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Investigation of Effects of Geometry and Geotechnical Properties on Seismic Response of Concrete Gravity Dam

Pawan Chand[1], Dr. Rajan Suwal[2]

[1]*Department of Civil Engineering, Institute of Engineering, Tribhuvan University, Kathmandu, Nepal*

[1]*Department of Civil Engineering, Institute of Engineering, Tribhuvan University, Kathmandu, Nepal*

Abstract: In the present study proposed a dam of Nalgaad hydropower project is chosen for the analysis with some modification has been done for the analysis. Finite element modeling has been done considering dam-reservoir- foundation interaction. Model analysis has been performed to find out the effect of the foundation modulus of elasticity on a fundamental natural frequency of a dam. It has been found that the foundation modulus of elasticity has a significant effect on fundamental natural frequency up to certain values i.e. ratio of modulus of elasticity of foundation to that of the dam is approximate to 4. Also, it has been found that the modulus of elasticity of foundation has more effect on the fundamental frequency when the reservoir is empty rather than the reservoir is full. The modal analysis concludes that if the ratio of modulus of elasticity of foundation to that of the dam is greater or equal to four, dynamic analysis can be done assuming a fixed base condition of the dam. Also, analysis has been performed for dam shape optimization. Two different shapes of the dam having the same cross-sectional area are chosen, one having downstream shape curve and others have downstream shape slope. Non-linear time history analysis has been performed for both models. Concrete damage plasticity (CDP) is used for material non-linearity. Responses of both models compared in terms of crest displacement, principal stress, plastic strain, and toe slip. It has been concluded that dam having a downstream shape curve has better seismic performance that of dam having downstream shape slope.

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

1. Introduction

Nepal lies in the region of a highly active tectonic zone. Construction of each critical structure inside the country requires a high degree of seismic performance. Nepal has a high potential of hydropower generation but the country is facing a 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 that takes of all external forces simply by its weight, shape, and strength of concrete. The concrete gravity dams are subjected to the static type of loads viz., dead loads, reservoir and tailwater loads, uplift pressure, silt pressures, etc., and the dynamic type of loads viz., seismic forces, wind forces, etc., but the 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 significant importance in studying the various aspects influencing the seismic response of large concrete gravity dams for its safety. The magnitudes of compressive/tensile stress within the dam body rapidly change and a huge variation in stresses can be observed during the earthquakes. Therefore, 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 a dam requires high capital, manpower, and time. However, the failure of such a dam due to various reasons can be devastating. There is research work in the dam shape optimization to the 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 has been done on the behavior of a concrete gravity dam studied the nonlinear time history response of a high dam to near field earthquake [1]. This study shows that near field ground motions are more vulnerable than that of far-field ground motions. Peak ground velocity and frequency content are also responsible along with PGA. [2] Studied the effect of a 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 a significant effect on the dam response. [3] Preliminary design and evaluation of concrete gravity sections are usually performed using the simplified response spectrum method proposed by Fenvis and Chopra.[4] Shows that modeling parameter's effects on the dynamic properties of a dam. It shows that the reservoir modeling with acoustic elements gives a better estimation of hydrodynamic forces than that calculated by Westerguard added mass method. The modeling procedure and analysis method is based on EM-1110-2-6051.

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, cracking strain at the heel, and toe slip. Also, this study aims to analyze the effect of change in modulus of elasticity (E_f) of the dam foundation on the fundamental natural frequency of the dam.

4. Theoretical Approach

The theoretical basis of the modeling is as below[6]

4.1 Dam-Reservoir Interaction

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

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

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

4.2 Dam-foundation-reservoir interaction

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

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

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

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 the reservoir respectively.[Q] is the coupling matrix,$\{F_1\}$ is a vector of body force and hydrostatic force. 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. $\{\ddot{u}\}$ is the ground acceleration and ρ is the density of the fluid.

