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Seismic analysis of concrete arch dams considering hydrodynamic effect using Westergaard approach

Muhammet Karabulut*[1], Murat Emre Kartal[2]

ABSTRACT

Earthquake response of arch dams should be calculated under strong ground motion effects. In this study, three-dimensional linear response of an arch dam is investigated. The hydrodynamic effect of water is taken into account with Westergaard approach. Different ground motion effects and also foundation conditions are considered in the finite element analyses. For this purpose, the Type 3 double curvature arch dam was selected for numerical examples. All numerical analyses are carried out by SAP2000 program for full reservoir cases. According to numerical analyses, maximum horizontal displacements and maximum normal stresses are presented by dam height in the largest section. These results are evaluated for five different elastic foundation conditions. The selected foundation conditions of the all models have different sandstone material parameters. Furthermore, near-fault and far-field ground motion effects on the selected arch dam are taken into account by different accelerograms obtained from the Loma Prieta earthquake at various distances.

Keywords: elastic foundation, far field motion, near fault motion, sandstone material, Westergaard approach

1. INTRODUCTION

Arch dams should be constructed on high strength rock foundation not only bottom of the dam but also at slopes because of their design. The arch dams transmit the load of reservoir water and partially weight of dam body to slopes. Consequently, these structures require sophisticated engineering for design and construction to avoid risks from dam failure and ensuing damage. Despite the fact that dam failures are rare, a number of factors including age, construction deficiencies, inadequate maintenance and weather or seismic events contribute to the possibility of a dam's failure [1,2]. Besides, full reservoir conditions should be investigated especially for arch dams. The arch dams design in order to hold huge water pressure behind them. We wonder what if arch dams have full reservoir conditions, how the dam’s behavior changes under strong ground motion effects.

Rigorous analysis of concrete arch dam–reservoir systems is based on the FE and FE–HE method (i.e., Finite Element - (Finite Element–Hyper Element)). This means, the dam is discretized by solid finite elements, while, the reservoir is divided into two parts, a near field region (usually an irregular shape) in the vicinity of the dam and a far field part (assuming a uniform channel), which extends to infinity [3].

In our country, dams which have been built up until now, consist of approximately 75% earthfill dams, 17% rockfill dams and only 2% arch dams

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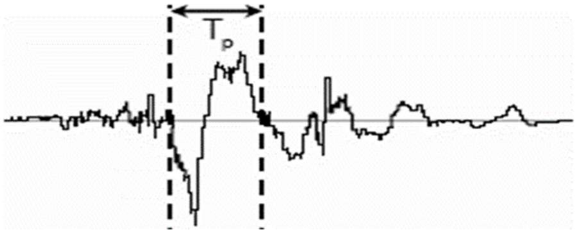
[4]. Arch dams transfer pressure of water to slopes via arch. Arch dams have thinner sections than compare with concrete gravity dams and it causes saving concrete. Generally, arch thickness has to be smaller than 60% height of arch. When the thickness of arch section rises, arch gravity and concrete gravity dam must be considered. Constructing of an arch dam is more beneficial to produce water energy if only suitable valley status and foundation conditions are available. However, disadvantage of arch dam is that analyses and design process are more complex than other alternative dam types. Besides, the qualification of the slope process must be carried out very carefully. Valley must have high bearing capacity for foundation and also slopes to construct an arch dam.

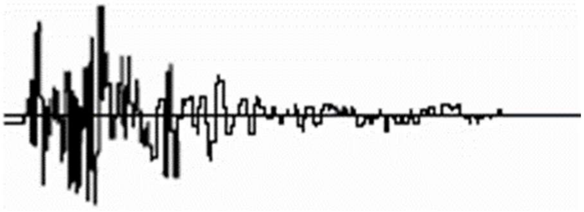
In this study, we investigated the effect of the elastic foundation conditions on the response of the Type 3 arch dam, which is one of the five type models suggested in Arch Dams Symposium organized in England [5]. For this purpose, we designed a finite element model. This model composes of dam body and rock foundation. We analyzed this model under near-fault and far-field ground motion effects considering various rock properties. According to numerical analyses, horizontal displacements and maximum normal stresses are calculated and evaluated for the elastic foundation conditions. This study also reveals the response of the dam under empty and full reservoir conditions.

2. EFFECTS OF NEAR-FAULT AND FAR-FIELD GROUND MOTION

Ground motions produced from earthquakes differ from one another in characteristics, magnitude, distance and direction from the rupture location and local rock conditions. The effects of near-fault and far-field ground motion on civil engineering structures such as buildings, tunnels, bridges and dams have been the subject of recent studies but they are insufficient. Several investigators have studied the effect of near fault-far field ground motion on the seismic behavior of dams and all of them are agree that the effect of near-fault ground motion is vital importance [6]. It can be clearly seen from this study that the importance of near-fault and far field ground motion effects on the linear dynamic response of structures has been highlighted. The characteristics of the near-fault ground motions can cause considerable damage during an earthquake. The near fault strong ground motion accelerograms with far fault strong ground motions is compared [7] and shown in Figure 1.



a) Near-fault ground motion



b) Far-field ground motion

Figure 1. The accelerograms of ground motions.

3. MATHEMATICAL MODEL OF TYPE 3 ARCH DAM AND WESTERGAARD APPROACH

In all the valleys for which construction of arch dams are considered, the L peak length to H height ratio (L/ H) is taken as basis (Figure 2). When the factors such as dam height and center angle are considered to be equal for comparison, arch formed at the projected dams in wide valleys are more prone to bow in terms of cantilever stiffness than arches in narrow valleys. In addition, most of the load appliying to the dam is transferred to the right and left slopes by the console effect.

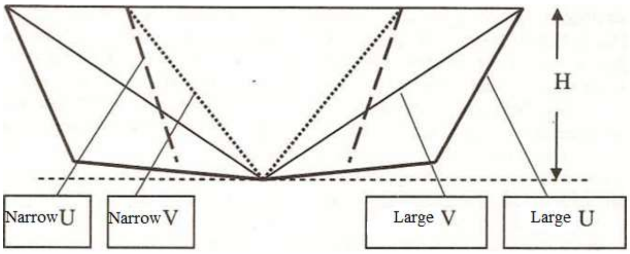


Figure 2. Diagram of various valley shapes

As the most important criterion for classifying the arch dams, the shape of rotary object which used in the arch is considered. Arch dams can be classified into three types in terms of their main features:

1) Constant radius arch dams

2) Constant center angle arch dams

3) Variable radius and center angle arch dams

Type 3 arch dam is a double curvature arch dam. It is an arch dam with curved upstream surface. The type 3 arch dam has constant center angled and the upstream surface is vertical.

