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Earthquake Analysis of Concrete Arch Dams Considering Elastic Foundation Effects

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Abstract Dynamic effects on an arch dam should be taken into account for the ground motions. This study presents three-dimensional linear earthquake response of an arch dam. Different ground motion effects and besides rigid and elastic foundation conditions are considered in the finite element analyses. For this purpose, the Type 3 double curvature arch dam was selected due to numerical solutions. All numerical analyses are carried out by SAP2000 V.17 program for empty reservoir case. In the scope of this study, linear modal time-history analyses are performed using three dimensional finite element model of the arch dam and arch dam-foundation interaction systems. Furthermore, near-fault and far field ground motion effects on the selected arch dam were taken into account by different accelerograms obtained from the Loma Prieta earthquake at various distances. According to numerical analyses, maximum horizontal displacements and maximum normal stresses are presented by height and these are evaluated for both foundation conditions.

Index Terms— Elastic foundation, Far-field ground motion, Near-fault ground motion, Type 3 arch dam.

I. INTRODUCTION

ARCH dams are constructed for various crucial functions and serve humans through flood control, industrial needs, navigation, and provision of drinking water, irrigation and hydroelectric power. Consequently, these structures require sophisticated engineering for design and construction to avoid risks from a dam's 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].

Rigorous analysis of concrete arch dam–reservoir systems is based on the FE- (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 75% earthfill dams, 17% rockfill dams and only 2% arch dams [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. To construct an arch dam, valley must have high bearing capacity for foundation and also slopes.

In this study, we investigated the effect of the rigid and 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 in 1968 is considered in this paper [5]. For this purpose we designed two finite element models. First model includes only arch dam body including fixed boundary condition. The second one composes of dam body and foundation soil. We analyzed the both models under near-fault and far-field ground motion effects. According to numerical analyses, horizontal displacements and maximum normal stresses are calculated and evaluated for the rigid and elastic foundation conditions.

Empty reservoir conditions should be investigated

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especially for arch dams. The arch dams design in order to hold huge water pressure behind them. We wonder what happens in empty reservoir conditions, how the dam's behavior changes under strong ground motions.

II. MATHEMATICAL MODEL OF TYPE 3 ARCH DAM

In this study, finite element method was used for modelling and analyses. Dam body was divided 204 eight-noded solid finite elements. This paper presents linear modal time-history analyses of dam-foundation interaction systems. We selected different foundation boundary 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. Contraction joints between concrete blocks were ignored. Acceptation of rigid foundation makes easier the solution of dam-foundation interaction problems. The two type finite element models are presented in Figs 1 and 2

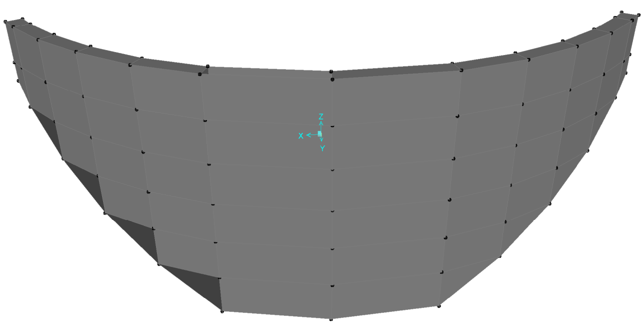


Figure 1. Finite element model of arch dam body.

It was taken into account by different accelerograms 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. The main idea of massless foundation assumption is preventing resonance at the low frequencies obtained from dam-foundation system [6]. Disadvantage of this approach is that damping of material and propagation are not considered. A dynamic analysis must include these damping effects because of the loads on dam.

