View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Challenge Journal Publications (TULPAR Academic Publishing)

CHALLENGE JOURNAL OF STRUCTURAL MECHANICS 3 (2) (2017) 102–107

Challenge Journal of Structural Mechanics

Elastic foundation effects on arch dams

Muhammet Karabulut *, Murat Emre Kartal, Omer Faruk Capar, Murat Cavusli

Department of Civil Engineering, Bülent Ecevit University, 67100 Zonguldak, Turkey

ABSTRACT

Earthquake response of an arch dam should be calculated under ground motion effects. This study presents three-dimensional linear earthquake response of an arch dam. Thereby, we considered different ground motion effects and also foundation conditions in the finite element analyses. For this purpose, the Type 3 double curvature arch dam was selected for application. All numerical analyses are carried out by SAP2000 program for empty reservoir cases. 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. 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 rigid and various elastic foundation conditions. 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.

ARTICLE INFO

Article history:
Received 2 February 2017
Accepted 25 February 2017

Keywords:
Elastic foundation
Far-field ground motion
Near-fault ground motion
Type 3 arch dam

1. Introduction

Arch dam construction is the most difficult type because of its geometrical shape design. The arch dam bodies transmit the load of reservoir water pressure and partially weight of dam body to valley. Therefore, these dam type requires more sophisticated engineering than other dam types. 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 (Mosallam and Banerjee, 2007; Mirzaei et al., 2010). Besides, empty reservoir conditions should be investigated especially for arch dams. The arch dams design in order to hold huge water pressure behind them. We study that what happens in empty reservoir conditions and how the dam's behavior changes under earthquake.

Rigorous analysis of concrete arch dam–reservoir systems is based on the finite element method. This means, the dam is discretized by solid finite elements. 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 (Calamak et al., 2013). 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 there is a suit region to build an arch dam. However, arch dam has some disadvantages such as analyses and design process. 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 three type models proposed in Arch Dams Symposium organized in England (Dennis, 1968). For this purpose, we designed three finite element models. All models compose of dam body and foundation soil. We analyzed these three 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 elastic foundation conditions. Some parameters are crucially important on stresses such as modulus of elasticity, Poisson's ratio and cohesion value.

* *Corresponding author.* Tel.: +90-537-9859663 ; Fax: +90-372-2514023 ; E-mail address: karabulut@beun.edu.tr (M. Karabulut)
ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2017.02.006

If soil elasticity value changes, maximum stress and displacement changes. It is clear that soil elasticity value increases, maximum stress and horizontal displacement decrease. Besides, ratio of concrete elasticity of dam body and soil elasticity (E_c/E_f) should be lower than 4 especially for arch dams.

2. Effect of Near Fault and Far Field Ground Motion

Ground motions produced from earthquakes differ from one another in characteristics, distance, magnitude and direction from the rupture location and local soil conditions. The effects of near fault and far field ground motion on civil engineering structures such as bridges, tunnels, buildings and dams have been the subject of recent studies but they are not enough. A number of 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 (Davoodib et al., 2013). 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 unique characteristics of the near-fault ground motions can lead to significant damage during an earthquake. 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 accelerograms of Loma Prieta were used in numerical analyses.

3. Mathematical Model of Type 3 Arch Dam

In this study, finite element method was used for modelling and analyses. Dam body was divided to 204 eight-noded solid finite elements. This study presents linear modal time-history analyses of dam-foundation interaction systems. We selected different elastic 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. Contraction joints between concrete blocks were ignored. The finite element models are presented in Fig. 1(a, b).

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.