In this study, finite element method was used for modelling and analyses. Dam body was divided to 204 eight-noded solid finite elements. This paper presents linear modal time-history analyses of dam-foundation interaction systems. We selected different foundation conditions.

The height of the dam is selected as 120 m. The depth of the foundation is taken into consideration as the dam height. Three-dimensional finite element model of Type 3 dam includes eight-noded finite elements. These elements have three degree of freedom in every nodal point as displacements of directions x, y and z. Three dimensional finite element model of the arch dam has 263 nodal points and 204 number of solid elements. Arch components of dam are assumed as monolithic, homogeny and isotropic in linear modal time-history analyses under ground motion effects.

The response of the structures mostly depends upon the interface between structure and foundation. If the friction is clearly effective, friction contact should be considered at interface. Furthermore, the concrete and rock has very good interaction and conjunction. Therefore, the friction may be ignored in such cases. It is well known that arch dams are built on hard rock foundations. Because of the same reason, contraction joints between concrete blocks were also neglected. All models have the same geometry but they have different modulus of elasticity of sandstone presented in Figs. 3 and 4.

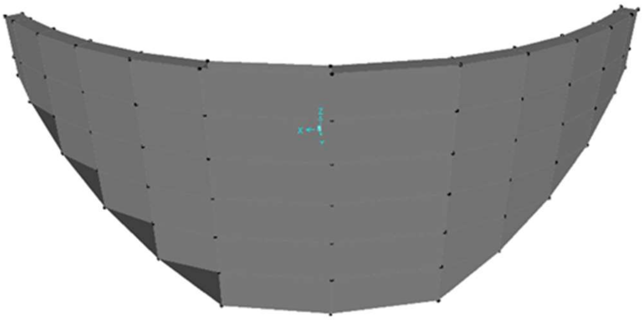


Figure 3. Finite element model of arch dam body

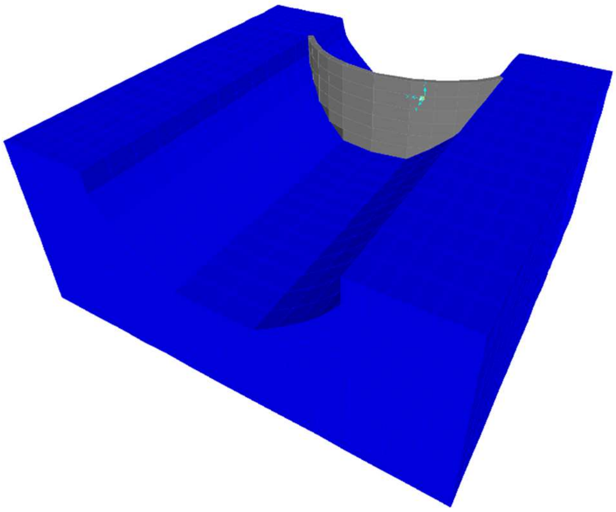


Figure 4. Finite element model of arch dam-foundation interaction model.

The accelerograms were obtained from the Loma Prieta earthquake at various distances. The distance for near-fault effect is 5.1 km and it is 93.1 km for far-field effect. The north-south, east-west and vertical (x, y and z) directions of accelerogram of Loma Prieta were used in numerical analyses. Dam-foundation dimension size must be at least one or two times of dam height provides sufficient approach on downstream and upstream parts of dam. If one should want to obtain reservoir water effects, the upstream side should be at least three times of the dam height. The fixed boundary conditions were used for foundation rock in the finite element model.

With dynamic effects such as earthquakes, dam and liquid behavior change significantly. In dynamic analysis of arch dams in particular, the dynamic characteristics of the reservoir and the effects on its behavior should not be neglected. In this study, the mass addition approach proposed by Westergaard is used to account for the hydrodynamic effects that occur during an earthquake. This approach considers a mass distribution that oscillates with the dam, similar to the hydrodynamic pressure distribution that occurs along the dam upstream side as a result of the dynamic effect. Single loads added to node points using this distribution:

$$m = \frac{7}{8}\frac{w}{g}\sqrt{Hz} \tag{1}$$

It is calculated by (1) correlation.

m: Mass distribution due to reservoir depth

w: Weight of water unit volüme (10kN/m^3)

H: Reservoir depth

z: The water depth from the surface of the water.

4. MATERIAL PROPERTIES

Foundation rock parameters (Young's modulus and densities) were determined for sand stone material properties using required resources (Hudson, 1989). Poisson ratios were determined as proposed by Gercek [8]. Poisson ratio of rock were selected 0.25 for all models. Intact elasticity modulus of foundation rock for sandstone (E_i) was taken as 35 GPa. But, we determined rock mass elasticity modulus (E_{rm}) for numerical analysis. Then we calculated the E_{rm} values for the different five sandstone material properties models. Foundation models were categorized in Table 1 for material properties.

Model 1 consists of two different materials which are concrete and sandstone. Model 1 has two different mechanical properties of solids elements. One of both solids has arch dam body metarial mechanical properties for model 1. Finite element model of arch dam body has same material properties for all models. It color is grey in Figure 3. Weight per unit volume of arch dam body is 2400 kg/m^3, elasticity modulus (E) of arch dam body is 32000 MPa and its poisson ratio is 0.2. Second solid represents soil and valley parts of model 1. It has blue color in Figure 4. Weight per unit volume of solid 2 is 1700 kg/m^3, E is 8200 mPa and its poisson ratio is 0.25.

All other models have the same geometry but they have different elasticity modulus of sandstone material. Modulus of elasticity of all models are given in Table 1. In this study, it is aimed to understand how the modulus of elasticity of the rock foundation affects the change of displacements and normal stress componentes.