4.3 Concrete damaged plasticity

Under uniaxial tensile loading, damage propagates in a direction transverse to the stress direction[9]. The nucleation and propagation of damage, therefore, causes a reduction of the available load-carrying area, which in turn leads before to an increase in effective stress. This effect is less pronounced under compressive loading since damage runs parallel to the loading direction; however, after a significant amount of crushing, the effective load-carrying area is significantly reduced. The effective uniaxial stresses, $\underline{\sigma}_t$ and $\underline{\sigma}_c$.The tensile inelastic behavior of concrete is calculated based on the simplified damage plasticity model for concrete. The concrete tensile behavior is defined in terms of a stress-strain relationship. A plot of tensile stress and inelastic strain is plotted as shown in figure-1, in which σ_t and ε_p denote the tensile stress and cracking strain respectively. Different experiments show that the tensile strength of concrete is about 10% of maximum compressive strength

$$\underline{\sigma}_t = \frac{\sigma_t}{(1-d_t)} = D_0(\varepsilon_t - \varepsilon_t^p) \qquad (4)$$

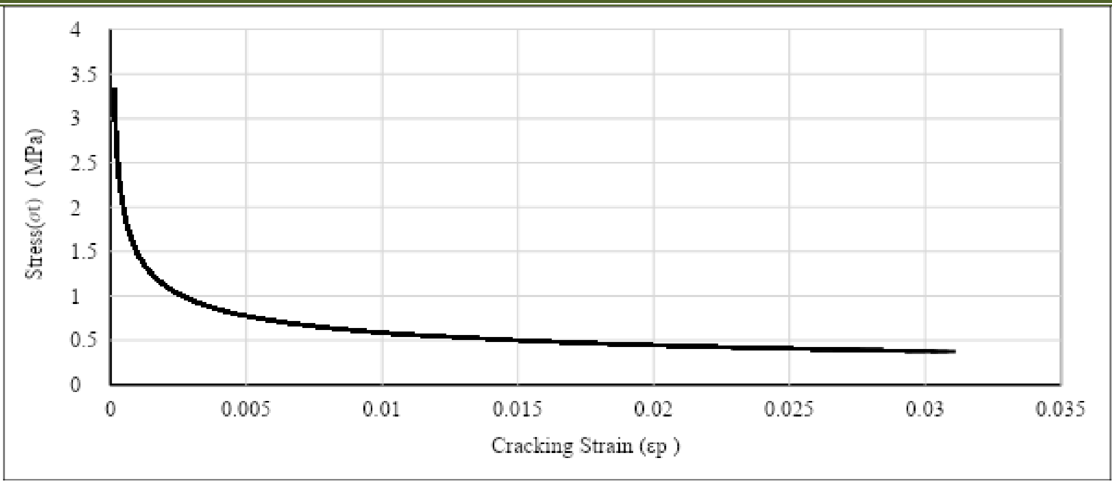

Fig. 1: Non-linear tensile behavior of M30 Concrete

Experimental tests show that concrete behaves in a highly nonlinear manner in uniaxial compression. Uniaxial stress-strain shows linear relations up to 50% of the maximum compressive strength of concrete. Compressive stress rises to maximum compressive strength, this part is known as hardening. After that curve falls gradually, this part is known as softening. For M30 grade of concrete, the compressive stress-strain curve shows a linear relationship up to 15 MPa, after that it shows non-linear behavior is as

$$\underline{\sigma}_c = \frac{\sigma_c}{(1-d_c)} = D_0\left(\varepsilon_c - \varepsilon_c^p\right) \quad (5)$$