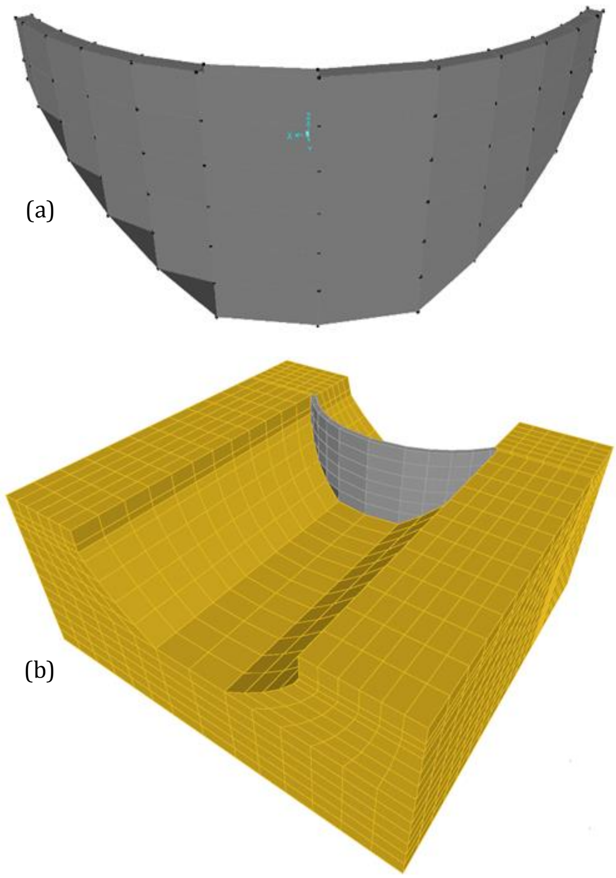

Fig. 1. Finite element model of: (a) arch dam body; (b) arch dam-foundation interaction.

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

Models	Colors	Modulus of Elasticity E (kN/m²)	Compressive Strength (kN/m²)	Poisson's Ratio ν
Dam Body	Grey	32000000	30000	0.20
Model 1	Blue	8200000	9389	0.25
Model 2	Green	14064000	18084	0.25

All different soil conditions 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 (Hoek et al., 2002). 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 of Model 1. Model 2 GSI value picked 65 and then Model 3 GSI value picked 75. The non-linear Hoek-Brown Failure criterion is

$$\sigma_1' = \sigma_3' + \sigma_{ci}' \times \left(m_b \times \frac{\sigma_3'}{\sigma_{ci}'} + s\right)^a , \quad (1)$$

$$m_b = m_i \times e^{\left(\frac{GSI-100}{28-14\times D}\right)} v = \sqrt{\left(\frac{V_n - V_p}{bd_v}\right)^2 + \left(\frac{T_n}{1.7A_{oh}t_w}\right)^2} , \quad (2)$$

$$s = e^{\left(\frac{GSI-100}{28-14\times D}\right)} , \quad (3)$$

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

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 (Romana, 2003).

Foundation material was chosen as sand stone. Typical uniaxial compressive strength (σ_{ci}) values of sand stone, as suggested by Hudson (Hudson, 1989), are in the range of 25–175 MPa. It is suggested that typical values of m_i are 17±4 for sandstone. s and a are the constants of rock. D is disturbance factor which permits for the severe effects and stress relaxation. D can 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 classified 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 (Romana, 2003).

These parameters and Eq. (5) were used to determine the modulus of elasticity (E_{rm}) of sandstone material (Hoek and Diederichs, 2006). Finally, determining foundation E_{rm} depends on a formulas:

$$E_{rm}(\text{GPa}) = E_i \times (0.002 + \frac{1 - D/2}{1 + e^{\left(\frac{(60+15\times D - GSI)}{11}\right)}} . \quad (5)$$

4. 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 (E_c is the concrete deformation modulus).

If E_c/E_f value is lower than 4, there is no problem on dams. The minimum value of E_f should be around 5 GPa for a dam. When E_f is less 5 GPa, there happens serious troubles (fracture included) due to the low value of E_f (Romana, 2003).

In this study, we have three different E_c/E_f ratios. Every case has a different E_c/E_f value. It was investigated that how the stresses and displacements change by E_c/E_f value. The numerical analysis results were compared each other. The E_c/E_f ratios change between 1.6 and 3.9 for three different models.

5. 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.

