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Effect of earthquake directionality in seismic performance of concrete gravity dam

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Abstract
The purpose of this study is to examine the influence of earthquake direction on the seismic performance of a concrete gravity dam under a single earthquake event. For this purpose, the proposed dam of Nalgaad Hydropower Project is selected with slight modifications in which the earthquake events in two directions are applied along the horizontal axis, namely from upstream to downstream and another from downstream to upstream to assess the maximum structural demands. A non-linear dynamic analysis of the Dam-reservoir-foundation system subjected to seven recorded seismic events is conducted to study the effects of a single earthquake event where the responses of models are compared in terms of crest displacement with respect to bottom of the dam, principal stress at the heel, plastic strain at the heel and toe slip of the dam. The results show that the damage parameters and crack propagation processes of concrete gravity dam can significantly change with the applied direction of earthquake.

Keywords
Concrete gravity dam, Earthquake direction , Single earthquake event,damage demand

1. INTRODUCTION

As Nepal lies in an exceedingly high active seismic region, construction of every structure here requires a high degree of seismic performance. A concrete gravity dam is a solid structure fabricated from concrete, designed to retain water using only the weight of the material and its resistance to the foundation to withstand the horizontal pressure of water pushing against it. The concrete gravity dams are subjected to the static loads viz., dead loads, reservoir and tailwater loads, uplift pressure, silt pressure. etc. and dynamic loads viz., seismic forces, wind forces, etc. Due to the low tensile strength of concrete material, concrete dams will suffer crack damage under strong ground movement. Considering that seismic activity can cause the dam to collapse which can result in many casualties and large property losses, assessing the seismic safety of tall dams remains a key issue in dam construction. To perform a reasonable evaluation of the seismic safety of dams, it is necessary to study the process of failure by cracking and the possible failure modes of concrete dams under the action of strong earthquakes, which deserve further investigation and attention. The horizontal inertial force acts from upstream to downstream and from downstream to upstream. Similarly, the vertical inertial force acts from bottom to top as well as from top to bottom direction. Hence, the dam is designed for the worst combination i.e., for the horizontal and vertical inertial forces. The inertia effect between the dam and the reservoir causes the hydrodynamic action on the dam during which the compressive/tensile stress in the dam body changes rapidly and large changes in stress can be observed during the earthquake event. In the absence of actual dam failure process monitoring data, dynamic model tests and finite element methods are the main methods to understand the nonlinear dynamic response behavior of concrete dams and earthquake failure modes. Therefore, it is very important to use the finite element program for the dynamic seismic stress analyses to obtain transparent information on the response behavior of concrete gravity dams.

[1] proposed a two-step process for the dam safety assessment and elastic design analysis: a simplified

analysis procedure in which the response caused by only the fundamental vibration mode is directly estimated from the seismic design spectrum; and a refined response history analysis procedure for finite element idealizations of the dam monolith, both of these analysis procedures included the dam-water-foundation interaction effects and water compressibility. Further changes have been made to the simplified procedure, which is a "static correction" method used to account for the response contribution of higher vibration modes. [2] carried out a study of the parameters in the Koyna dam.To simulate the damage caused to the dam under seismic movement in real time the Nonlinear characterisitcs of the concrete are considered through the concrete damaged plasticity model. The behavior of dam structure under the action of an earthquake depends largely on the foundation and the reservoir. As the foundation modulus decreases, the displacements increases. [3]concluded that the linear model provides a good starting point for preliminary design of the dam. Precise estimation of vibration modes, including the effects of foundation flexibility can better estimate inertial forces and hydrodynamic interactions. When the modulus of elasticity of the bedrock to the dam concrete is low, considering the flexibility of the foundation when determining the mode shapes has a significant influence on the effective modal quality, hydrodynamic pressure, and foundation shear. The time history method has been extensively used to dertermine the seismic behavior of dams. The selected ground motion accelerograms as the seismic input for two-dimensional analyses of concrete dams are usually applied to the foundation base in the upstream-downstream direction whereas the input in downstream-upstream direction is usually neglected. But the past studies have indicated that the direction of the seismic input relative to the major structural axis has a significant impact on the structural response. Changing the direction of this seismic input would result in a completely different structural response, which can fundamentally change the analysis results of the damage characteristics and damage level.