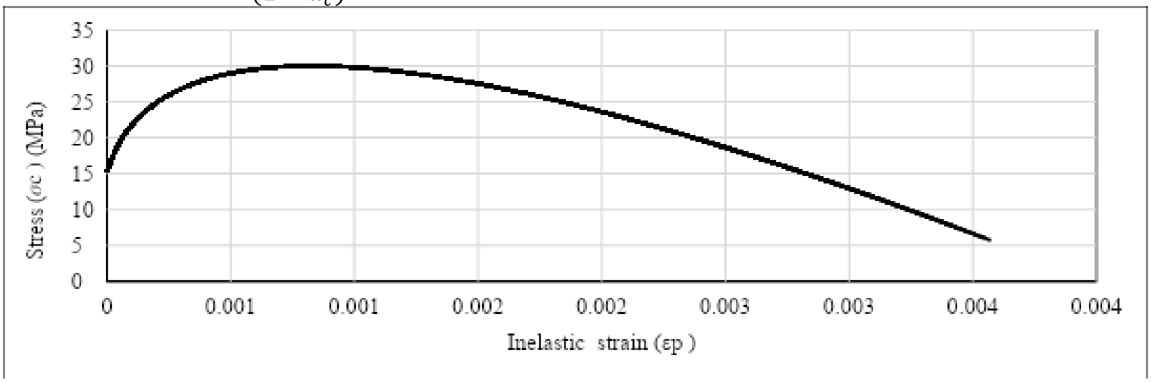

Fig. 2: Non-linear compressive behavior of M30 concrete

5. FEM modeling and material properties

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

5.1 Dam

The proposed dam of the Nalgaad hydropower project modeled for analysis. The height of the dam is 210m, base width is 224m and crest width is 10m. Modulus of elasticity is 31Gpa, density is 2400kg/m3, Poissons ratio is 0.20[7]. It is modeled with 2D plane strain elements.

5.2 Foundation

Size of dam chosen for analysis as per the EM-1110-2-6053[5]. The 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 0.20, the foundation is modeled as 2D plane stain elements.

5.3 Reservoir

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

5.4 Boundary Conditions

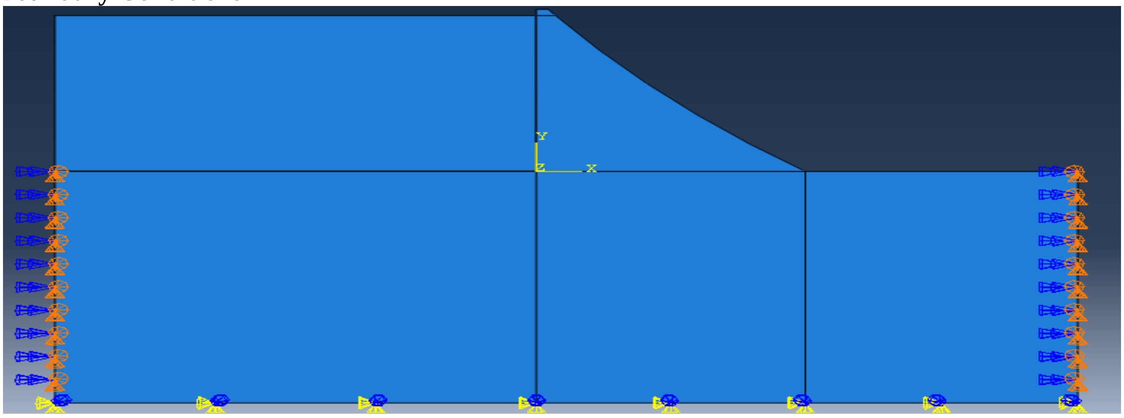

Fig. 3: Support conditions of dam-foundation reservoir system

Support conditions are used as per EM-1110-2-6051[5]. Roller support is used at vertical sides of the foundation in which displacement in the horizontal direction is allowed. Fixed support is used at the base of foundation and input ground motion is applied at the base of the foundation. At top of the reservoir, acoustic pressure is always equal to the atmospheric pressure[4] back end reservoir acoustic impedance boundary condition for nonreflecting waves. Foundation reservoir is defined with defining impedance by using wave reflection coefficient 0.44.

To properly simulate the mechanical behavior at the dam-foundation interface, contact-based pair is defined at the 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 countries 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 (M_w=6.69), 1994 near field ground motion is selected as input ground motion for the analysis. PGA of an earthquake is 0.5683g. Direct peak scaling is done to 1.24g PGA of safety evaluation earthquake (SEE) for the Nalgaad dam.