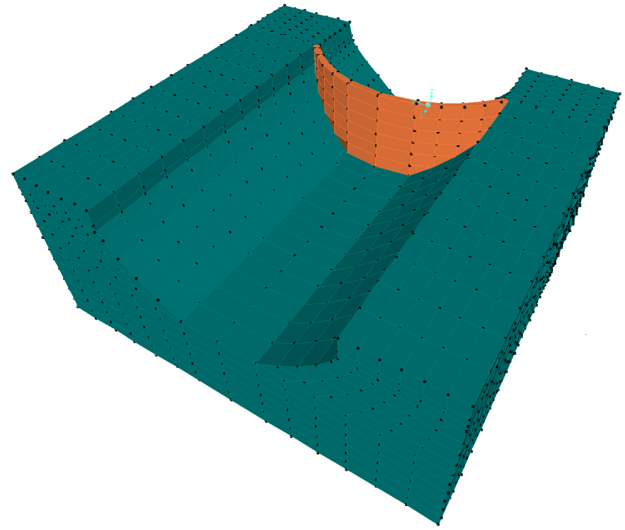


Figure 2. Finite element model of arch dam-foundation interaction model.

III. MATERIAL PROPERTIES

Foundation soil parameters (Young's modulus and densities) were determined to sand stone using required resources [7]. Poisson ratios were determined as proposed by Gercek [8]. Foundation models were categorized in Table 1 for material properties.

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

Models	Colors	Modulus of Elasticity E (kN/m^2)	Compressive strength (kN/m^2)	Poisson Ratio ν
Dam Body	Grey	32000000	30000	0.20
Elastic Foundation	Green	40513800	8480	0.35

Rigid foundation has fixed boundary condition. Material properties of elastic foundation 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 non-linear Hoek-Brown Failure criterion is

$$\sigma_1^{/} = \sigma_3^{/} + \sigma_{ci}^{/}\left(m_b \frac{\sigma_3^{/}}{\sigma_{ci}^{/}} + s\right)^a \tag{1}$$

$$m_b = m_i e^{\left(\frac{GSI-100}{28-14D}\right)} \tag{2}$$

$$s = e^{\left(\frac{GSI-100}{9-3D}\right)} \tag{3}$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right) \tag{4}$$

Where σ_1' and σ_3' are the major and minor effective principal stresses at failure. m_b is 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. Typical uniaxial compressive strength (σ_{ci}) values of sand stone, as suggested by Hudson [7], are in the range of 25–175 MPa. It is suggested that typical values of mi is 17±4 for sandstone. s and a are constants of the rock. D is the disturbance factor influenced by excavation, stress relaxation and blasting [9]. In this study, mechanical excavation was considered for the foundation construction; therefore, D was chosen 0.7. These parameters and Equation 5were used to determination modulus elasticity (E_{rm}) of sandstone material [10].

$$E_{rm}(GPa) = \left(1 - \frac{D}{2}\right)\sqrt{\frac{\sigma_{ci}}{100}} \cdot 10^{\left(\frac{GSI-10}{40}\right)} \rightarrow \sigma_{ci} \leq 100\ Mpa \quad (5)$$

IV. 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. The numerical analyses are realized during 30 sec. Besides, 0.01 second was selected as the time step. The analysis was performed for empty reservoir situation. Rayleigh damping is considered in the solutions with (α,β) constants (Table 2).

Table 2: Rayleigh damping constants (α,β)

Rayleigh damping constants	Rigid Foundation	Elastic Foundation
α	1.35973	0.752733
β	0.001556	0.00328731

Type 3 double curved arch dam was analyzed under seismic excitations (Table 3). Three dimensional linear dynamic analysis was executed by taking into account different ground motion effects and analyses include different foundation boundary conditions and ground motion types for empty reservoir condition (Figs. 3-8).

