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Seismic Response of Concrete Gravity Dam: Effect of Foundation Elasticity and Geometry of Dam

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Abstract
The Dynamic properties of any structures are function of its mass and stiffness distribution. And the stiffness and mass distribution is defined by the geometric profile of the structure. A gravity dam is uniform along its longitudinal axis, therefore the cross-sectional profile plays an important role for dynamic properties of the dam. A concrete gravity dam (210m) proposed for Nalgad hydropower project in Jajarkot, Nepal is modeled in ABAQUS 2017 considering the dam-foundation-reservoir interaction. A modal analysis has been performed to access the effect of foundation elasticity (E_f) on fundamental natural frequency of the dam. A linear time history has been carried out using Northridge ground motion to find out the seismic response of dam having different dam geometry. It has been found that the change in modulus of elasticity of foundation effects the fundamental frequency of the dam up to a particular value. Additionally, it has been found that dam downstream (D/S) shape effects the seismic response of dam, curved shape at downstream instead of slope gives less response values for same cross sectional area.

Keywords
Gravity dam, dam-foundation-reservoir interaction, seismic response, modulus of elasticity.

1. Introduction

Nepal lies in the region of highly active tectonic zone. Construction of each mega structure inside the country requires high degree of seismic performance. Nepal has high potential of hydropower generation but the country is facing high firm energy deficit. To increase the firm energy capacity it requires to develop storage high dam hydropower projects. A concrete gravity dam is a solid structure which takes of all external forces simply by its own weight, shape and strength of concrete. The concrete gravity dams are subjected static type of loads viz., dead loads, reservoir and tail water loads, uplift pressure, silt pressures etc., and dynamic type of loads viz., seismic forces, wind forces etc, but current study ignores silt pressure and wind load. The seismic forces on a structure depend largely on the ground motions during the earthquakes. The response of a dam subjected to seismic loading, exhibits a combined effect of the interaction among dam, reservoir and foundation systems. Hence, there is a significant importance in studying the various aspects influencing the seismic response of a large concrete gravity dams for its safety. The magnitudes of compressive/tensile stress within the dam body rapidly change and huge variation in stresses can be observed during the earthquakes. Therefore, a paramount importance is gained for the dynamic seismic stress analyses with finite element procedures to obtain a clear insight into the response behavior of concrete gravity dams. Construction of such dam requires high capital, manpower and time. However failure of such dam due to various reason can be devastating .There are research work in the dam shape optimization to seismic response. Almost work performed for D/S slope shape, there no study for D/S shape other than slope.This inspires me to the research in D/S shape optimization of the dam.

2. Literature survey

Recently many research work have been done on the behavior of concrete gravity dam.[1] Studied the nonlinear time history response of a high dam to near field earthquake. This study shows that near field ground motions are more vulnerable than that of far field ground motions. Peak ground velocity and frequency content is also responsible along with PGA.[2] Studied the effect of geometric change on the seismic response of a dam. It shows that downstream (D/S) slope of a dam and the height to base width ratio have significant effect on the dam response. [3] Preliminary design and evaluation of concrete gravity sections is usually performed using the simplified response spectrum method proposed by Fenvis and Chopra.[4] Shows that modeling parameters effects on the dynamic properties of a dam. It shows that the reservoir modeling with acoustic elements gives better estimation of hydrodynamic forces than that of calculated by Westerguard added mass method.

3. Objective of Research

The main objective of this research is to find out the effect of downstream (D/S) shape of a dam on the seismic response, e.g. crest displacement, principal stress and toe slip. In addition, this study aims to analyze the effect of change in modulus of elasticity (E_f) of dam foundation on the fundamental natural frequency of the dam.

4. Theoretical Approach

Theoretical basis of the modelling is as below[5]

4.1 (i) Dam-Reservoir Interaction

The motion of a reservoir can be represented by Helmholtz's equation

$$\frac{1}{C^2} \times \ddot{P} = \nabla^2 \times P \quad (1)$$

Where P is hydrodynamic pressure and C is speed of wave in water. Pressure at free surface of reservoir is zero.