Table 1. Material properties of concrete arch dam body and foundation

Models	Colors	Young' s Modulus E (kN/m^2)	Compressive Strength (kN/m^2)	Poisson's Ratio ν
Dam Body	Grey	32.000.000	30000	0.20
Model 1	Blue	8.200.000	9389	0.25
Model 2	Brown	10.974.000	13050	0.25
Model 3	Green	14.064.000	18084	0.25
Model 4	Purple	17.828.000	25008	0.25
Model 5	Red	20.128.000	34536	0.25

All models include fixed boundary condition in the edge of the foundation. Material properties of elastic foundations was calculated by means of the Hoek-Brown failure criterion for rock masses [9,10]. Their semi-theoretical approach is extensively acknowledged to produce input data for rock-mechanic analyses. The Hoek–Brown approach using Geological Strength Index (GSI) is widely used for assessing stiffness and shear strength parameters. The values of GSI change between 55 and 75. The minimum GSI value picked 55 for the foundation for Model 1. GSI value for Model 2 was picked 60 and then GSI value was increased 5 for every model. Finally, GSI value for Model 5 was picked as 75 for determining E_{rm} of rock foundation. Here, non-linear Hoek-Brown Failure criterion is

$$\sigma_1' = \sigma_3' + \sigma_{ci}' \times \left(m_b \times \frac{\sigma_3'}{\sigma_{ci}'} + s \right)^a \tag{2}$$

$$m_b = m_i \times e^{\left(\frac{GSI-100}{28-14\times D}\right)} \tag{3}$$

$$s = e^{\left(\frac{GSI-100}{28-14\times D}\right)} \tag{4}$$

$$a = \frac{1}{2} + \frac{1}{6} \times \left(e^{\frac{-GSI}{15}} - e^{\frac{-20}{3}} \right) \tag{5}$$

Where σ_1' and σ_3' are the major and minor effective principal stresses at failure. m_b is a reduced value of m_i which is a constant and also function of rock type. σ_{ci} is uniaxial compressive strength of the intact rock. s and a are constants of the rock. D is the disturbance factor influenced by excavation, stress relaxation and blasting [9].

Foundation material was chosen as sand stone in all numerical analyses. Typical uniaxial compressive strength (σ_{ci}) values of sand stone, as suggested by Hudson [11], are in the range of 25–175 MPa. It is suggested that typical values of m_i are in the range of 17±4 for sandstone. s and a are the constants for rock. D is disturbance factor which permits for the severe effects and stress relaxation. D can also be forecast according to guidelines given for several constructions, however not for dams. Because of D is very low for excavations of dam foundations, it cannot be ‘0’ due to decompression. D can be classification as follows:

- Good rock condition D=0.4
- Normal rock condition D=0.2
- Bad rock condition D=0.2

In this study, mechanical excavation was considered for the foundation construction; therefore, D was chosen as 0.4 [12]. These parameters and Eq. (6) were used to determine the Young’s modulus (E_{rm}) of sandstone [13].

$$E_{rm}(GPa) = E_i \times \left(0.02 + \frac{1 - D/2}{1 + e^{((60+15\times D - GSI)/11)}} \right) \tag{6}$$

5. INFLUENCE OF THE ELASTICITY RATIO ON THE DAM BEHAVIOR (E_C/E_F)

Dam engineers consent on which two cases. The situations are dangerous for the behavior of an arch dams: if E_f (foundation deformation modulus) diverges majorly across dam foundation, and other case is that E_c/E_f attains values where E_c is the concrete deformation modulus. The most common accepted rule for arch dams is given in Table 2.

As it is shown in Table 2, if E_c/E_f value is lower 4, there is no problem on dams. The minimum value of E_f should be around 5 Gpa for an arch dam. When E_f is less than 5 GPa, there happens serious troubles (fracture included) due to the low value of E_f [11]. In this study, we have five different E_c/E_f ratios. Every model has a different Ec/Ef value. It was investigated that the stresses and displacements by the change of E_c/E_f value. Then, the numerical analysis results were compared each other. The E_c/E_f ratios change between 1.6 and 3.9 for five different models.

Table 2. E_c/E_f influences on arch dam’s behavior [14]

Ec/Ef	Effect on arch dam	Troubles
<1	Ignore	Nothing
1-4	Less importance	Nothing
4-8	Important	Some
8-16	Very important	Critical
>16	Special measures	Most dangerous

6. DYNAMIC ANALYSIS

The ground motion effects on the arch dam are considered with east-west, north-south and vertical components of the Loma Prieta earthquake record. 5% damping ratio was used in calculations for the dam-foundation interaction systems. The numerical analyses were realized during 30 seconds. Besides, 0.01 second was selected as the time step. The analysis was performed for empty and full reservoir condition. Rayleigh damping is considered in the solutions with (α,β) constants (Table 3).

Table 3. Rayleigh Damping constants (α,β)

Models	Rayleigh Damping Constant	
	(α)	(β)
Model 1	1.15983	0.00189452
Model 2	1.22801	0.00177721
Model 3	1.28314	0.00168853
Model 4	1.32983	0.00161351
Model 5	1.35167	0.00158081

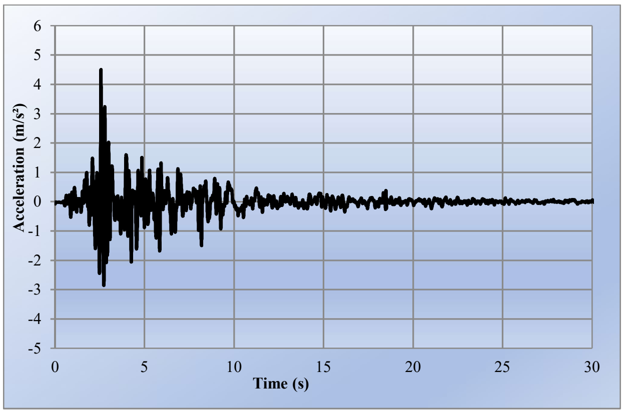
The Type 3 double curved arch dam was analyzed under seismic excitations (Table 4). Three-dimensional linear dynamic analyses were executed by considering different accelerograms for full reservoir condition (Figure 5, 6).