Table 3. 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 Fault	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 Fault	North-South	93.1	0.032
	East-West		0.124
	Up		0.106

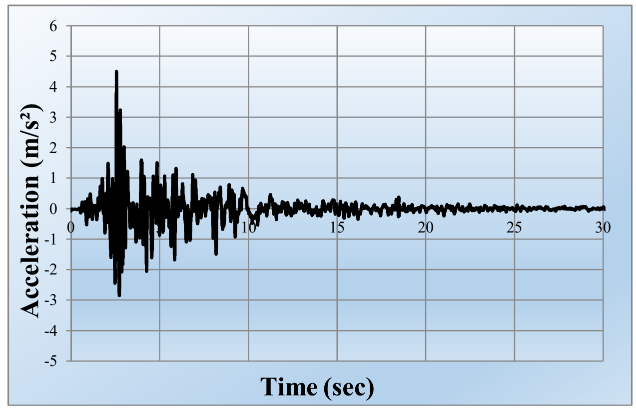


Figure 3.Accelerogram of the north-south component of Loma Prieta Earthquake for near-fault effect.

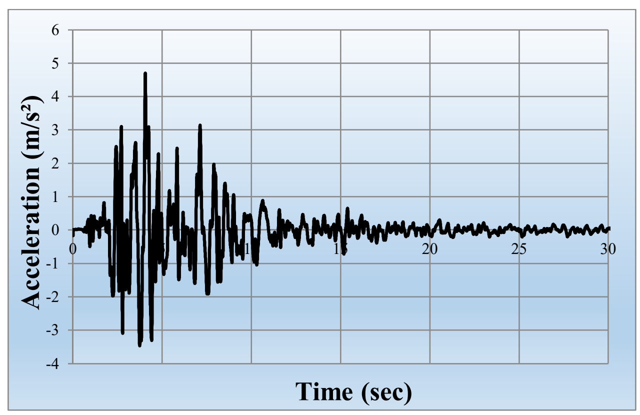


Figure 4. Accelerogram of the east-west component of Loma Prieta Earthquake for near-fault effect.

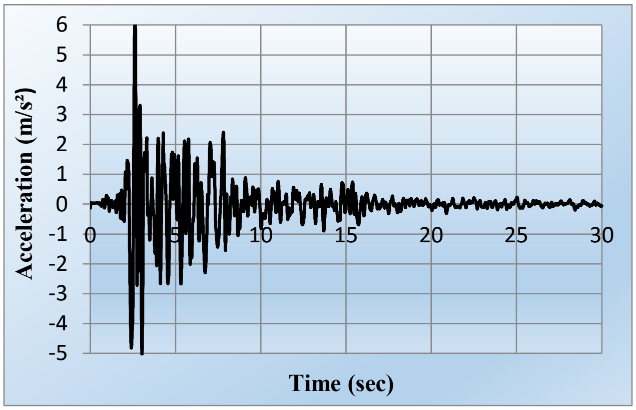


Figure 5. Accelerogram of the vertical component of Loma Prieta Earthquake for near-fault effect.

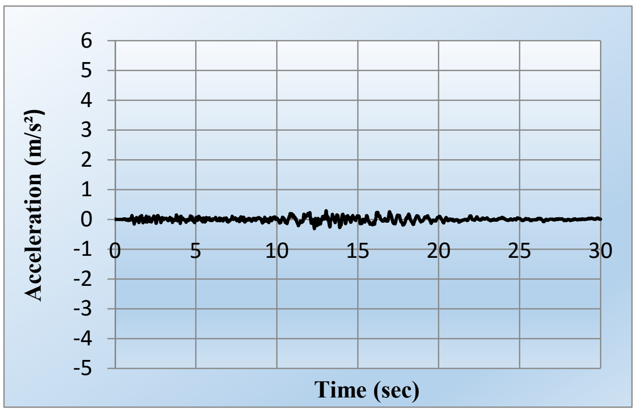


Figure 6. Accelerogram of the north-south component of Loma Prieta Earthquake for far-field effect.