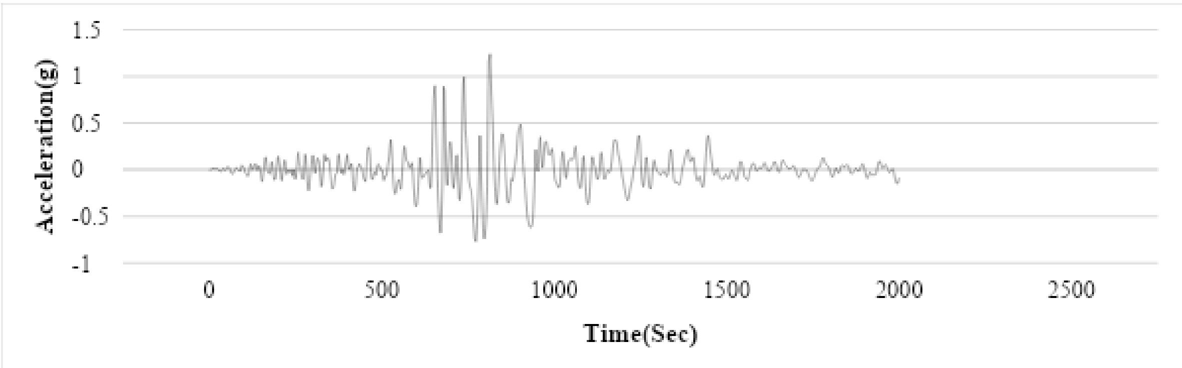

Fig. 4: Scaled time history of Northridge earthquake

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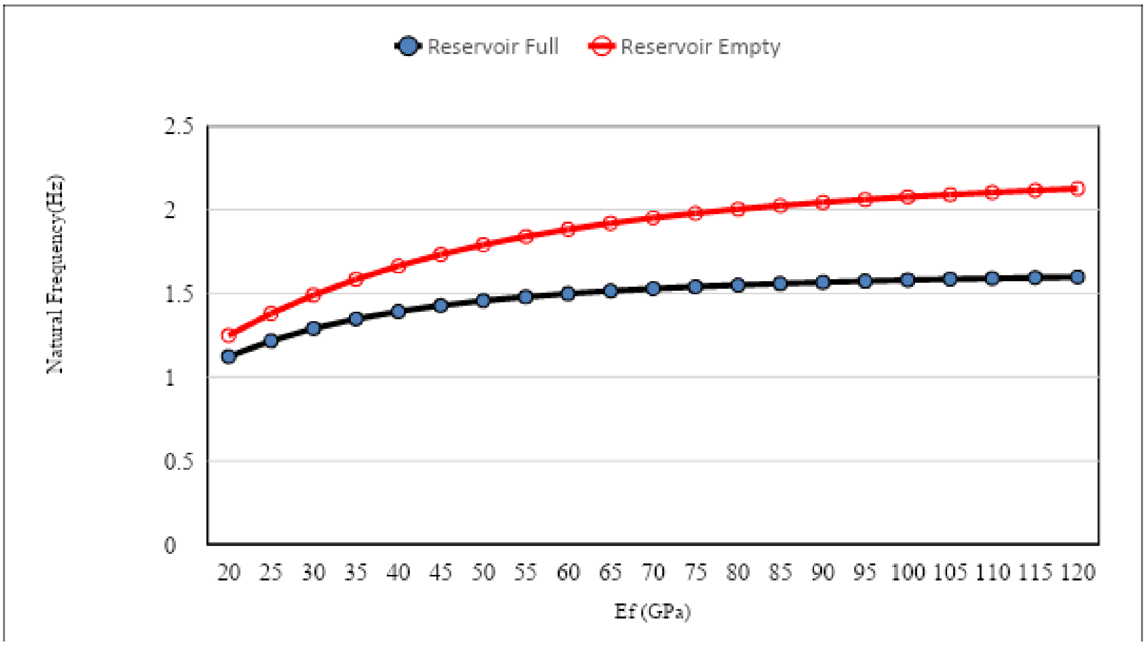
7. Result and Discussion

(i) Free vibration analysis is performed to find out the relationship between the modulus of elasticity of foundation and the fundamental natural frequency of the dam. Keeping the dam parameter constant, a 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 5.



From figure 5, it is seen that initially, the graph has a steep slope, it means that the lower value of E_f has a higher effect on the natural frequency of the dam. As the value of E_f increases line becomes flattered and flatter, it means that as the value of E_f increases its effect on natural frequency decreases. A particular value E_f around 90-100GPa graph becomes flatter, it means that if the value of E_f is 3 to 4 times greater than that of the dam, foundation elasticity doesn't have any significant effect on the natural frequency of dam.