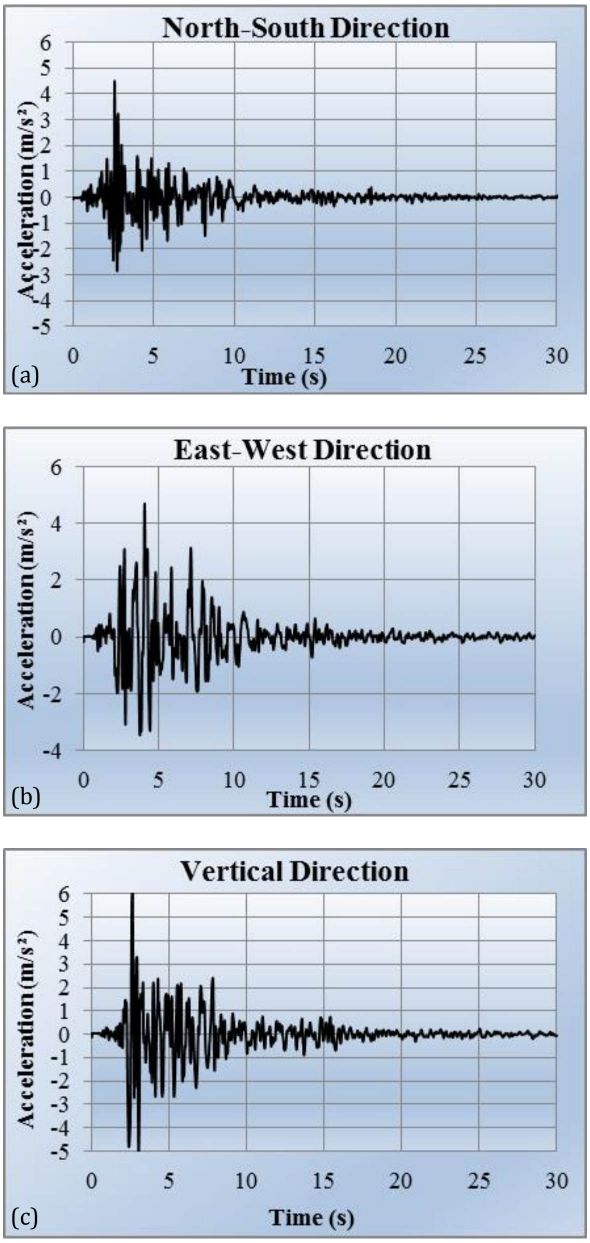

Fig. 2. Accelerogram of Loma Prieta Earthquake for near-fault effect: (a) north-south; (b) east-west; (c) vertical component.

