Advances in Concrete Construction, *Vol. 6, No. 3 (2018) 269-283*
DOI: https://doi.org/10.12989/acc.2018.6.3.269

Geometrical dimensions effects on the seismic response of concrete gravity dams

Barış Sevim*[1,2]

[1]*Yildiz Technical University, Department of Civil Engineering, Esenler, Istanbul, Turkey*
[2]*İstanbul Gelişim University, Department of Civil Engineering, Avcilar, Istanbul, Turkey*

(Received December 24, 2017, Revised March 30, 2018, Accepted April 4, 2018)

Abstract. This study presents the effects of geometrical dimensions of concrete gravity dams on the seismic response considering different base width/dam height (L/H) ratios. In the study, a concrete gravity dam with the height of 200 m is selected and finite element models of the dam are constituted including five different L/H ratios such as 0.25, 0.5, 0.75, 1.00, 1.25. All dams are modeled in ANSYS software considering dam-reservoir-foundation interaction. 1989 Loma Prieta earthquake records are applied to models in upstream-downstream direction and linear time history analyses are performed. Dynamic equilibrium equations of motions obtained from the finite element models of the coupled systems are solved by using Newmark time integration algorithm. The seismic response of the models is evaluated from analyses presenting natural frequencies, mode shapes, displacements and principal stresses. The results show that the L/H ratios considerably affect the seismic response of gravity dams. Also, the model where L/H ratio is 1.00 has more desirable results and most appropriate representation of the seismic response of gravity dams.

Keywords: base width-dam height ratio (L/H); finite element modeling; geometrical dimensions effect; gravity dams; seismic response

1. Introduction

Gravity dams are massive concrete hydraulic structures that retain the impounded water by resisting the forces imposed on them mainly by their own weight. Relatively long and straight concrete gravity dams built as independent monoliths separated by transverse contraction joints may be idealized using a 2D finite element model including the foundation rock and the impounded water. Oriented normal to the dam axis, these vertical joints extend from the foundation to the top of the dam and from the upstream face to the downstream face in the 2D dam-water-foundation model, usually of the tallest cross section, may be analyzed as a single system in the time domain using the standard finite element procedures. Traditionally, analysis of a gravity dam considered a very simple mathematical model of the structure. Such a method was based on the concept that the resistance to external forces was 2D in nature, so only a unit slice of the dam taken in the upstream-downstream direction was analyzed. For the amplitude of motion expected during strong earthquakes, the shear forces transmitted through the contraction joints are

---

*Corresponding author, Associate Professor, E-mail: basevim@yildiz.edu.tr

http://www.techno-press.org/?journal=acc&subpage=7 ISSN: 2287-5301 (Print), 2287-531X (Online)

small compared with the inertia forces of the monoliths. For this condition, the monoliths in a long and straight gravity dam tend to vibrate independently, and their responses to earthquakes can be evaluated on the basis of a 2D model. In the literature researchers performed many 2D analyses on gravity dams to assess the behavior (Calayır *et al.* 1996, Proulx and Paultre 1997, Ghaemian and Ghobarah 1999, Guanglun *et al.* 2000). The studies consist of linear and nonlinear procedure, fluid-structure interaction, foundation flexibility, seismic fragility and damage assessments and experimental investigations of gravity dams (Tekie and Ellingwood 2003, Calayır and Karaton 2005, Arabshahi and Lotfi 2008, Bayraktar *et al.* 2009, Zhu *et al.* 2010, Shariatmadar and Mirhaj 2011, Valamanesh *et al.* 2011, Lotfi and Sami 2012, Bilici and Bayraktar, 2012, Ardebili *et al.* 2013, Wang *et al.* 2014, Akpinar *et al.* 2014, Ghanaat *et al.* 2015, Zeidan 2015, Alembagheri 2016).