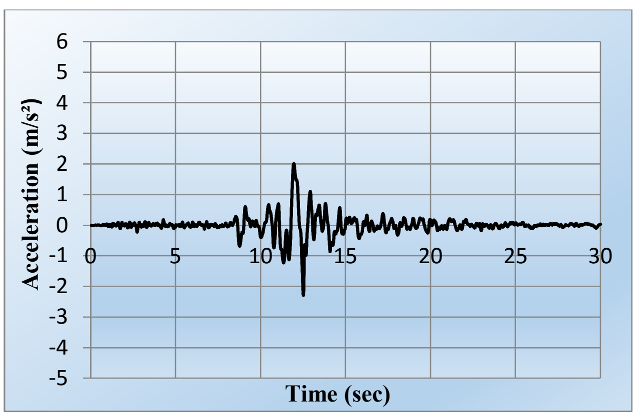


Figure 7. Accelerogram of the east-west component of Loma Prieta Earthquake for far-field effect.

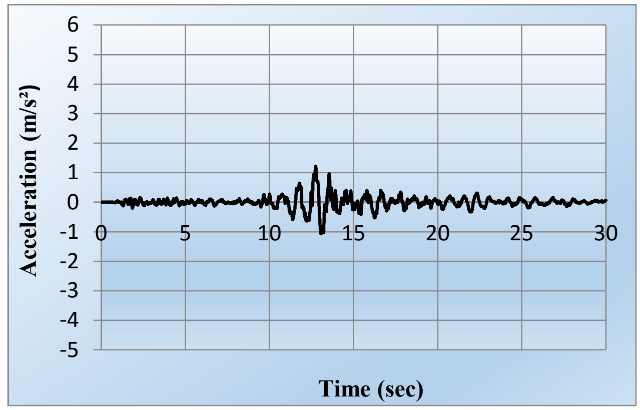


Figure 8. Accelerogram of the vertical component of Loma Prieta Earthquake for far-field effect.

V. Numerical Results

It was expected that near-fault ground motions are more effective than far-field for both foundation conditions. This case was observed in all 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 27 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 16035 kPa. All dynamic analysis results show the rigid model involve lower stress and displacements.

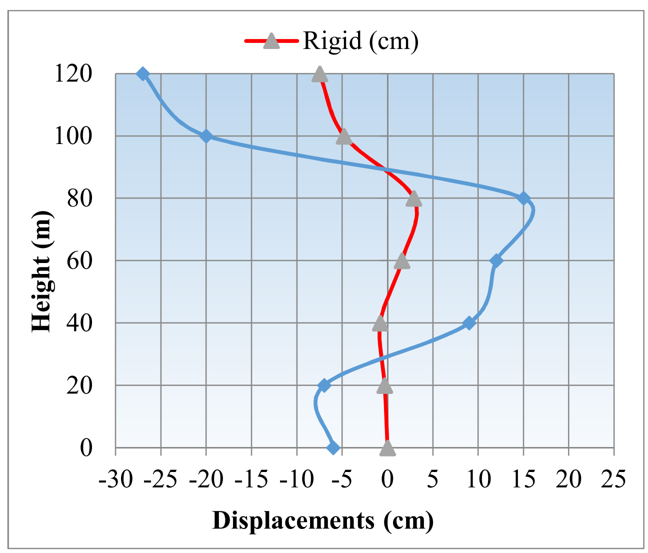


Figure 9. Displacements in upstream direction for near-fault ground motion effect.