It can be seen that when, E_f/E_d =1, reservoir empty case has about 13.5% more value of fundamental natural frequency than that of reservoir full condition and, when E_f/E_d=4, reservoir empty case has about 24.5% more value of fundamental natural frequency than that of reservoir full condition. It shows that increased damping decreases the effect of modulus of elasticity on the fundamental natural frequency of the dam.

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

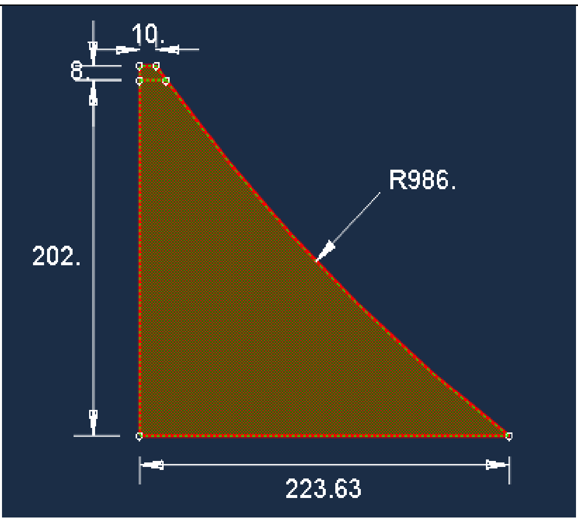


Fig. 6: Model-1(M1), downstream shape curve

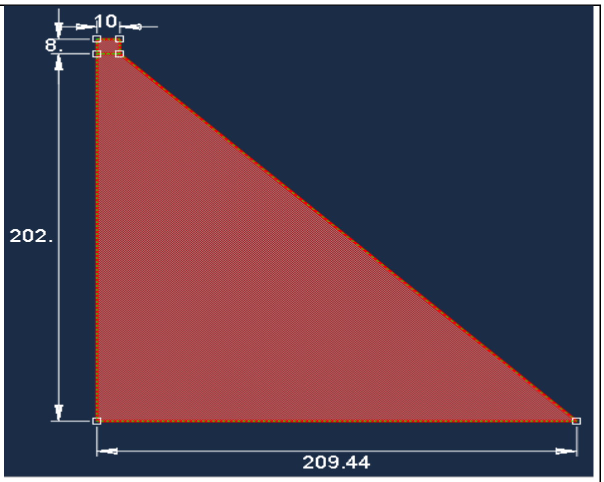


Fig. 7: Model-2(M2), Downstream shape slope

(a) Crest displacement response to the Northridge earthquake

The non-linear analysis also shows that model-1 has less crest displacement that of model-2. The maximum crest displacement of model-1 is 0.2646 m whereas that for model-2 is 0.2981m. Model-1 shows permanent displacement around 10 cm whereas that for model-2 is 20 cm.