One of the main effect on earthquake response of gravity dams is geometrical dimensions. Because, dimensions of reservoir, foundation or geometry of dam body provide different response subjected to mode shapes, natural frequencies, displacement and stresses which are obtained from modal, static and dynamic analyses (USACE 2003). Millan *et al.* (2007) studied about the effects of reservoir geometry on the seismic response of gravity dams. For the purpose, a boundary element method (BEM) model in the frequency domain is used to investigate the influence of the reservoir geometry on the hydrodynamic dam response. Important conceptual conclusions about the dam-reservoir system behavior are obtained using the model and the results show that the reservoir shape influences the seismic response of the dam. Bayraktar *et al.* (2010) investigated the effect of reservoir length on seismic performance of gravity dams to near and far-fault ground motions. For the aim, Folsom Gravity dam is selected for numerical example and it is modeled considering four reservoir lengths and foundation. In the numerical analyses reservoir length are considered as H, 2H, 3H and 4H (H: dam height), and response of the models are investigated. Altunışık and Sesli (2015) are aimed to determine the dynamic response of concrete gravity dams using different water modeling approaches such as Westergaard, Lagrange and Euler. In the study, a gravity dam is modeled considering dam-reservoir-foundation interaction using ANSYS software. Reservoir effects are considered from three approaches such as Westergaard, Lagrange and Euler. To determine the structural response of the dam, the linear transient analyses are performed using 1992 Erzincan earthquake ground motion record. Seismic response is evaluated including dynamic characteristics, displacements, and principal stresses for each model. Khosravi and Heydari (2015) investigated to find the optimal shape of concrete gravity dams including dam-water-foundation rock interaction. In the study, 2D model of Koyna Graviy dam constituted for four times considering different assumptions such as, dam with empty reservoir and rigid foundation, dam with empty reservoir and flexible foundation, dam with full reservoir and rigid foundation, and dam with full reservoir and flexible foundation. All models and analyses are performed using ANSYS software. The result are presented comparatively from all models and evaluated to find optimal shape of dam. Ziaolhagh *et al.* (2016) investigated the dynamic characteristics of a flexible gravity dam- compressible rectangular reservoir system. In the study finite element model of the system is constituted using classical 8-node element and a new 21-node element separately. In the study it is concluded that the one high-order element treats more precisely than the eight-node elements. According to literature review, seismic response of gravity dams are generally performed by 2D models and analyses considering dam-reservoir-foundation interaction. The reservoir is generally modeled using fluid finite elements considering translation and pressure degree of freedoms. Also the length of the reservoir should be chosen as 3 dam heights which its effects on deflections, stresses, and natural frequencies of the dam become

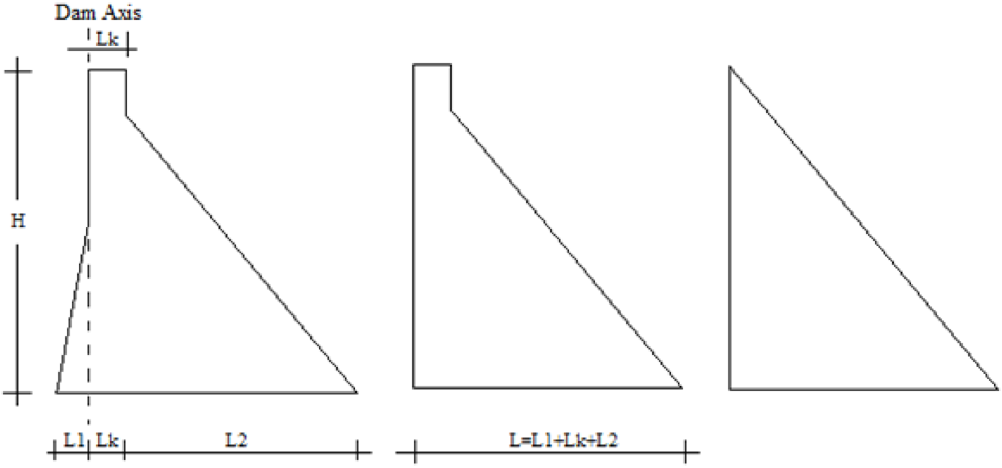


Fig. 1 Typical geometrical shapes of gravity dams

negligible. The foundation model should be preferred as massless in which only the effects of foundation flexibility are considered. The size of the foundation model should be determined based on the modulus ratio of the foundation to the concrete *Ef /Ec*. If *Ef /Ec*≥1, the foundation model should be extended one dam height in the upstream, downstream, and downward directions to neglect the effects of dam body. So these assumptions are generally used to model and evaluate the gravity dams.