Table 4. Ground motion effects
a) Moment magnitude and ground velocity

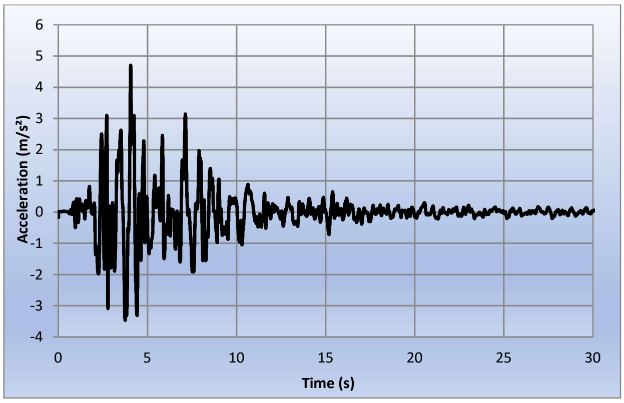
Earthquake Effects	Components	Moment Magnitude	Ground Velocity (cm/s)
Near-Fault	North-South	6.9	17.7
	East-West		55.2
	Up		45.2
Far-Field	North-South	6.9	4.4
	East-West		17.3
	Up		14.2

b) Distances from epicenter and ground acceleration

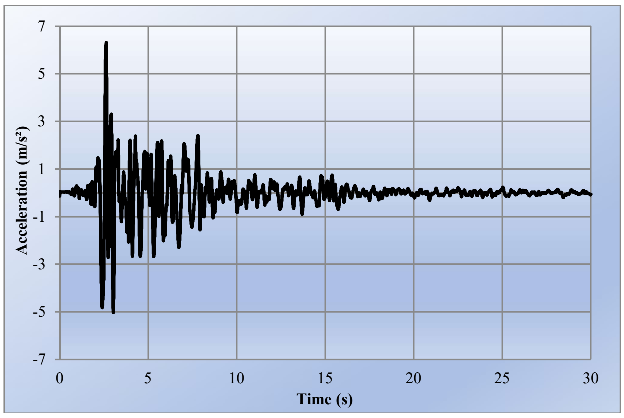
Earthquake Effects	Components	Distances from Epicenter (km)	Ground Acceleration (g)
Near-Fault	North-South	5.1	0.455
	East-West		0.644
	Up		0.479
Far-Field	North-South	93.1	0.032
	East-West		0.124
	Up		0.106



a) North-South component

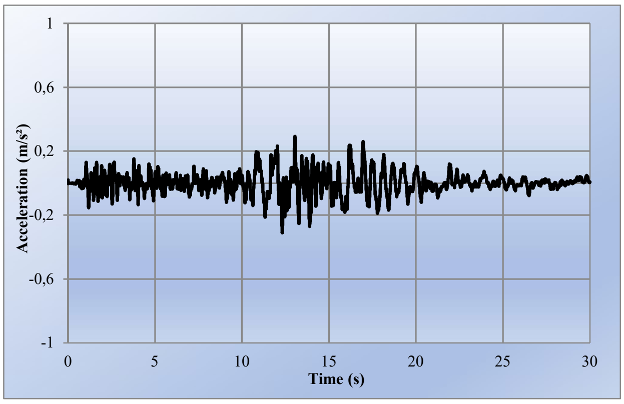


b) East-West component

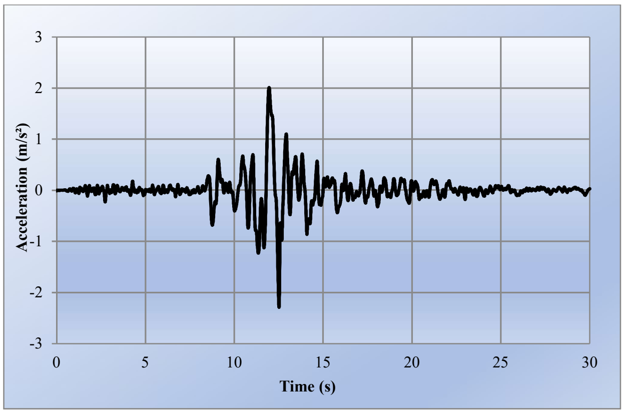


c) Vertical component

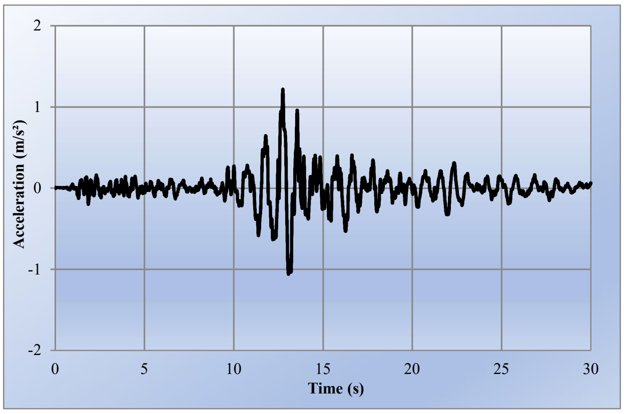
Figure 5. Accelerograms of Loma Prieta Earthquake for near-fault effect.



a) North-South component



b) East-West component

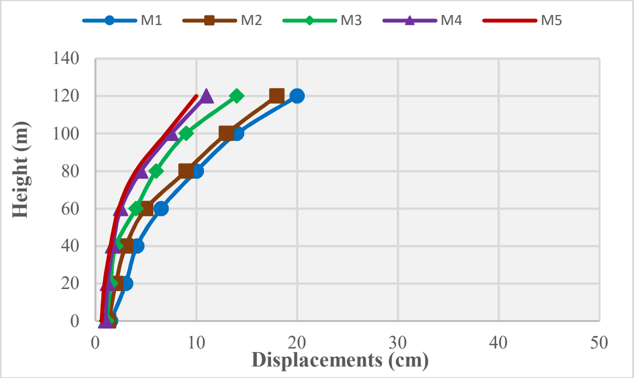


c) Vertical component

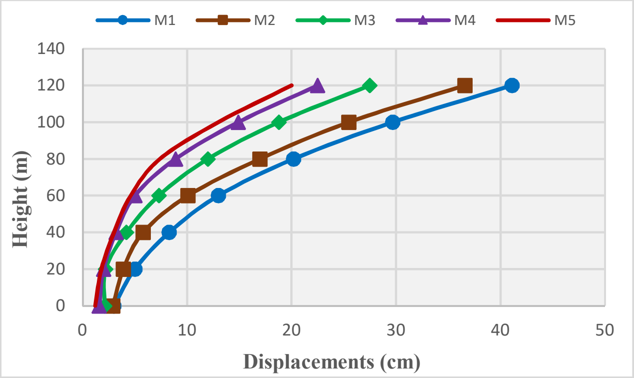
Figure 6. Accelerograms of Loma Prieta Earthquake for far-field effect.