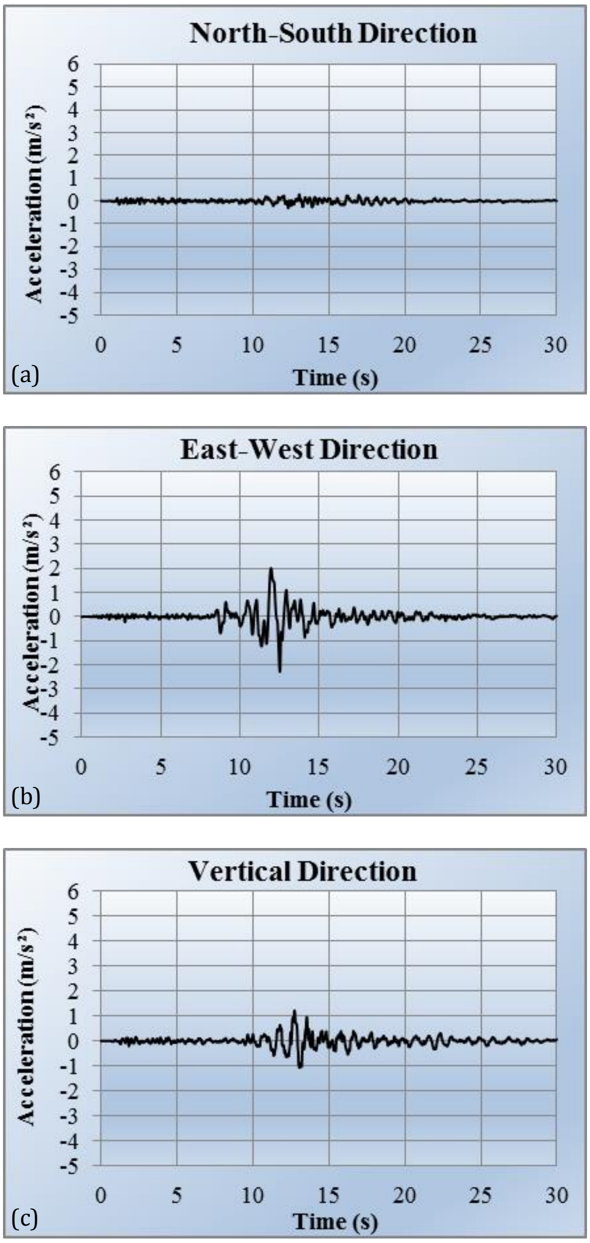

Fig. 3. Accelerogram of Loma Prieta Earthquake for far-field effect: (a) north-south; (b) east-west; (c) vertical component.

The analysis was performed for empty reservoir situation. Rayleigh damping is considered in the solutions with (α, β) constants (Table 2).

According to numerical solutions, it was seen that near-fault ground motions are more effective than far-field for three models. This case was observed in all different numerical models. 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 18.9 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 9074 kPa. All dynamic analysis results show the Model 3 involves lower stress and displacements. Because, Model 3 has bigger modulus of elasticity than the others. In addition, the maximum displacements occurred in Model 1 due to the lower elasticity modulus value. Besides, it is obvious that the distances of the fault have an important role in sizableness of stresses and displacements.

Table 2. Rayleigh damping constants (α, β).

Models	Rayleigh damping constant (α)	Rayleigh damping constant (β)
Model 1	1.15983	0.00189452
Model 2	1.28314	0.00168853
Model 3	1.35167	0.00158081

6. Conclusions

In this study, an arch dam was modeled by SAP2000 software. The arch dam body was composed with solid elements. Then, soils having different modulus of elasticities were modeled. After that the material parameters were assigned. Finite element method was used for solution in SAP2000 software. Loma Prieta earthquake at various distances records were selected to application on dam body and foundation models. Different faults records were used for dynamic linear analysis on three directions. Changing effects of E_c/E_f ratio on the maximum and minimum normal stresses of dam body was investigated.

According to linear modal time-history analysis, the material properties of the foundation affects dam behavior obviously. In addition, different fault distances could 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 of the dam may include various soil materials. The followings can be deducted from this study:

- Maximum displacements were obtained for near-fault effects,
- Maximum displacements obtained in upstream direction,
- Maximum normal stresses occurred at arch direction
- The stresses and displacements for the Model 3 are lower than those including different elasticity modulus of foundation conditions,
- If the modulus of elasticity 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.