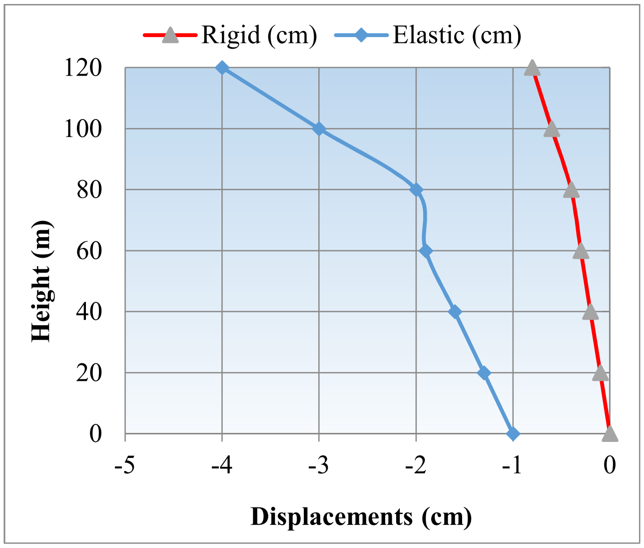
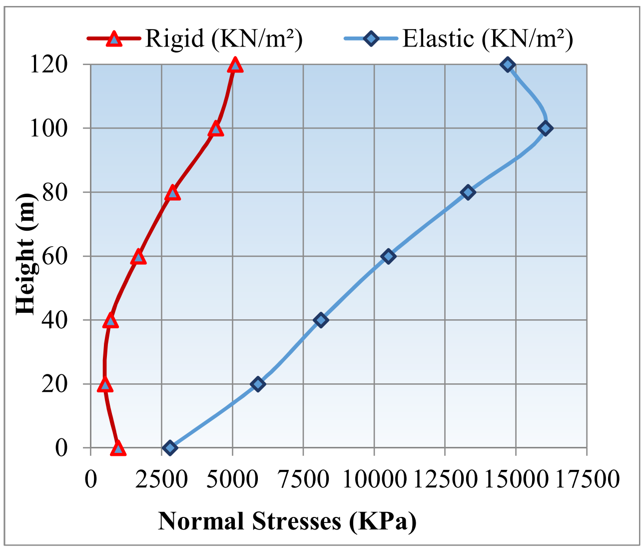
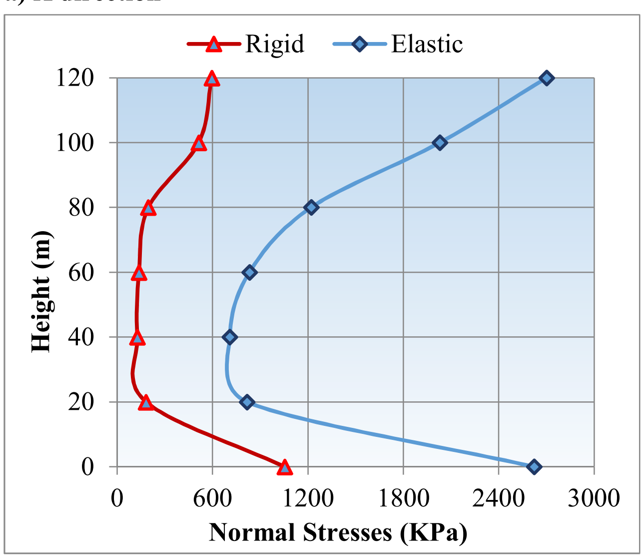


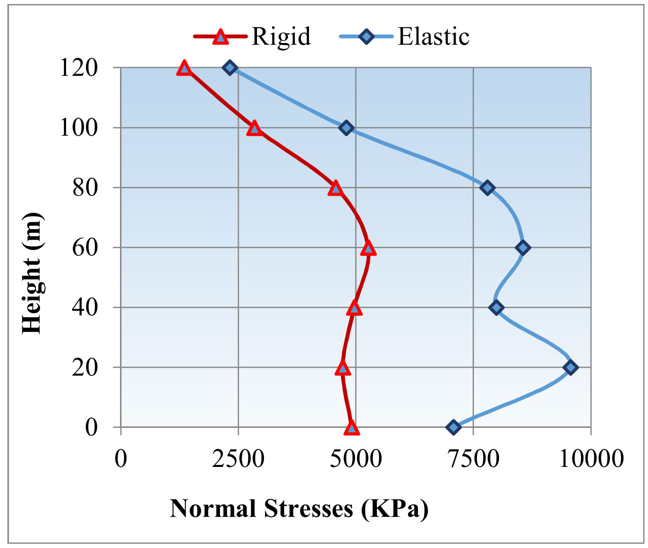
Figure 10. Displacements in upstream direction for far-field ground motion effect.