7. NUMERICAL ANALYSIS

According to numerical solutions, it was seen that near-fault ground motion is obviously effective than far-field one for each model (Figures 7-16). This case was observed in all different numerical results. Such as, maximum displacements were obtained from the model subjected to near-fault earthquake records in linear modal time history analyses. The maximum displacement is 42,1 cm and occurred at upstream direction. The maximum normal stresses occurred at arch direction of the arch dam model and the maximum normal stress is 14127 kPa. All dynamic analysis results show the Model 5 involves lower stress and displacements. Because, Model 5 has bigger Young's modulus than the others. In addition, the maximum displacements occurred in Model 1 due to the lower Young's modulus. Besides, it is obvious that the distances of the fault from epicenter have an important role in sizableness of stresses and displacements.

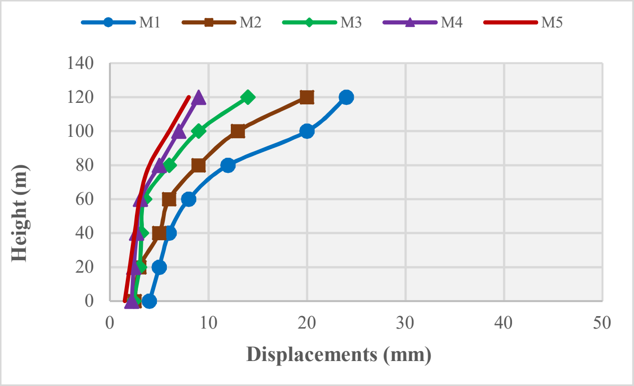


a) Empty Reservoir Condition

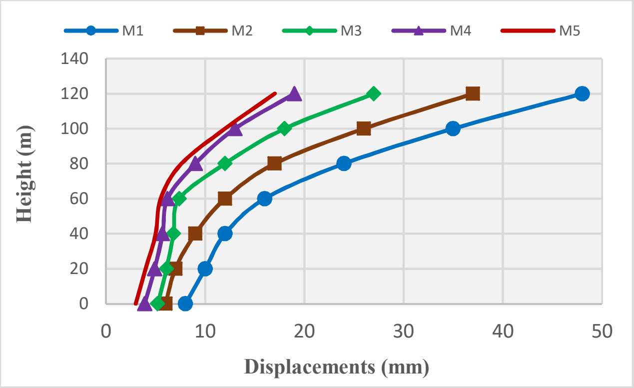


b) Full Reservoir Condition

Figure 7. Maximum displacements at upstream direction for near-fault ground motion effect

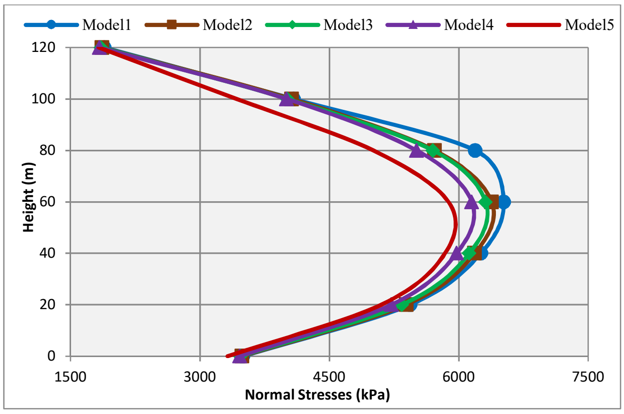


a) Empty Reservoir Condition



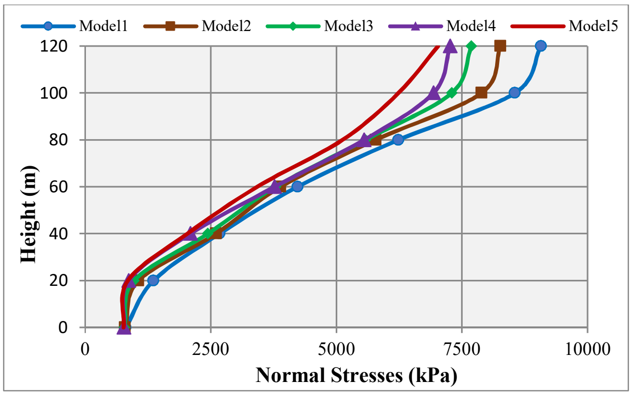
b) Full Reservoir Condition

Figure 8. Maximum displacements at upstream direction for far-field ground motion effect

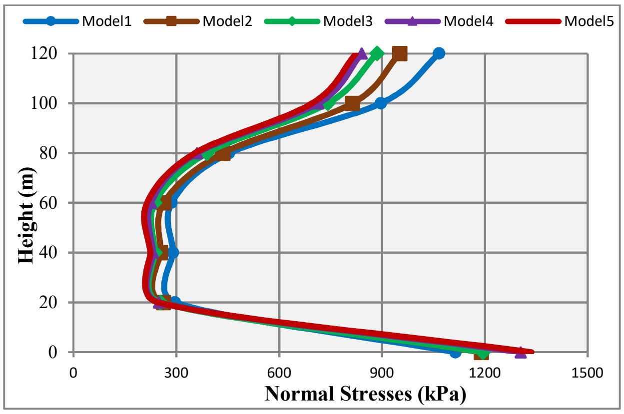


c) Vertical direction

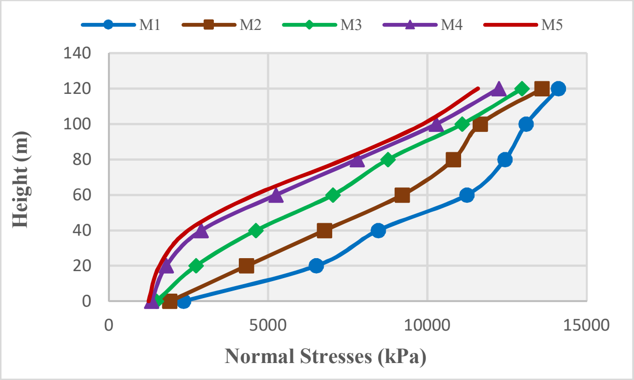
Figure 9. Maximum normal stresses-empty reservoir condition for near-fault ground motion effect.