4.2 Dam-foundation-reservoir interaction

The effect of dam-reservoir-foundation interaction can be written as follows

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} - [M]\{\ddot{u}_g\} = \{F_1\} + \{Q\}\{P\} \quad (2)$$

$$[G]\{\ddot{p}\} + [C']\{\dot{p}\} + [K']\{p\} = \{F_2\} - \rho[Q]\{\ddot{u}\} \quad (3)$$

Where $[M]$,$[K]$,$[C]$ are the mass, stiffness and damping matrix respectively of structure including dam and foundation. $[G]$,$[K']$,$[C']$ are the mass, stiffness and damping matrix of reservoir respectively.$[Q]$ is coupling matrix,$\{F_1\}$ is vector of body force and hydrostatic force. $\{F_2\}$ is the component of the force due to acceleration at the boundaries of the dam-reservoir and reservoir-foundation. $\{p\}$ and $\{u\}$ are the vectors of pressures and displacements. $\{\ddot{u}_g\}$ is the ground acceleration and ρ is the density of the fluid.

5. FEM modeling and material properties

2D finite element modeling of the dam-foundation-reservoir assembly has been done in ABAQUS/CAE 2017.

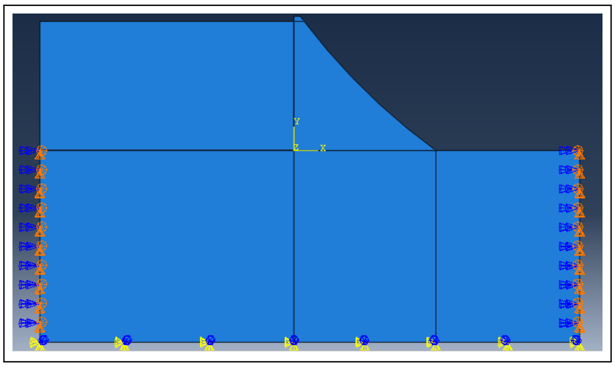

Figure 1: Dam-foundation-reservoir model

5.1 Dam

The proposed dam of Nalgaad hydropower project modeled for analysis. Height of the dam is 210m, base width is 224m and crest width is 10m. Modulus of elasticity is 31Gpa, density is 2400kg/m^3, Poissons ratio is 0.20[6].It is modeled with 2D plane stress elements.

5.2 Foundation

Size of dam chosen for analysis as per the EM-1110-2-6053[7]. Length is 950m and depth is 300m. Modulus of elasticity is taken as 41.4 GPa, density is 2500kg/m^3, Poisson's ratio is 0.33, foundation is modelled as 2D plane stain elements

5.3 Reservoir

Reservoir is modeled at full supply level i.e. 202 m height from toe of the dam and length is 400m. Bulk modulus water is 2.07 GPa, density of water is 1000 kg/m^3. To incorporate the hydrodynamic effects, the reservoir is modeled using acoustic elements.

5.4 Boundary Conditions

Support condition are used as per EM-1110-2-6051[7]. Roller support are used at vertical sides of foundation in which displacement in horizontal direction is allowed. Fixed support is used at base of foundation and input ground motion are applied at base of foundation. At top of the reservoir acoustic pressure is always equal to the atmospheric pressure[4] back end reservoir acoustic impedance boundary condition for non-reflecting waves. To properly simulate the mechanical behavior at the dam-foundation interface, contact based pair is defined at dam foundation interface. The surface based fluid-structure interaction approach (Abaqus 2017) is utilized for the modeling of the dam-reservoir and foundation-reservoir interaction[8].

6. Ground Motion Input

While performing the analysis of large dams in tectonically active country like Nepal, it would be more appropriate to use the near-field records than code based method or far-field earthquake records[1]. Therefore, Northridge (Mw=6.69), 1994 near field ground motion is selected as input ground motion for the analysis. PGA of earthquake is 0.5683g. Direct peak scaling in done to 1.24g PGA of safety evaluation earthquake (SEE) for Nalgaad dam.