a) X direction

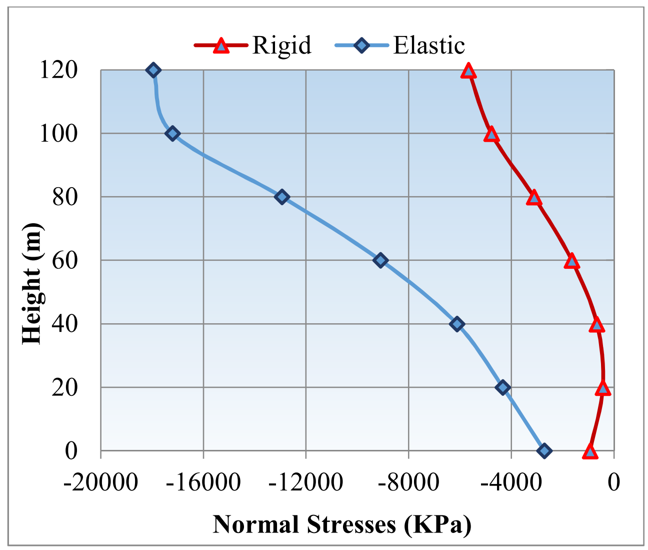


b) Y direction

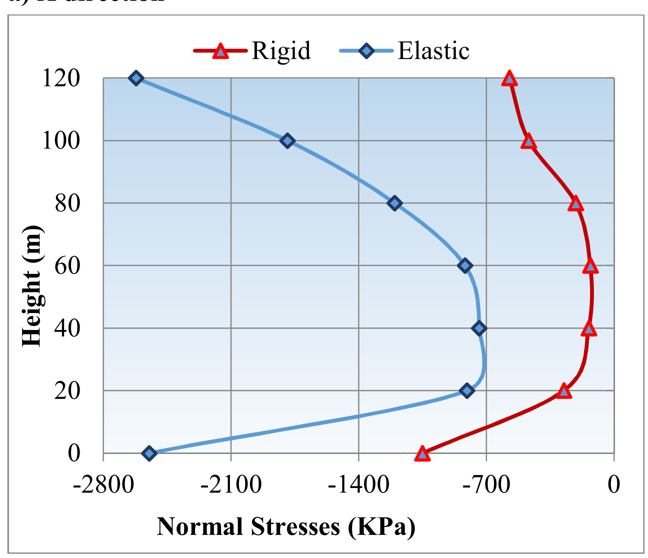


c) Z direction

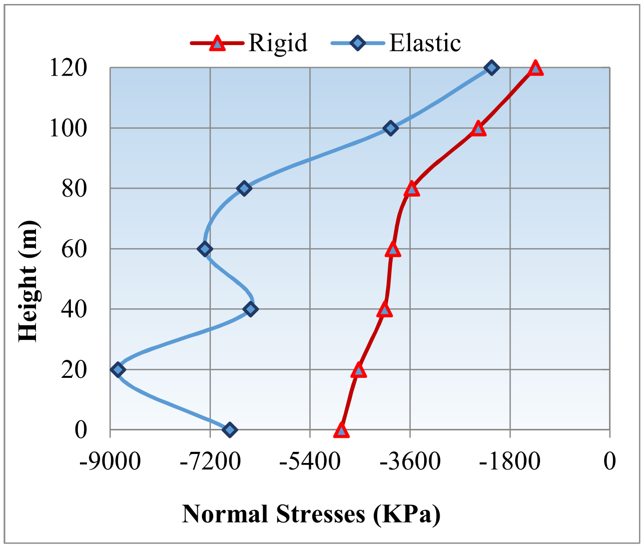
Figure 11. Maximum normal stresses at each direction for near-fault ground motion effect.