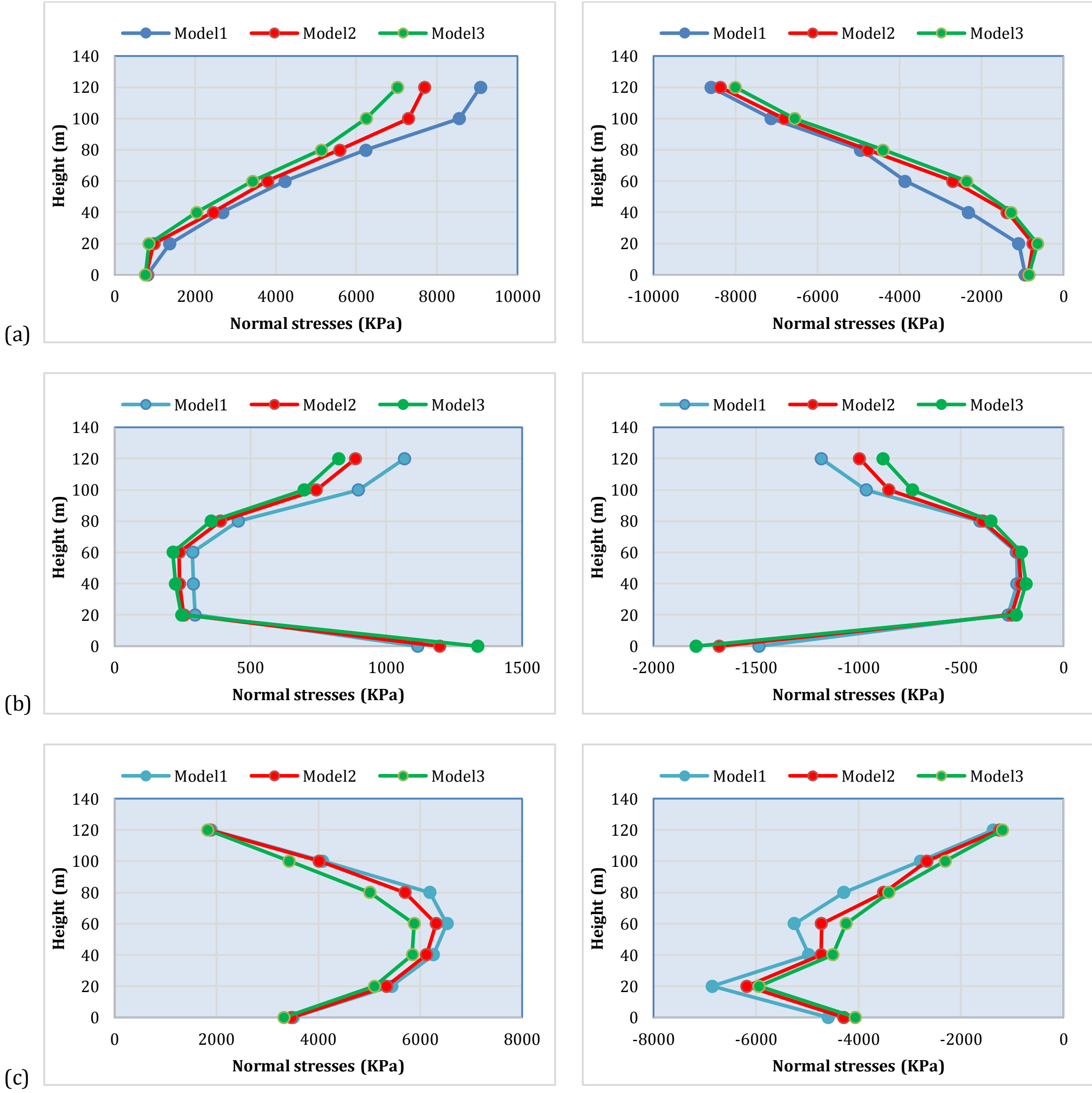

Fig. 4. Maximum and minimum normal stresses at each direction for near-fault ground motion effect: (a) *x* direction; (b) *y* direction; (c) *z* direction.