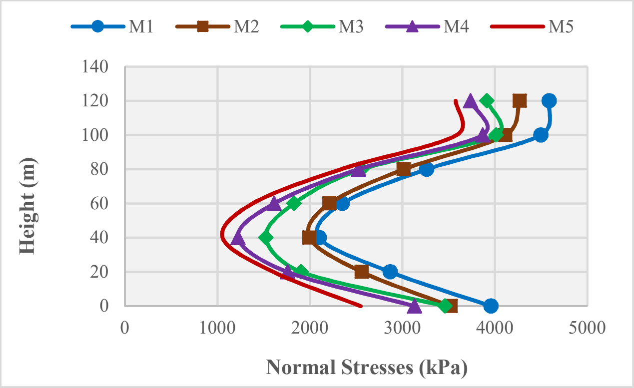
a) Arch Direction



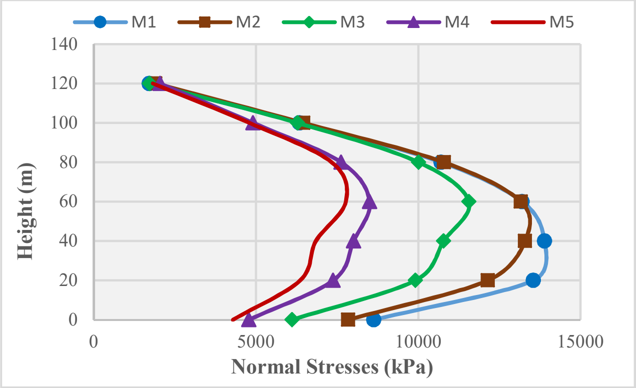
b) Upstream-downstream direction



a) Arch direction

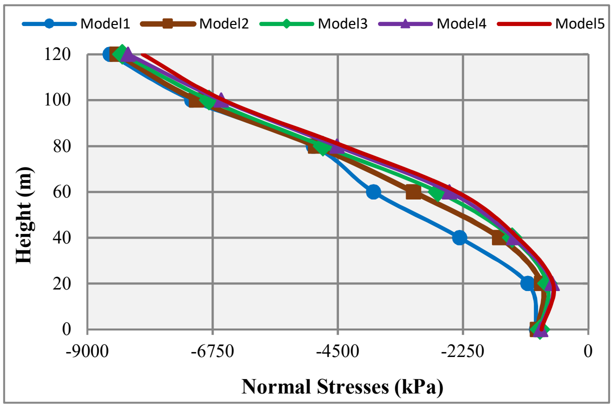


b) Upstream-downstream direction

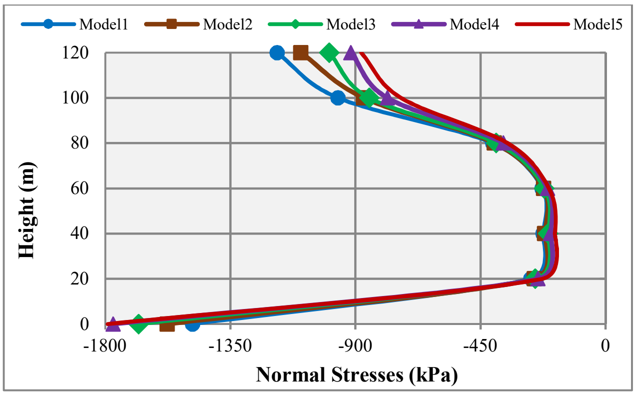


c) Vertical direction

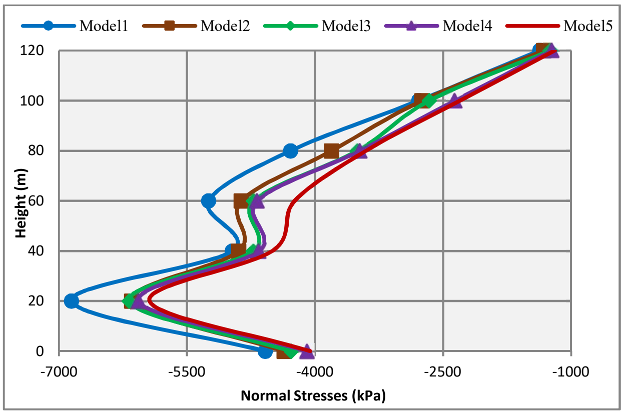
Figure 10. Maximum normal stresses-full reservoir condition for near-fault ground motion effect.



a) Arch direction

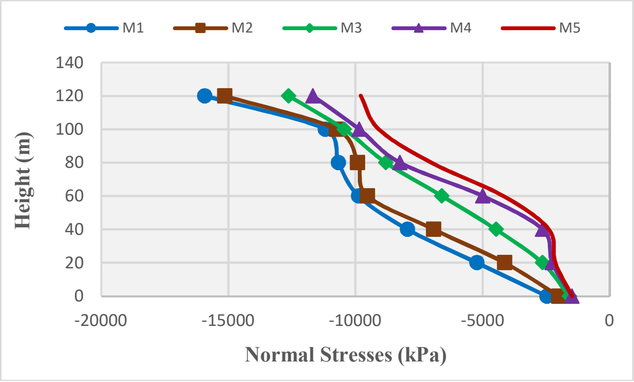


b) Upstream-downstream direction

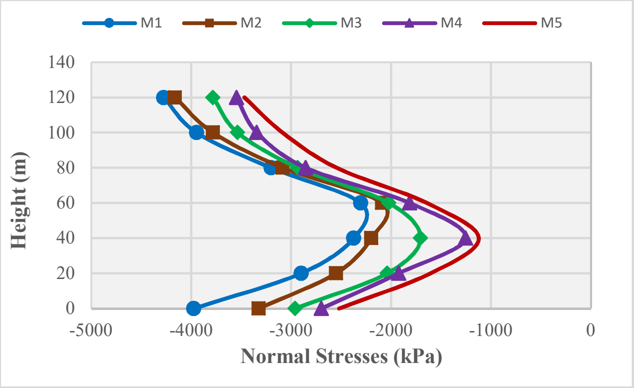


c) Vertical direction

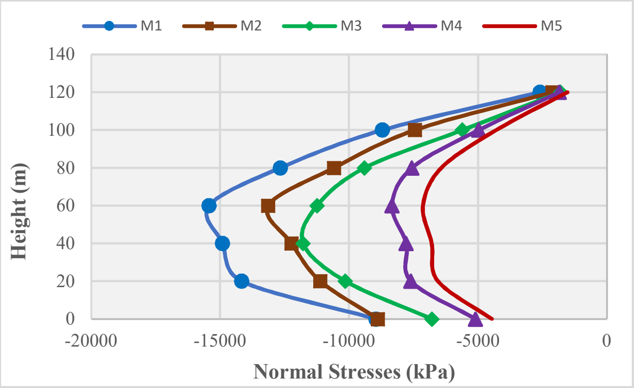
Figure 11. Minimum normal stresses-empty reservoir condition for near-fault ground motion effect.