a) X direction

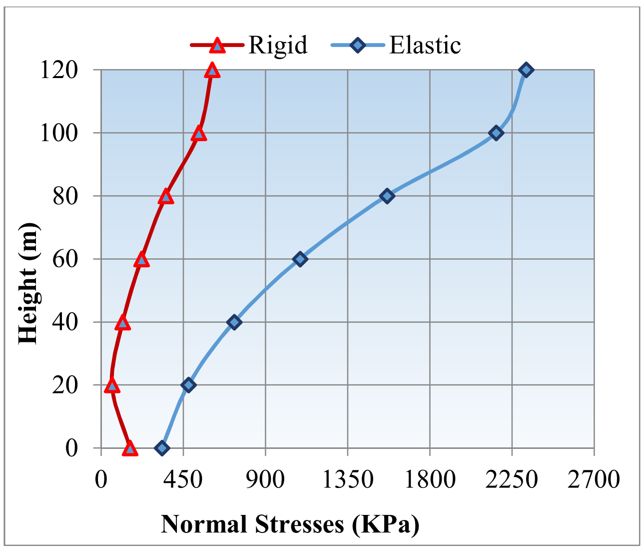


b) Y direction

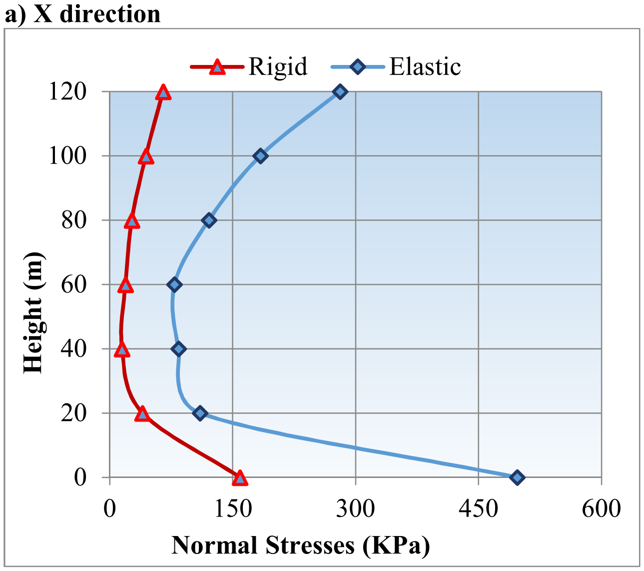


c)Z direction

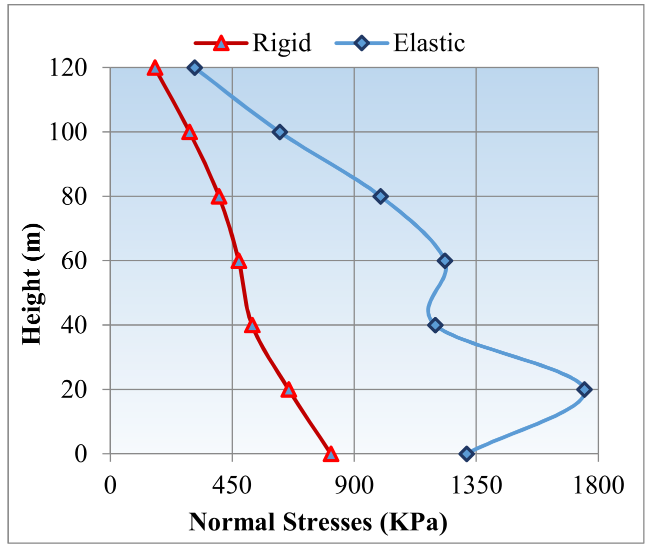
Figure12. Minimum normal stresses at each direction for near-fault ground motion effect.