The direction of earthquake event will affect the cumulative failure process of dams, resulting in different damage mechanisms. The purpose of this research is to better understand the differences in structural response and damage parameters of the concrete gravity dam in the single seismic event with incident directions. To achieve this goal,seismic events in two directions were applied along the upstream-downstream and downstream-upstream directions along the horizontal axis of the proposed Nalgaad dam 2D model. The non-linear dynamic response of the concrete gravity dam-reservoir-foundation system is carried out under the recorded seismic event. Then the influence of the direction of a single earthquake is studied.[4]

2. INCIDENT EARTHQUAKE DIRECTION FOR TWO-DIMENSIONAL SEISMIC PERFORMANCE ANALYSIS

The length of the concrete dam along the axis is generally long. The concrete gravity dam adopts independent integral structure separated by contraction joints to meet the deformation requirements of the foundation and reduce the cracking caused by contraction. Due to the existence of shrinkage joints, most of the non-linear dynamic response analyses of concrete dams are carried out through two-dimensional models. In the time history analysis method for evaluating the seismic behavior of 2D concrete gravity dam model, the seismic accelerations are applied to the foundation as input. However, due to the uncertainty of the epicenter position of the next earthquake, the different incident directions of the selected strong ground motion records must be considered to assess the maximum structural requirements. Therefore, for the analysis of 2D seismic performance of the concrete gravity dam reservoir foundation system, two directions of earthquake occurence should be considered i.e. one in upstream-downstream direction and the other in downstream-upstream direction.

3. FINITE ELEMENT MODEL

3.1 Finite element model of dam-resrvoir-foundation system

The concrete gravity dam of Nalgaad Hydropower Project, Jajarkot, Nepal has been taken as a reference model with some modifications for the analysis. A 2D finite element modelling is used for the analysis considering the dam-reservoir-foundation interaction which requires contact modelling, fluid modelling, interaction, linear and non-linear analysis. ABAQUS/CAE 2020 has been used as the finite element software for the analysis. The geometry, finite element discretization and material parameters of the Nalgaad dam-reservoir-foundation system is shown in table 1. The tensile strength of concrete is 2.9 MPa and compressive strength is 24.1 MPa. The reservoir water is assumed to be linearly elastic, inviscid and irrotational. In order to consider the energy dissipation in dam-reservoir foundation system, the Rayleigh damping ration of 5 percent is applied to the natural frequencies of the first and third vibration modes which are 16.353 and 39.236 rad/sec. Mass proportional damping coefficient is found out to be 1.154 and the stiffness proportion damping coefficient is found to be 0.0018. The applied loads include self-weight of the dam, hydrostatic force, uplift force, hydrodynamic force and seismic force.

Table 1: Material Properties

Material	Modulus	Poisson's ratio	Density (kg/m^3)
Dam concrete	31 (Elastic modulus)	0.2	2400
Reservoir water	2.07(Bulk modulus)	-	1000
Foundation rock	27.58(Elastic modulus)	0.33	2500

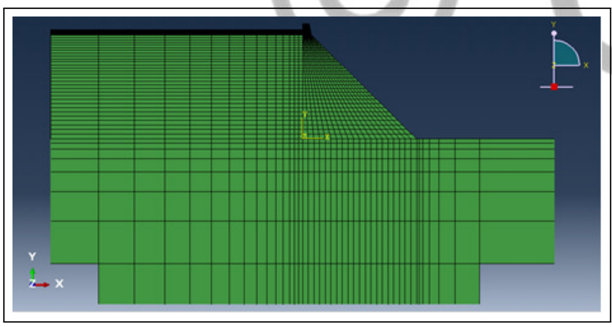

Figure 1: Concrete dam-reseervoir-foundation system on a 2-D model

Dam The analysis model of Nalgaad concrete gravity dam has been modelled with slight modifications in shape and size from the proposed one for the project. The height of the dam is 205m, base width is 204m and crest width is 12m. The dam part is modelled as 2D Plane strain with 900 linear quadrilateral elements of type CPE4R.

