numerical modelling of Koyna dam under the effect of earthquake loads

The displacement-time history of dam in transverse and vertical directions due to the earthquake according to Chopra and Chakrabarti is shown in Figures 6 and 7, respectively. The displacement-time history of dam in horizontal (transverse) and vertical directions under the effect of earthquake from the present study is shown in Figures 8 and 9, respectively. From these results it can be stated that, a good agreement is achieved.

![Figure 6: The horizontal displacement at the first node of Koyna dam corresponding to Chopra and Chakrabarti in inch units.](image)
Figure 7: The horizontal displacement at the second node of Koyna dam corresponding to Chopra and Chakrabarti in inch units.

Max. Amplitude of disp. = 1.1083 in = 28.151 mm

Figure 8: The horizontal displacement at the first node of Koyna dam in inch units using ABAQUS program with height of water of (91.75 m).

Max. Amplitude of disp. = 0.477 in = 12.116 mm

Figure 9: The horizontal displacement at the second node of Koyna dam in inch units using ABAQUS program with height of water of (91.75 m).
3. Effect of variation of depth of water on dynamic response of dams

A nonlinear analysis of dam, as a plane strain, which is subjected to the ground motion is performed by the finite element method using ABAQUS program. The geometry and concrete properties of Koyna dam as in the previous section is considered except that the height of water in the reservoir is taken equal to zero. It means that the effect of water on Koyna dam has been neglected. Also, another parametric study is performed by taking the height of water in the reservoir equals to half of the Koyna dam which is 51.511 m above the base of Koyna dam. The same transverse (horizontal) and vertical components of Koyna earthquake is applied.

The dynamic response of Koyna dam with height of water in the reservoir equals to zero and half of Koyna dam (i.e., 51.5112 m) above the base of Koyna dam are studied. The relative horizontal displacement of Koyna dam at the same two nodes shown in Figure 5 (The first node is at the downstream crest of Koyna dam and the second node is in the abrupt change of the downstream slope of Koyna dam) due to the transverse (horizontal) and vertical components of Koyna earthquake are shown in Figures 10 to 13.

![Figure 10: The horizontal displacement at the first node of Koyna dam in inch units using ABAQUS program with height of water of (0 m).](image1)

![Figure 11: The horizontal displacement at the second node of Koyna dam in inch units using ABAQUS program with height of water of (0 m).](image2)
Figure 12: The horizontal displacement at the first node of Koyna dam in inch units using ABAQUS program with height of water of (51.5112 m).

Figure 13: The horizontal displacement at the second node of Koyna dam in inch units using ABAQUS program with height of water of (51.5112 m).

From the results of the history of time-displacement of dam subjected to an earthquake with different levels of height of water it can be stated that, considering the relative displacement of dam due to earthquake, the maximum relative displacement in the downstream direction is occurred when the height of water in the reservoir is at the middle of the dam. In case of the water level in the reservoir is at the base of the dam, the maximum relative displacement of the dam is at the upstream. The node in the downstream crest (the first node) of Koyna dam had the maximum relative displacement with different water levels than the node in the abrupt change of the downstream slope (the second node) of Koyna dam.

4. The post-cracking damage of dams due to an earthquake
The concrete tensile damage is used to define post-cracking damage (or stiffness degradation) properties of the concrete damaged plasticity material model. It is used to inference about the presence of cracks due to tensile loading of the concrete dam. Figures 14-16 show the cracking damage of concrete of dam with different levels of water. The zone of cracks is presented with a red color and means that the elements of the dam have approximately loss all of their properties, while the blue color means that these elements have all of their properties without any lose.
Figure 14: The cracking damage of concrete for Koyna dam with a height of water of (91.75 m)

Figure 15: The cracking damage of concrete for Koyna dam with water at the dam base.

Figure 16: The cracking damage of concrete for Koyna dam with a height of water of (51.51 m)

By comparing the results of concrete cracking damage for the concrete dam with three different levels of water in the reservoir, it found that the maximum cracking damage of concrete is when the water
level is (51.51 m) only positioned in the abrupt change of dam slope in which lots of elements is damaged and also a few number of damaged parts is occurred in a small distance bellow this abrupt change of the slope. While, the minimum cracking damage of concrete is in the case of water level at 91.75 m in which this damage is being positioned in the abrupt change of the dam slope but, with a little number of damaged parts than that when the water level is at 51.51 m. Also, there is a number of damaged parts occurs in the lower left (upstream) corner of the dam. When water level is at the base of dam, the cracking damage of concrete is occurred in the same positions as that when the (91.75 m) water level is 91.75 m, except that the number of damaged parts in the case of water level is at the base of dam are less than the damaged parts when the water level is at 91.75 m. Finally, from the previous results it can be stated that the critical state for the cracking damage of concrete material of dam is occurred when the height of water in the reservoir is at the middle of the dam.

5. Conclusions
In this study, in which the structural analysis of the dam was carried out and based on its stability on the weight of the facility only. The results obtained from finite element analysis indicate that the importance of taking into account the consideration when analyzing this type of structures, the water level behind the dam, which directly affects the dynamic response of dam. The design of this type of dam also requires the conduct of the dam material, which must include the identification of cracks that occur during the earthquake.

In this research, the effect water-structure interaction on the dynamic response of dam is studied. In addition, the nonlinear behavior of concrete gravity dam is assumed with a concrete damage plasticity model to specify the position and direction of cracks that occurs in the dam due to the earthquake. The conclusions of the study as follow as:
(1) The maximum relative displacement in the downstream direction of a dam subjected to an earthquake is occurred when the height of water in the reservoir is at the middle of the dam.
(2) In case of the water level in the reservoir is at the base of the dam, the maximum relative displacement of the dam is occurred at the upstream.
(3) The point in the downstream crest (the first node) of Koyna dam had the maximum relative displacement with different water levels than that the point in the abrupt change of the downstream slope (the second node) of dam.
(4) The maximum cracking damage of concrete is when the water level is at the middle of dam, and only positioned in the abrupt change of dam slope in which lots of elements is damaged and also a few numbers of damaged parts is occurred in a small distance bellow this abrupt change of the slope.
(5) The minimum cracking damage of concrete is in the case of water level is at the crest of dam in which this damage is being positioned in the abrupt change of the dam slope but with a little number of damaged parts than that when the water level is at the middle of dam.

References
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