On the other hand, one of the main parameters which effects the response of gravity dams is base width (*L*)-height (*H*) ratio. The ratio is generally taken less than 1 in design. However there is not more accurate approach to decide the ratio. Typical geometrical shapes of gravity dams are given in Fig. 1. Al types of these shapes can be changed seismic response of gravity dams. This study aims to investigate the effects of *L/H* ratios of gravity dams on seismic response. So the study presents the earthquake response of gravity dams considering different *L/H* ratios. In the study a gravity dam with the height of 200 m is selected and finite element models of the dam are constituted considering for five different *L/H* ratios such as 0.25, 0.5, 0.75, 1.00, 1.25. All dams are modeled in ANSYS software considering dam-reservoir-foundation interaction. 1989 Loma Prieta earthquake records are applied to models in upstream-downstream direction. The seismic response of the models are evaluated by analyses results considering displacements, principal stresses and demand-capacity ratios. In the content of the study, firstly literature review is presented, then dam-reservoir-foundation interaction is given. After that, numerical example is considered and lastly, conclusions inferred from the study are presented.

2. Dam-Reservoir-Foundation interaction

Reservoir considerably affects the dynamic response of dams during earthquakes. Three approaches are generally used to consider reservoir effects in the analyses: Westergaard, Euler and Lagrangian approaches. In Westergaard approach (Westergaard 1933), reservoir is considered as a vibrated mass dispersion with the dam, which is similar to being hydrodynamic effect dispersion towards the dam upstream face. In Eulerian approach (Dungar 1978), the displacements are the variables in the structure; the pressures are the variables in the fluid. However, in Lagrangian approach, the displacements are the variables in both the fluid and the structure. Therefore, there is no need any extra interface equations in Lagrangian approaches (Wilson and Khalvati 1983). For that reason, compatibility and equilibrium are automatically satisfied at nodes along the interfaces between fluid and structure.

In this study, reservoir is modeled by FLUID29 elements in ANSYS (2017) software which is generally used for modeling the fluid medium and the interface in fluid-structure interaction problems. Typical applications include sound wave propagation and submerged structure dynamics. The governing equation for acoustics, namely the 2-D wave equation, has been discretized taking into account the coupling of acoustic pressure and structural motion at the interface. The element is compressible and inviscid. The element has four corner nodes with three degrees of freedom per node: translations in the nodal x and y directions and pressure. The translations, however, are applicable only at nodes that are on the interface. The interactions of the reservoir-dam and reservoir-foundation at a mesh interface cause the acoustic pressure to exert a force applied to dam and foundation. So interaction equations of motion related to structure (dam and foundation) and reservoir (fluid) can be given as Eqs. (1) and (2), respectively.

$$[M_s]\{\ddot{U}\}+[K_s]\{U\}=\{F_s\}+[R]\{P\} \tag{1}$$

$$[M_f]\{\ddot{P}\}+[K_f]\{P\}=\{F_f\}-\rho_0[R]^R\{\ddot{U}\} \tag{2}$$

In Eqs. (1), (2), [*R*] is a “coupling” matrix that represents the effective surface area associated with each node on the fluid-structure interface. The coupling matrix [*R*] also takes into account the direction of the normal vector defined for each pair of coincident fluid and structural element faces that comprises the interface surface. The positive direction of the normal vector, as the ANSYS program uses it, is defined to be outward from the fluid mesh and in towards the structure. Both the structural and fluid load quantities that are produced at the fluid-structure interface are functions of unknown nodal degrees of freedom. Placing these unknown “load” quantities on the left hand side of the equations and combining the two equations into a single equation) produces Eq. (3). The equation implies that nodes on a fluid-structure interface have both displacement and pressure degrees of freedom.

$$\begin{bmatrix} M_s & 0 \\ \rho_0 R^T & M_f \end{bmatrix}\begin{pmatrix} \ddot{U} \\ \ddot{P} \end{pmatrix}+\begin{bmatrix} K_s & -R \\ 0 & K_f \end{bmatrix}\begin{pmatrix} U \\ P \end{pmatrix}=\begin{pmatrix} F_s \\ F_f \end{pmatrix} \tag{3}$$