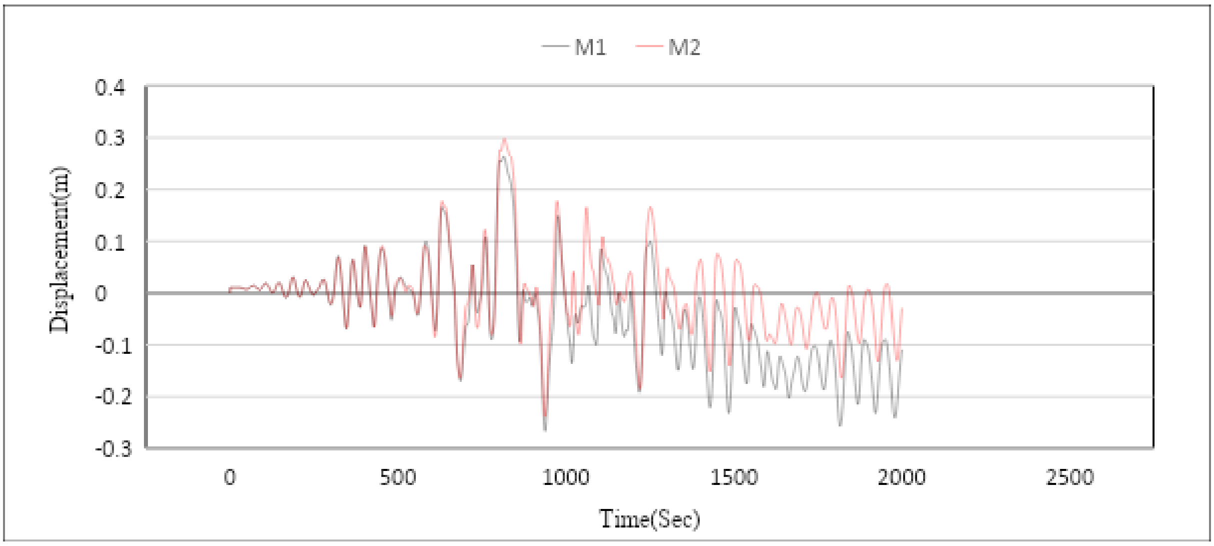


Fig. 8: Crest displacement time history

(b) Principal stress response 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. The maximum value of principal stress for model-1 is 2.61 MPa and that of model-2 is 3.30 MPa. The Dam having curve shape in the D/S is seen to have less principal stress than that of having a slope.

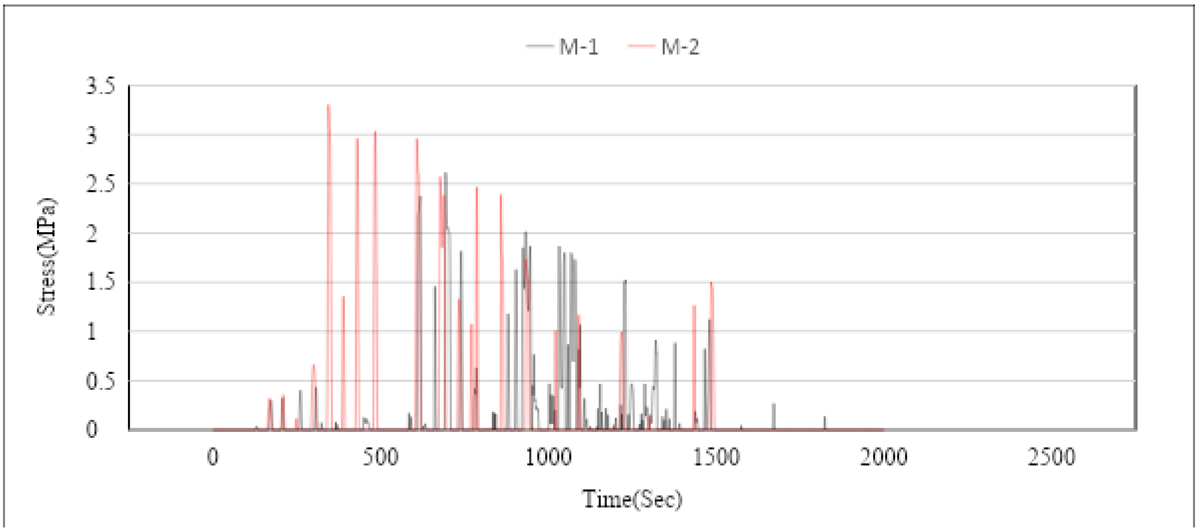


Fig. 9: Principal stress time history at the heel of the dam

(c)Toe slip response of dam.