a) Arch direction

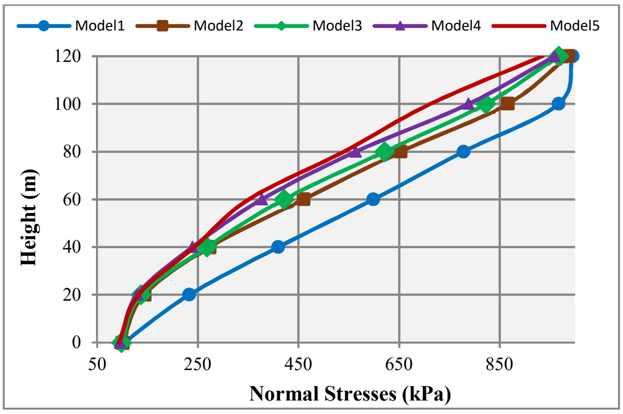


b) Upstream-downstream direction

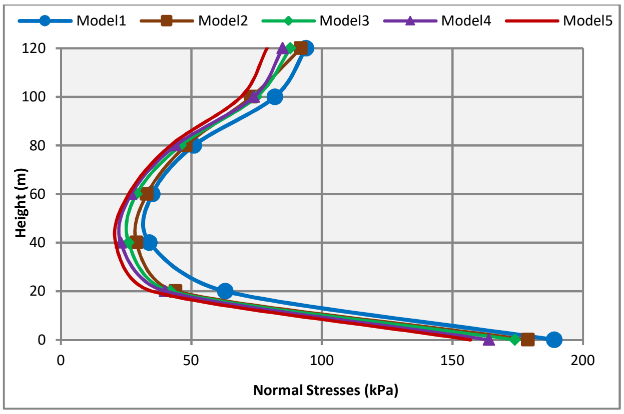


c) Vertical direction

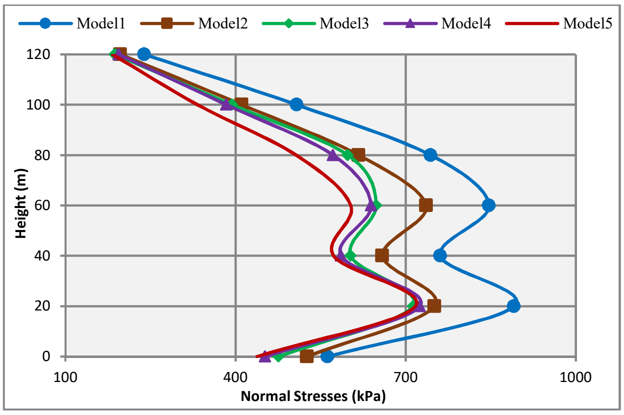
Figure 12. Minimum normal stresses- full reservoir condition for near-fault ground motion effect.



a) Arch direction

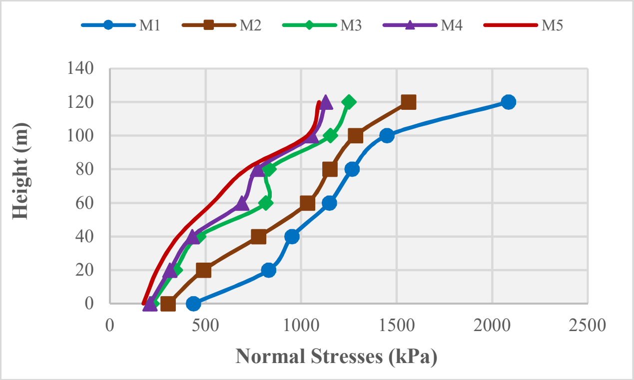


b) Upstream-downstream direction

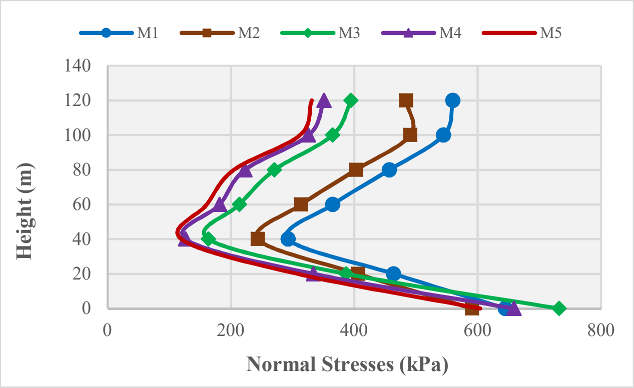


c) Vertical direction

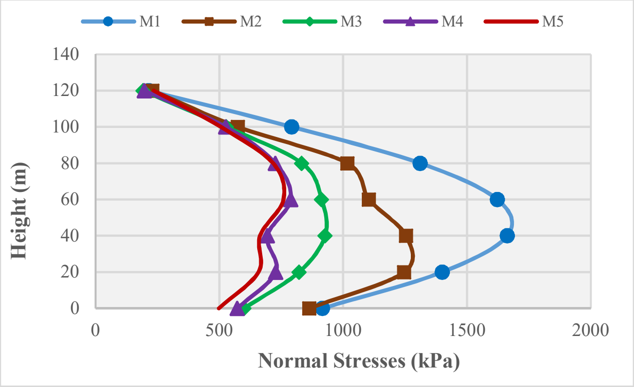
Figure 13. Maximum normal stresses-empty reservoir condition for far-field ground motion effect.