3. Numerical example

3.1 Description of gravity dam and finite element models

The study aims to investigate geometrical dimensions of dam body on the seismic response of dam-reservoir-foundation systems. So a gravity dam with 10 m constant crest width and 200 m constant height (*H*) is selected and base width (*L*) assumed as variably. Base width is calculated according to *L/H* ratio and the ratios are preferred as 0.25, 0.5, 0.75, 1.0, and 1.25, respectively. Therefore five different gravity dam models are decided for the study. Finite element models of the dams are constituted two dimensionally by ANSYS (2017) software considering dam-reservoir-foundation (full reservoir) interaction effects (Fig. 2). Models are named as Model 1,

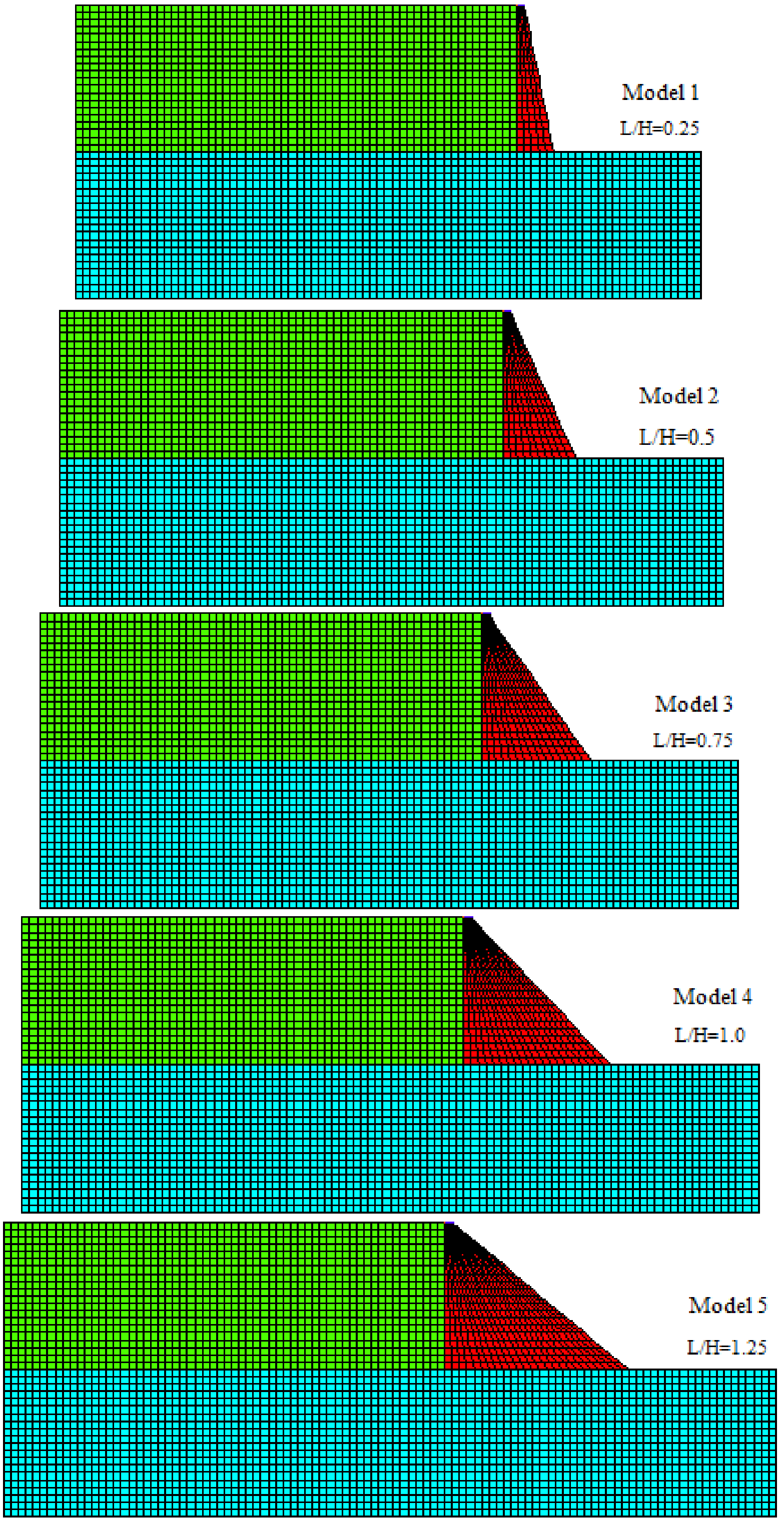


Fig. 2 2D Finite element models of gravity dam

Model 2, Model 3, Model 4, and Model 5, respectively for *L/H* ratios such as 0.25, 0.5, 0.75, 1.0, and 1.25 (See Fig. 2).