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

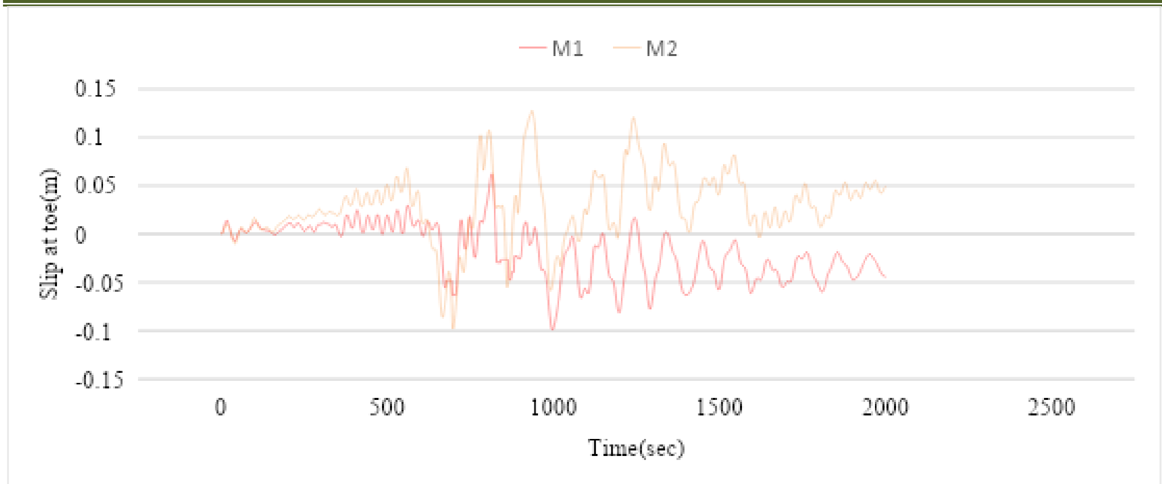


Fig. 10: Time history of toe slip of the dam.

(d) Plastic strain at the heel of the dam

From non-linear time history analysis plastic strain at the heel of the stress dam is calculated for model-1 and model-2. The response history of plastic strain for both models is presented in figure 11. It has been found that plastic strain generated in a model-1 is 0.0015 and that for model-2 is 0.0027.

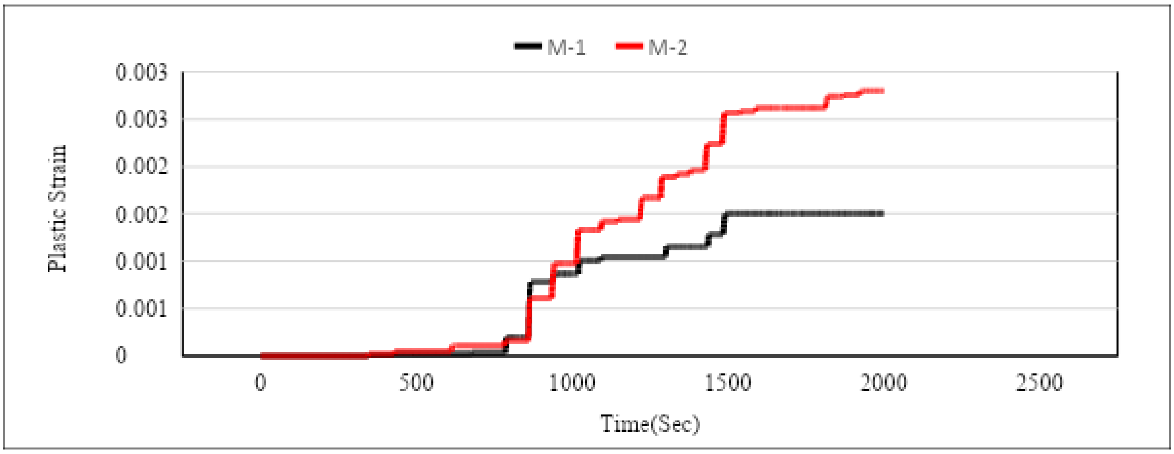


Fig. 11: Plastic strain time history at toe of the dam

8. Conclusions and Recommendations

From the above analysis following conclusions can be made

1. It shows that the effect of the foundation modulus of elasticity in the fundamental natural frequency of the dam up 100 GPa after which it doesn't affect the fundamental natural period significantly. If $E_f/E_d \geq 4$, the seismic analysis can be done assuming the fixed base condition of the dam.
2. Results show that if $E_f/E_d = 1$, the presence of the reservoir decreases the fundamental frequency by about 13.5%. When $E_f/E_d = 4$, the fundamental frequency decreases by about 25% due to the presence of a reservoir. It concludes that increased damping due presence of the reservoir decreases the effects of modulus of elasticity of the foundation on the fundamental natural frequency of the dam.
3. The result obtained in the present study shows that the dam having curve d/s shape shows less crest displacement, principal stress at the heel, plastic strain, and toe slip than that of dam having d/s shape slope. The dam with d/s shape curve shows better performance than that of the dam having d/s shape slope to the same ground motion input. Thus, for the optimization of dam shape, curved d/s is recommended instead of sloped.

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