Reservoir The reservoir is modelled with 645 linear quadrilateral elements of type AC2D4 which are acoustic elements. In full reservoir condition, the height of reservoir is 195m from the heel of the dam. The length of water reservoir is 450m from the upstream face of the dam. Different boundary conditions have applied for the top surface, bottom and at the back end of the reservoir. As hydrodynamic pressure is very important component for seismic analysis of concrete gravity dam, so to simulate the hydrodynamic pressure different boundary conditions have been applied and acoustic elements have been used.

Foundation EM-1110-2-6051, 2003 has been followed for the foundation size. The manual states that for the standard model, the minimum length of foundation along the downstream direction from the toe of the dam should be equal to the height of the dam. Also, the manual states that the minimum depth of foundation should be height of the dam. Accordingly, 2D plain strain with 336 linear quadrilateral elements with 56 elements of type DC2D4 and 280 elements of type CPE4R has been used for foundation modelling of size 900*295m. Analysis has been performed using foundation mass and damping.

Dam-foundation interaction For effective simulation of mechanical behavior at the dam-foundation interface, contact base pair is introduced at the dam-foundation interface. The dam-foundation interface is defined with the surface-to-surface contact. For the tangential behavior, penalty formulation is used for which the friction angle and a maximum elastic slip has to be specified. Friction angle is taken as 450 i.e., coefficient of friction is 1 and the maximum elastic slip is taken as 0.5 percent (0.0005 default value). For normal contact, formulation is set to hard contact.

Reservoir boundary conditions By neglecting the wave formation at the top of reservoir, pressure at the top of reservoir is always kept zero. The back end of the reservoir is non-reflecting wave condition, which implies that hydrodynamic waves does not reflect from the reservoir end. The bottom of the reservoir is taken as absorptive by assigning impedance at the reservoir-foundation interaction. The wave reflection coefficient is taken as 0.44.

Fluid-structure-interaction The surface-based fluid-structure interaction technique is utilized for the modelling of dam-reservoir and dam-foundation interaction whereby the fluid (reservoir) surface is taken as the slave surface and the solid (dam and

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foundation) surfaces are assigned as the master surface.

Load For the design of concrete gravity dams, the loads required for the stability and stress analysis of dam has to be determined. Loads considered in the seismic analysis of concrete gravity dam are static load which includes self-weight of the dam, hydrostatic pressure at the upstream dam face and uplift pressure at the base of the dam. and seismic load.

Support conditions The standard model is used as per EM-1110-2-6051. The base and side of the foundation is changed to infinite elements by changing the order of the nodes.

The linear analysis alone is not sufficient and requires non-linear analysis (EM-1110-2-6051, 2003). Therefore, for the accurate prediction of stress within a dam, concrete damage plasticity (CDP) is used to account for material non-linearity. The CDP model includes strain hardening/softening behavior to capture the initiation and propagation of cracks in the dam body. This model was first developed by Lubliner et al. (1989) and later improved by Lee and Fenves (1998) to provide the real fracture profile of the Nalgaad dam. The crack profile is by damage variables and plastic deformation.

Input ground motions To get the non-linear behavior of concrete gravity dams subjected to seismic event by time history analysis method, seven as-recorded single seismic event is selected namely Chichi (0.361 PGA), Imperial valley (0.3152 PGA), Kobe (0.3447 PGA), Kocaeli (0.349 PGA), Landers (0.7803 PGA), Loma Prieta (0.3674 PGA) and Northridge (0.5683 PGA).