In the finite element modeling, the dam body is represented using PLANE182 elements which are used for 2-D modeling of solid structures. The element has four nodes and has two degree of freedoms at each nodes such as *X* and *Y* translations. The element has the capabilities of plasticity, stress stiffening, large deflection, and large strain ANSYS (2017). In the modeling, reservoir is extended as three times as dam height through upstream direction. Such a modeling neglects the effects on deflections, stresses, and natural frequencies of the dam (USACE 2003, Sevim 2011, Sevim *et al.* 2011a, Sevim *et al.* 2011b, Sevim *et al.* 2012). Reservoir is represented using FLUID29 elements which are used both modeling fluid domain and fluid-structure interaction. The element has four nodes with three degrees of freedom per node: translations in the nodal x and y directions and pressure. The translations, however, are applicable only at nodes that are on the interface. Foundation is modeled using PLANE182 elements and extended as dam height through vertical and downstream directions. Also foundation is modeled on upstream direction under the reservoir. Boundary conditions for are fixed under and near side of the foundations. The foundation model should be preferred as massless in which only the effects of foundation flexibility are considered. The size of the foundation model should be determined based on the modulus ratio of the foundation to the concrete E_f/E_c (Ziaolhagh *et al* 2016). If $E_f/E_c \geq 1$, the foundation model should be extended one dam height in the upstream, downstream, and downward directions to neglect the effects of dam body. The assumptions told above are generally use to model and evaluate the gravity dam. Material properties assumed in the modeling are given in Table 1. A mesh study is done to decide optimum mesh size. According to this investigations the numbers of nodes and elements used each model are listed in Table 2.

3.2 Seismic analyses of gravity dam models

Modal analyses of gravity dam models are performed to obtain natural frequencies which are used to calculate Rayleigh damping coefficients. First nine natural frequencies obtained from

Table 1 Material properties assumed in finite element modeling of gravity dam models

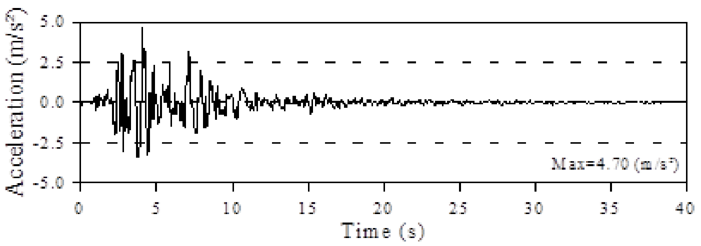
System	Element Type	Material Properties		
		Elasticity Modulus (MPa)	Poisson Ratio	Mass Density (kg/m^3)
Dam	PLANE182	35000	0.2	2500
Reservoir	FLUID29	2070	-	1000
Foundation	PLANE182	45000	0.3	-

Table 2 Numbers of nodes and elements used in finite element modeling of gravity dam models

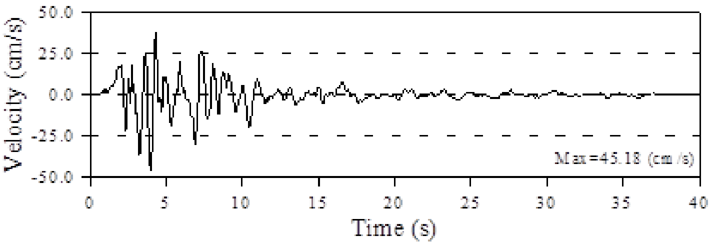
Models	Numbers of Nodes	Numbers of Elements		
		Dam PLANE182	Reservoir FLUID29	Foundation PLANE182
Model 1	3126	100	1200	1700
Model 2	3331	200	1200	1800
Model 3	3536	300	1200	1900
Model 4	3741	400	1200	2000
Model 5	3946	500	1200	2100