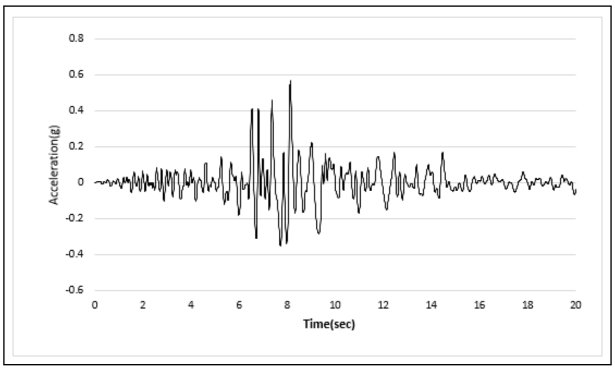

Figure 2: Acceleration Time history of Northridge earthquake

7. Linear Time History Analysis

Linear time history analysis of dam has been performed. The equation of nonlinear time history is

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = p(t) \tag{4}$$

Where m, c, k are mass, damping and stiffness of structure respectively. $u(t)$,$\dot{u}(t)$and $\ddot{u}(t)$ are nodal displacement, velocity and acceleration vectors respectively and p(t) is effective load vector. [9]

8. Result and Discussion

(i) Free vibration analysis is performed to find out the relationship between the modulus of elasticity of foundation and fundamental natural frequency of dam. Keeping dam parameter constant, different range of modulus of elasticity is used for the analysis. Modal analysis has been performed for reservoir full case and reservoir empty case. Result obtained analysis presented in figure 3.

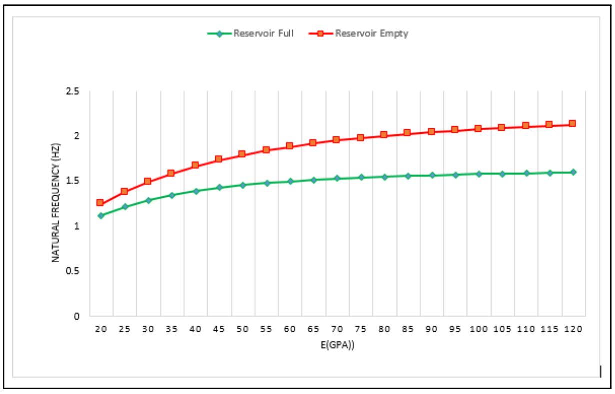

Figure 3: Modulus of elasticity of foundation vs fundamental frequency of dam

From the above graph, the curve for empty reservoir condition is seen steeper than that for full reservoir condition. It means that the foundation modulus of elasticity has less effect in the fundamental frequencies when the reservoir is full. The graph shows that if E_f of foundation is 3 to 4 times that of dam, E_f doesn't make significant effect on fundamental frequency.

(ii) Two different sections of the dam having different geometry but same cross sectional area has been analyzed for seismic response to Northridge earthquake using linear time history method.

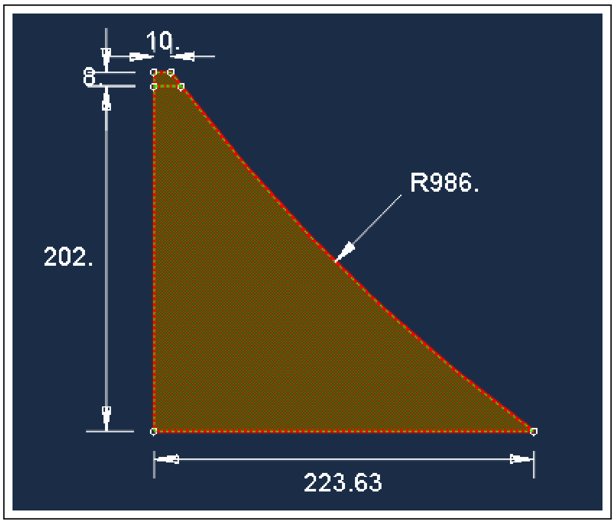

Figure 4: Model-1(M1), downstream shape curve (All dimensions are in meter)