4. EFFECTS OF EARTHQUAKE DIRECTION

When the time history analysis method is chosen to evaluate the seismic performance of concrete gravity dam based on the 2-D model, the earthquake accelerations (man-made or recorded) are applied to the foundation base as load input. Therefore, due to the uncertainty of the epicenter location of the next earthquake, different incident directions from the selected ground motion log must be considered to assess the maximum structural requirements. Therefore, for the seismic performance analysis of the two dimensional concrete gravity dam-reservoir-foundation system, the two incident directions of the earthquake should be considered.

To achieve this, seismic events in two directions (i.e., upstream-downstream and downstream-upstream) are applied along the horizontal axis of the two-dimensional model. The nonlinear dynamic response of the concrete dam reservoir foundation system under the seven-recorded main shock is studied. The influence of the direction of a single seismic event is then investigated. Results obtained from the analysis are compared in terms of crest displacement, tensile damage profile, principal stress at the heel, plastic strain at the heel.

4.1 Crest displacement

The time histories of the horizontal displacements at the crest of the dam with respect to dam bottom subjected to seven seismic events with two incidence directions are shown in fig.2. The positive displacement is assumed towards the downstream direction whereas negative displacement is assumed towards the upstream direction.

It has been observed from the figures that direction of earthquake has a significant influence on the nonlinear dynamic response of the dam. In most cases, a change in the direction of the earthquake affects the direction of the maximum horizontal displacement (represented by the positive and negative values) with five seismic events giving maximum crest displacement for upstream-downstream direction and two seismic events giving maximum crest displacement in downstream-upstream direction.

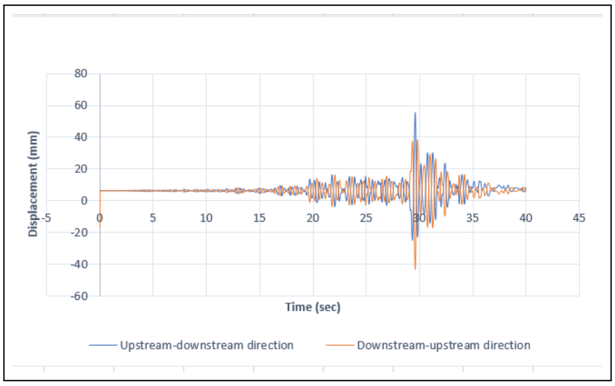

Figure 2: Relative displacement of crest with respect to bottom of dam for Chi Chi earthquake

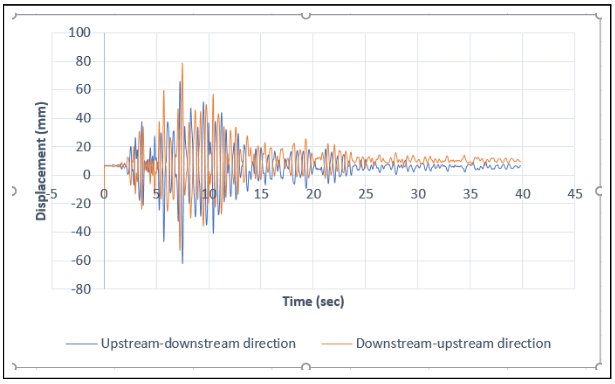

Figure 3: Relative displacement of crest with respect to bottom of dam for Kobe earthquake

4.2 Damage profile

Figure 4 shows the damage profile of the Nalgaad gravity dam after the major earthquakes in different incident directions. The contour values displayed on the damage model map are calculated using the CDP model and represent specific damage variables. In the CDP model, the concrete damage variable is found out using the corresponding tensile and compressive strain, which ranges from 0 (intact material) to 1 (fully damaged material). Figure 4 distinctly shows the differences in the damage patterns when the registered seismic events are applied along the upstream-downstream and downstream-upstream directions with three seismic events showing more damage in upstream-downstream direction and four seismic events showing more damage in downstream-upstream direction. The damage propagation processes of the upper part of the dam is significantly affected by changing the earthquake directions. The damage accumulated on the heel is not very sensitive to the direction of impact of the earthquake. Although cracked profiles at the top of the dam started at the change on the slope of the downstream face in most analyses, the direction of the propagation of cracks and the length of crack in the subsequent analysis differed significantly under different direction of the earthquake. In some cases, cracks are expected to form near the center of the upstream face and extend towards the downstream face of the dam when subjected to ground motions in the upstream-downstream direction. However, if subjected to the same ground movement in the downstream-upstream direction, the trajectory of the dam crack will completely change.