Table 3 Natural frequencies of gravity dams

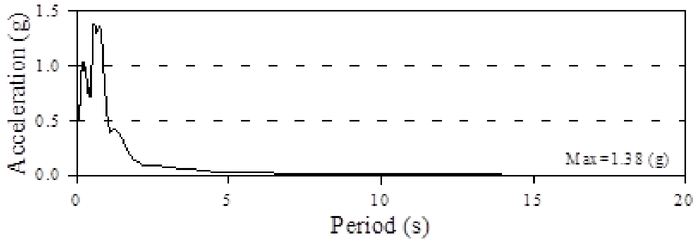
Modes	Natural Frequencies (Hz)				
	Model 1	Model 2	Model 3	Model 4	Model 5
1	0.18	0.28	0.31	0.32	0.33
2	0.75	0.95	1.10	1.17	1.20
3	1.57	1.68	1.80	1.91	1.99
4	2.11	2.58	2.62	2.63	2.65
5	2.77	3.16	3.36	3.41	3.42
6	3.55	3.61	3.67	3.70	3.70
7	3.79	3.79	3.76	3.74	3.72
8	3.90	3.97	4.08	4.14	4.15
9	4.45	4.51	4.53	4.41	4.30



(a) The time-history of ground motion acceleration



(b) The time-history of ground motion velocity



(c) Spectral accelerations (acceleration spectrum)

Fig. 3 The time-histories of (a) acceleration (b) velocity and (c) spectral accelerations subjected to CLS090 component of 1989 Loma Prieta earthquake

analyses for each model are listed in Table 3. As is seen in Table 3, natural frequencies are obtained between 0-5 Hz for all models. Also the natural frequencies are generally increased from Model 1 to Model 5 when compared to five models together. Results show that Model 5 is more rigidity than others, however natural frequencies of Model 4 are near to these of Model 5.

In this study, seismic response of gravity das are investigated under 1989 Loma Prieta earthquake. East-west component (CLS090) of the earthquake is applied to models on upstream-downstream direction. The time histories of acceleration and velocity of CLS090 component are plotted in Fig. 3(a)-(b), respectively (Url-1 2017). As is seen in Fig. 3(a)-(b) that peak ground acceleration and velocity values are 0.48g and 45.2 cm/s, respectively. In addition the spectral accelerations (acceleration spectrum) of the component obtained for % 5 damping are plotted in Fig. 3(c) (Url-1 2017). In time history analyses, the element matrices are computed using the Gauss numerical integration technique (Bathe 1996). The Newmark method is used in the solution of the equation of motions. Damping matrices of the systems are considered by Rayleigh damping which is represented related to mass and stiffness matrices. Rayleigh damping constants are calculated considering first nine natural frequencies for each model (see Table 3) assuming 5% damping ratios. Because of needed too much memory for the analyses, the first 15 seconds of the ground motion are taken into account in calculations for each model (See Fig. 3), which are the most effective durations.

3.3 Time history analyses results

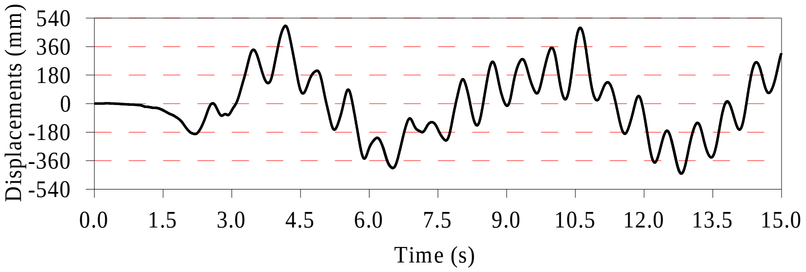
3.3.1 Displacements

The time-history of the horizontal displacements at the crest point of gravity dam obtained from linear analysis are respectively presented in Fig. 4 (a)-(e) from Model 1 to Model 5. As is seen in Fig. 4 that, when the maximum displacements are obtained for Model 1, the minimum displacements are occurred for Model 5. The maximum displacements at this point for each model are occurred as 52 cm, 41 cm, 37 cm, 21 and 18 cm, respectively. As is seen from Fig. 4 that the frequency contents of the displacements obtained from Model 1, Model 2 and Model 3 are different compared to each other. On the other hand the frequency contents of the displacements of Model 4 and Model 5 are different compared to those of Model 1, Model 2, and Model 3, but they are similar to for Model 4 and Model 5. The results show that the Model 4 is so desirable for finite element modeling.