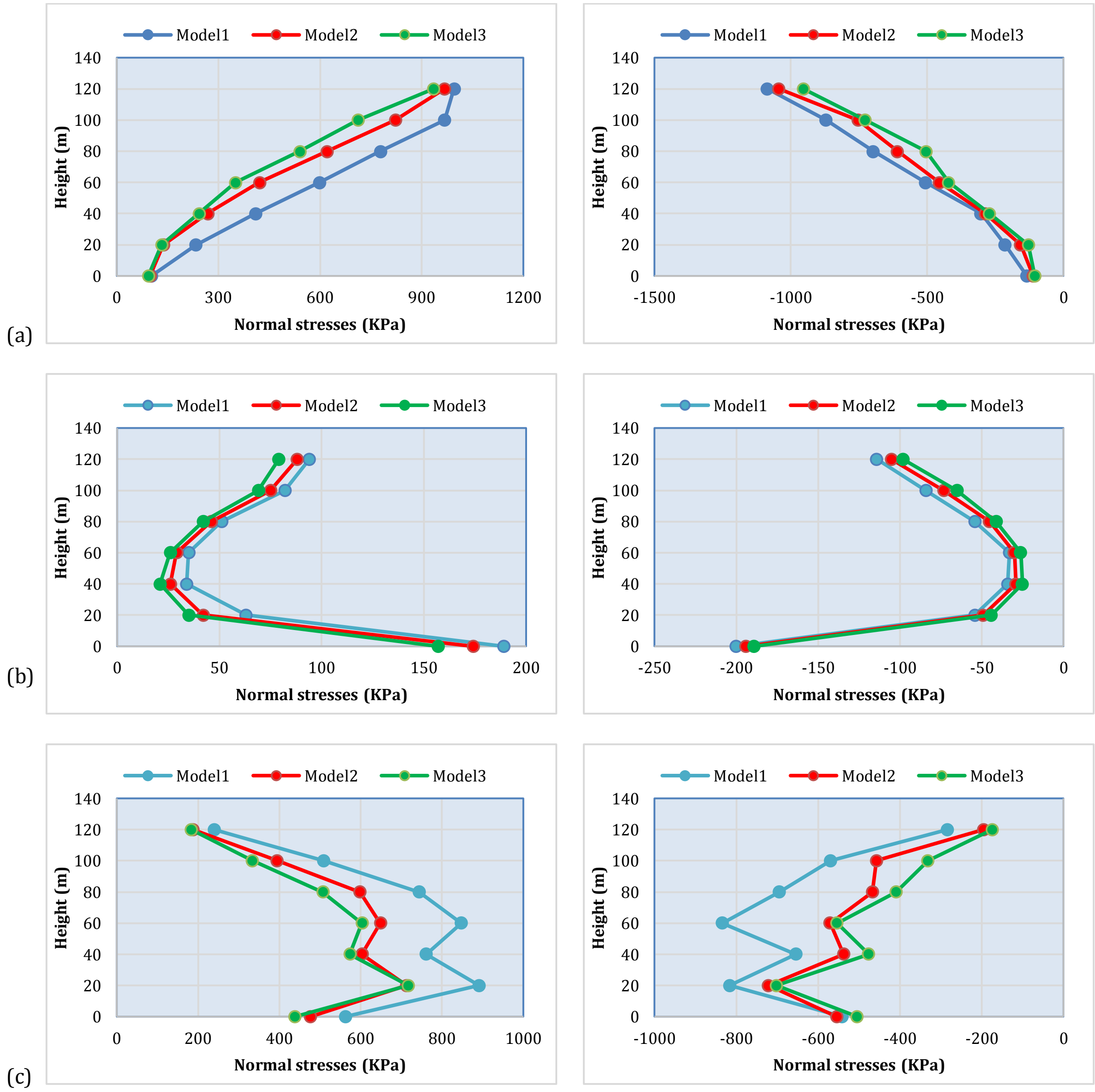

Fig. 5. Maximum and minimum normal stresses at each direction for far field ground motion effect: (a) *x* direction; (b) *y* direction; (c) *z* direction.

REFERENCES

Calamak M, Arıcı Y, Yanmaz AM (2013). An evaluation on the development on dam engineering in Turkey. Department of Civil Engineering, METU, Çankaya, Ankara, December (in Turkish).

Davoodib M, Jafarib MK, Hadiani N (2013) Seismic response of embankment dams under near-fault and far-field ground motion excitation. *Engineering Geology*, 158, 66–76.

Dennis TL (1968). Arch Dams: A review of British research and development. *Proceedings of the Symposium Held at the Institution of Civil Engineers*, London, England.

Gercek H (2007). Poisson's ratio values for rocks. *International Journal of Rock Mechanics & Mining Sciences*, 44, 1–13, Zonguldak, Turkey

Hoek E, Carranza-Torres C, Corkum B (2002). Hoek-Brown Failure Criterion – 2002 Edition. *5th North American Rock Mechanics Symposium and 17th Tunneling Association of Canada Conference: NARMS-TAC*, 267-271.

Hoek E, Diederichs MS (2006). Empirical estimation of rock mass modulus. *International Journal of Rock Mechanics and Mining Sciences*, 43(2), 203-215.

Hudson JA (1989). Rock Mechanics Principles in Engineering Practice. Butterworths, London

Mirzaei E, Vahdani S, Mirghaderi R (2010). Seismic analysis of double curved arch dams based performance. *Proceedings of the World Congress on Engineering and Computer Science (WCECS)*, 2, San Francisco, USA.

Mosallam AS, Banerjee S (2007). Shear enhancement of reinforced concrete beams strengthened with FRP composite laminates. *Composites: Part B*, 38(5-6), 781–93.

Romana M (2003). DMR (Dam Mass Rating): An adaptation of RMR geomechanics classification for use in dams foundations. *10th ISRM Congress*, Sandton, South Africa.