It can also be seen from the figure that there are significant differences in the failure profile of the top of the dam under the action of a single earthquake. This may be because the selected individual ground movement has different ground motion characteristics (i.e., frequency content, PGA, and strong motion duration).

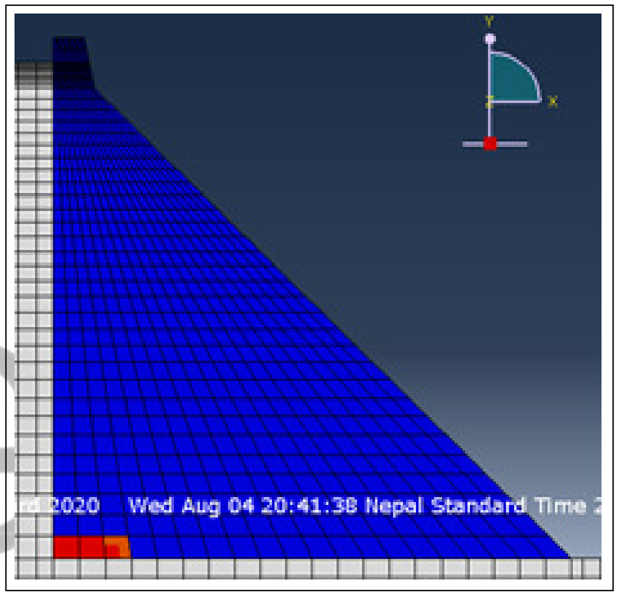

Figure 4: Upstream-downstream of Chi chi earthquake

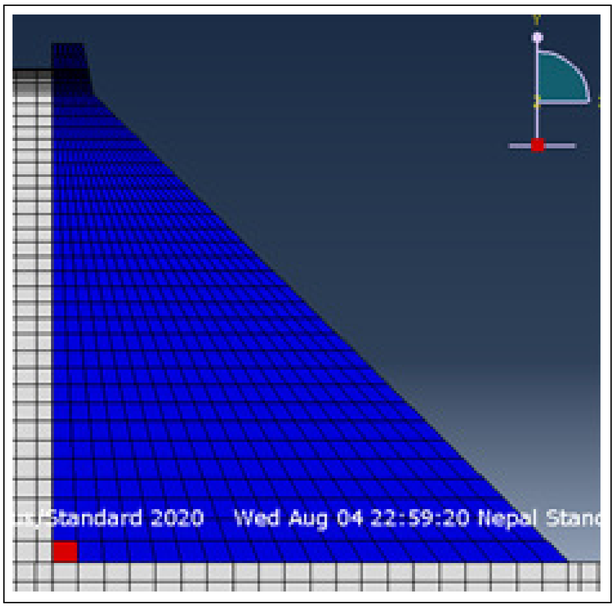

Figure 5: Downstream-upstream of Chi chi earthquake

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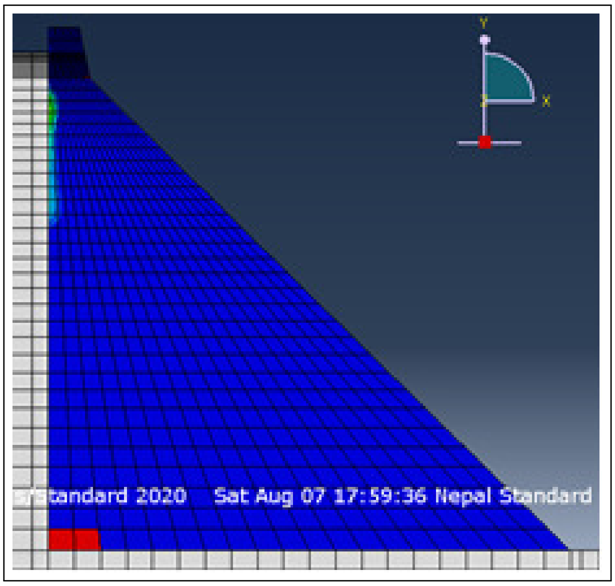