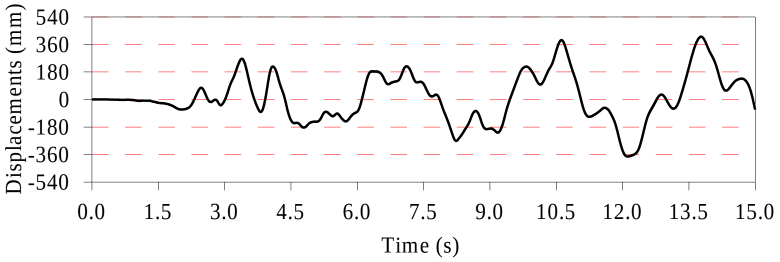
The variation of displacements on A-A section of each gravity dam are submitted in Fig. 5. It is obviously seen that displacements increase by the height of dams and maximum displacement occurs at the top of the dams. Also the displacements do not change considerably from bottom to 80 m height. However the displacement obtained at the crest points for Model 4 and 5 are smaller than those of Model 1, Model 2, and Model 3. The displacement at the crest point are nearly % 60 decreased from Model 1 to Model 4, and % 65 decreased from Model 1 to Model 5.

3.3.2 Principal stresses

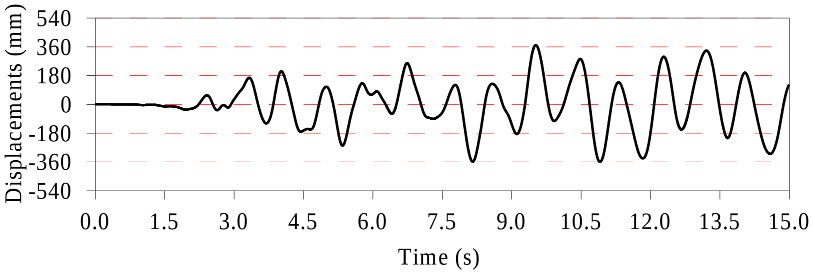
The maximum and minimum principal stresses obtained from I-I section, where is the bottom section, of each gravity dam model are plotted in Fig. 6 (a)-(b). As is seen in Fig. 6 (a)-(b) that, the maximum and minimum principal stresses are obtained at the downstream side of the dam for Model 1 and Model 2. Those are obtained at the upstream side of the dam for Model 3, Model 4, and Model 5. When examined principal stresses in Fig. 6 that, Model 1, Model 2 and Model 3 do not reflect a good response. The reason of it that although Model 4 and Model 5 have more rigidity than other models, the stresses on Model 4 and Model 5 are smaller than those of other models. The principal stresses of Model 4 and Model 5 have harmony compared to each other. However it has not forgotten that Model 5 has nearly % 25 more concrete volume than Model 4. So Model 4 is



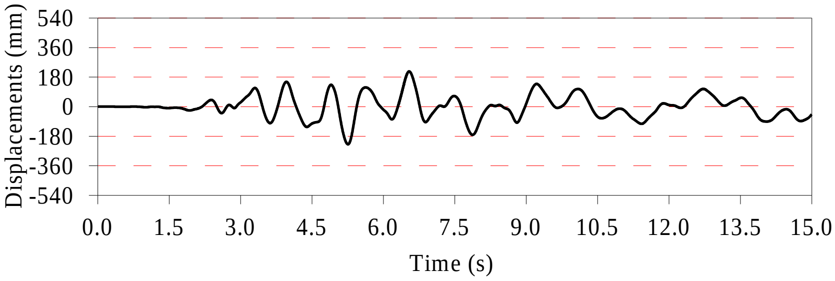
(a) The time-histories of displacements occurred Model 1



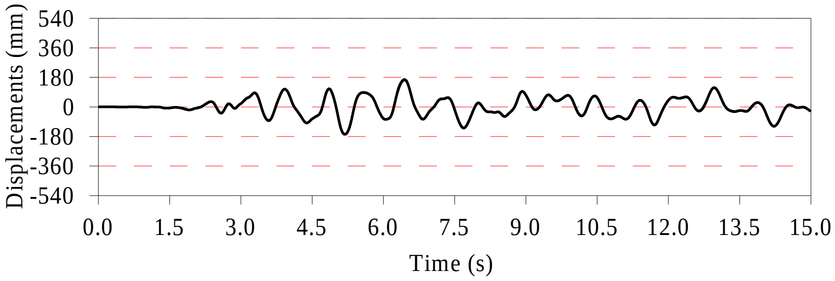
(b) The time-histories of displacements occurred Model 2