a) Arch direction

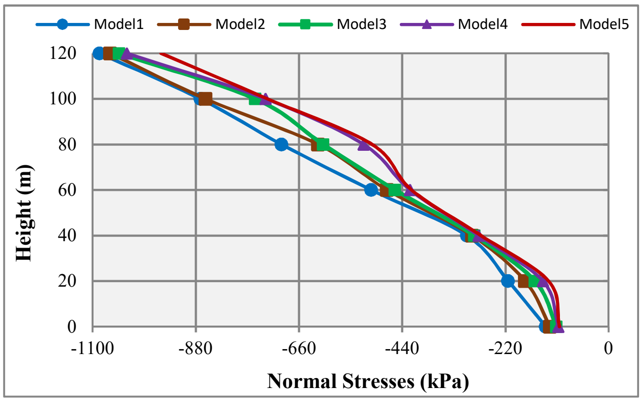


b) Upstream-downstream direction

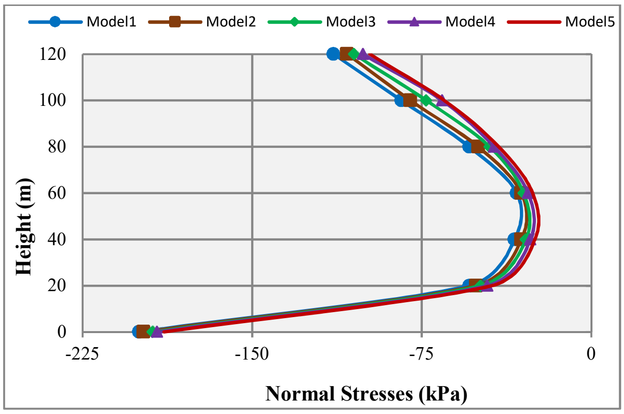


c) Vertical direction

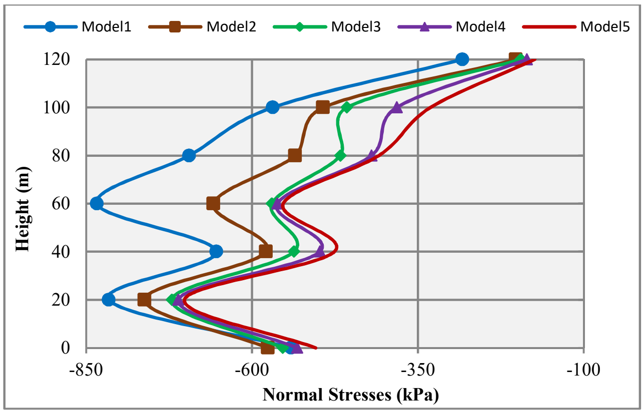
Figure 14. Maximum normal stresses- full reservoir condition for far-field ground motion effect.



a) Arch direction

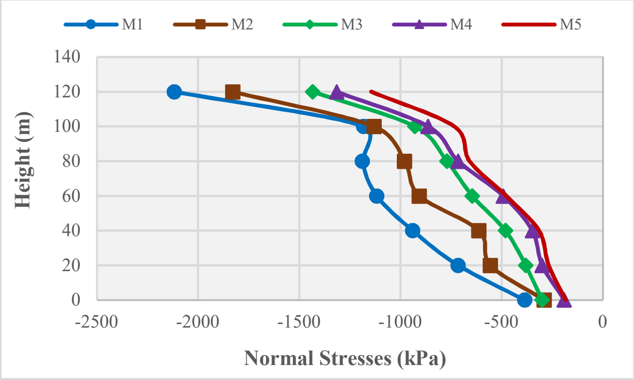


b) Upstream-downstream direction

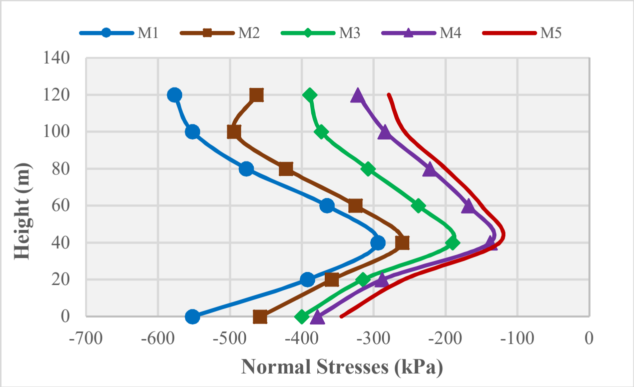


c) Vertical direction

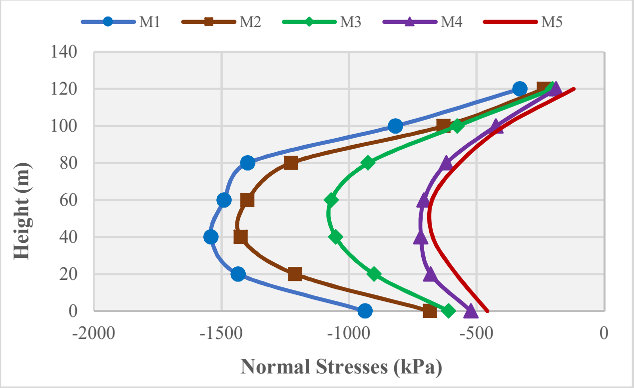
Figure 15. Minimum normal stresses-empty reservoir condition for far-field ground motion effect.



a) Arch direction



b) Upstream-downstream direction



c) Vertical direction

Figure 16. Minimum normal stresses- full reservoir condition for far-field ground motion effect.

8. CONCLUSIONS

This study presents earthquake analysis of arch type concrete dams. The main objective of this paper is to reveal the effect of the stiffness of the rock foundation under hydrodynamic effect of reservoir water. For this purpose, various Young's modulus valuse are obtained considering five different GSI values for sandtone.

According to linear modal time-history analysis, the material properties of the foundation significantly affects dam behavior. In addition, near-fault ground motion obviously more effective than far-field ones. Therefore, different fault distances should be taken into consideration according to the locations of the dam and faults. Besides, dam-foundation interaction must be considered in dynamic analyses with the most appropriate material properties. As the E_c/E_f ratio approaches 4, we see that the stress and displacement values in the dam body increase. Stress and displacement values should be considered in terms of safety when the E_c/E_f ratio is greater than 4. Considering possible strong ground motions should be considered where a dam will be built. Then, the followings can be deducted from this study:

- Maximum displacements and stresses were obtained for near-fault ground motion,
- Maximum displacements and stresses were obtained for full reservoir condition,
- Maximum normal stresses occurred at arch direction,
- The stresses and displacements are the lowest for the minimum value Young's modulus of rock foundation as seen from Model 5,
- If the Young's modulus of dam foundation increases, the stresses and displacements of the dam decrease,
- E_c/E_f is an important factor for the selected dam type in the construction location.

Further studies may be considered as follows;

- More realistic stress and displacement values can be obtained using viscous boundary conditions.
- Stress and displacement can be compared by investigating with other approaches for hydrodynamic pressure.
- Nonlinear response of the dam should be determined for higher stresses.

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