Figure 6: Upstream-downstream of Landers earthquake

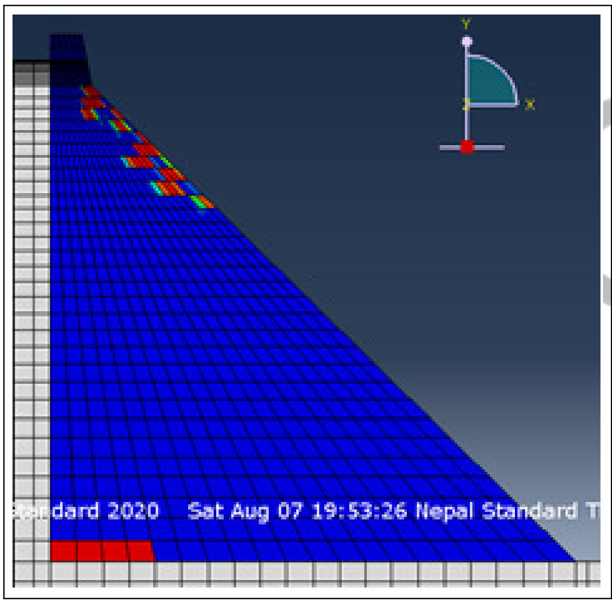

Figure 7: Downstream-upstream of Landers earthquake

4.3 Principal stress at the heel of dam

Studies on concrete gravity dam have shown that the principal stress is maximum at the heel, change of slope at downstream face and at the same level at upstream face. Though it depends on the character of ground motion as well. Results obtained from our analysis shows that the principal stress at the heel of dam is maximum when the incidence earthquake direction is from downstream-upstream direction for five seismic events while only for two seismic events it is maximum for the upstream-downstream direction.

4.4 Plastic strain at the heel of dam

Results obtained from non-linear time history analysis of plastic strain at the heel of the dam shows that out of seven seismic events four seismic events have shown higher plastic strain for the upstream-downstream direction whereas the other three seismic events have shown higher plastic strain for the downstream-upstream direction.

Thus, the differences in the damage parameters, maximum displacement demands, principal stresses, plastic strains with the earthquake direction shows different performances in different directions. This might be due to the distinctive variations and degradations of the structural properties (i.e., strength, stiffness and damping) in different directions, unsymmetric cross-section of concrete gravity dam, differences in ground motion characteristics (i.e., frequency content, PGA, strong motion duration, V/H ratio), near field and far field effects of selected ground motions.

5. CONCLUSION AND RECOMMENDATIONS

This study examined the non-linear dynamic behavior of a two-dimensional concrete gravity dam-reservoir-foundation system under a single earthquake event in two different directions and based on the 2-D model, the influence of direction on the structural requirements of the dam was assessed. Based on the results, the following conclusions can be drawn:

1. Changing the seismic direction of a single seismic event has a significant impact on the damage and the maximum displacement demands of the dam.

2. Applying seismic logs along the horizontal axis in the upstream-downstream direction can sometimes result in severe underestimation of the earthquake damage.

The above-mentioned conclusions are based on the non-linear dynamic response of the proposed Nalgaad gravity dam under seven specific seismic events. Therefore, these conclusions may not apply to all gravity dams and ground motions. In order to better assess the directional effects of earthquakes, three-dimensional seismic damage analysis, seismic fragility analysis, ample strong ground motion records and more angle of incidence should be considered for further research.

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