a) X direction

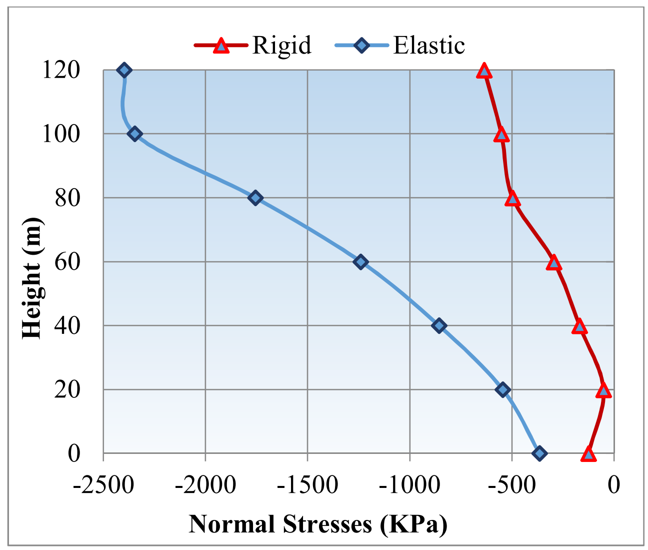


b) Y direction

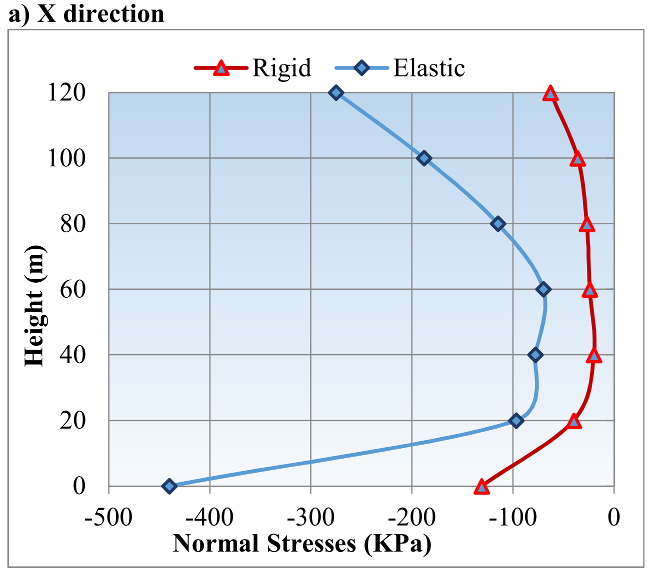


c) Z direction

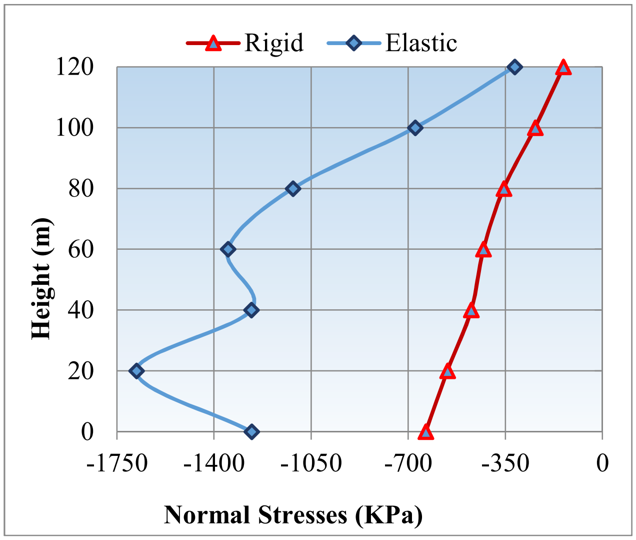
Figure 13. Maximum normal stresses at each direction for far-field ground motion effect.



a) X direction



b) Y direction



c) Z direction

Figure14. Minimum normal stresses at each direction for far-field ground motion effect.

VI. CONCLUSIONS

According to linear modal time-history analysis, the existence of foundation affects dam behavior significantly. In addition, different fault distances should be taken into consideration according to the locations of the dam and faults. Therefore, dam-foundation interaction must be considered in dynamic analyses. The foundation conditions may include lots of different soil materials.

The followings are deducted from this study;

- Maximum displacements were obtained for near-fault effects
- The maximum displacements occured in upstream direction.
- Maximum normal stresses occurred at arch direction
- The stress and displacements for the rigid foundation are lower than those for elastic foundation.

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