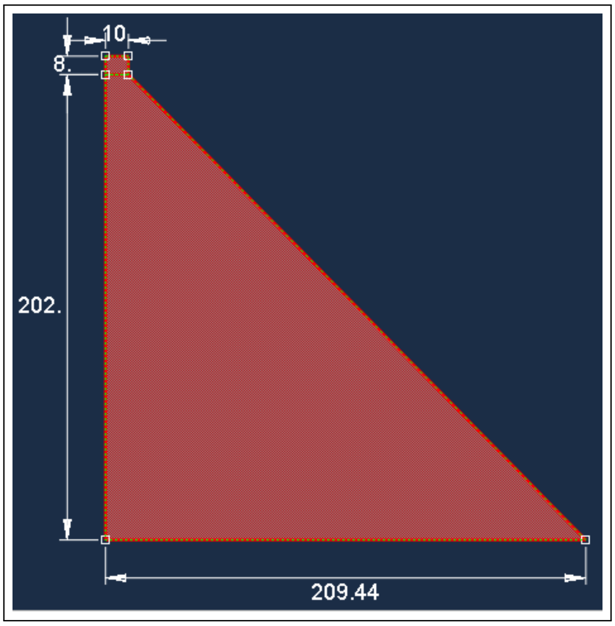

Figure 5: Model-2 (M2) downstream shape slope.

(a) Crest displacement response to Northridge earthquake Model-1 and model-2 are subjected to Northridge earthquake. Time history of crest displacement of both models are shown in figure-6. Maximum crest displacement for model-1 is found to be 0.1415 m and that of model-2 is 0.1869 m. From above analysis it can be said that section which have curve D/S shape has less crest displacement that of section having slope D/S shape.

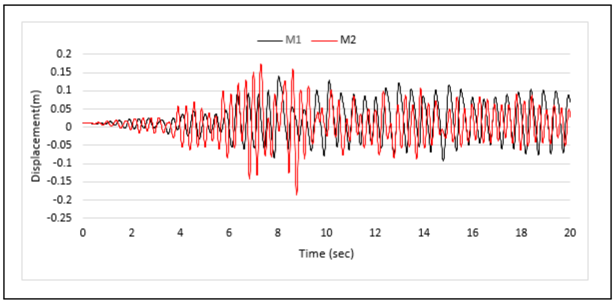

Figure 6: Crest displacement time history

(b) Principal stress response at heel of dam

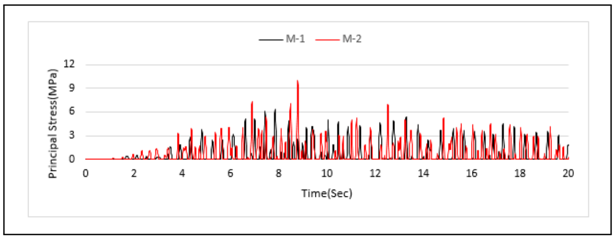

Figure 7: Principal stress time history at the heel of the dam

From the time history of principal stress of model-1 and model-2, it is seen that model -2 has more principal stress response in comparison of model- 1. Maximum value of principal stress for model-1 is 6.311 MPa and that of model-2 is 10.058 MPa. The Dam having curve shape in the D/S is seen to have less principal stress than that of having slope.

(c) Toe slip response of dam.

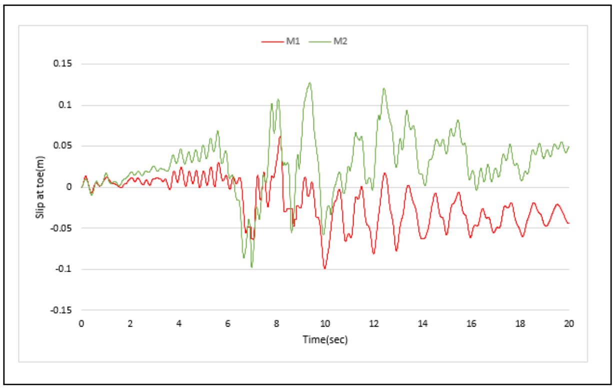

Figure 8: Time history of toe slip of dam.

Time history of toe slip show that the model-1 has less toe slip response than that of model-2. Also, the model-2 shows permanent displacement of about 5 cm.

9. Conclusion and Recommendations

From the above analysis following conclusions can be made

(i) This study concludes that the effect of foundation modulus of elasticity in the fundamental natural frequency of dam is significant up to certain value after which it doesn't effects the fundamental natural period significantly. If the modulus of elasticity of foundation value 3 to 4 times greater than that of dam, the seismic analysis can be assumed fixed base condition.

(ii) In addition, D/S shape of a dam plays significant role in the seismic performance. The dam with D/S shape curve shows better performance than that of dam having D/S shape slope to same ground motion input. Thus, for the optimization of dam shape, curved D/S is recommended instead of sloped.

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