(c) The time-histories of displacements occurred Model 3



(d) The time-histories of displacements occurred Model 4



(e) The time-histories of displacements occurred Model 5

Fig. 4 The time-history of the horizontal displacements at the crest point of gravity dam models

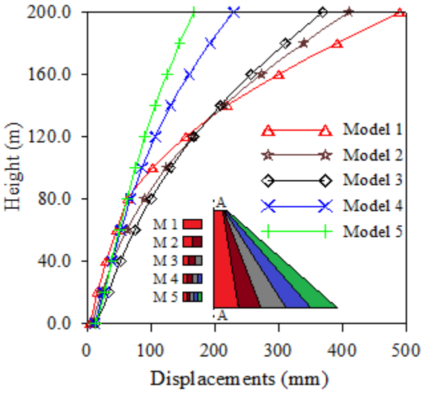
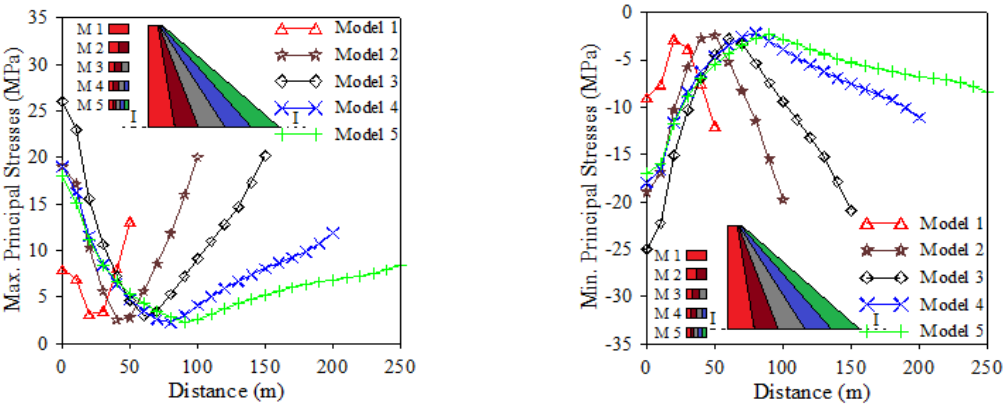


Fig. 5 Maximum horizontal displacements on A-A section of each gravity dam models



(a) Maximum principal stresses (b) Minimum principal stresses

Fig. 6 The maximum and minimum principal stresses on I-I section of each gravity dam model

Table 4 The peak values of the maximum and minimum principal stresses for each model

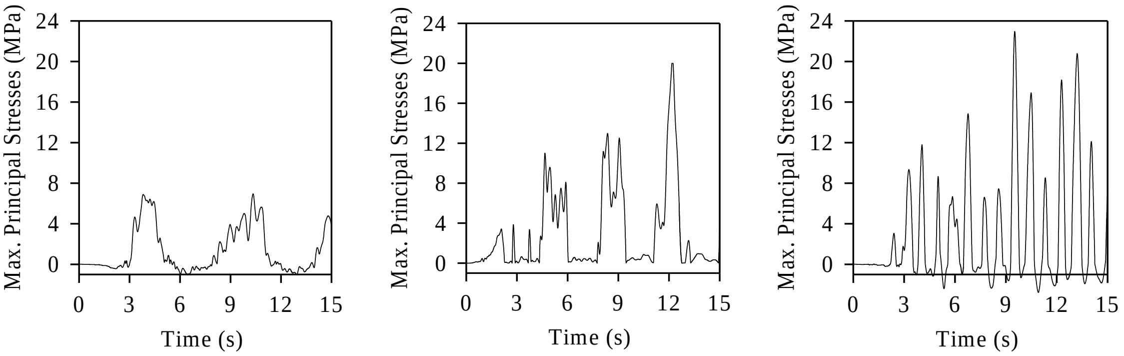
Stresses	Model 1	Model 2	Model 3	Model 4	Model 5
MTPS[1] (MPa)	13.0	20.4	23.0	16.2	15.1
MCPS[2] (MPa)	12.0	19.8	22.3	16.6	16.0

[1] MTPS: Maximum Tensile Principal Stress
[2] MCPS: Maximum Compressive Principal Stress

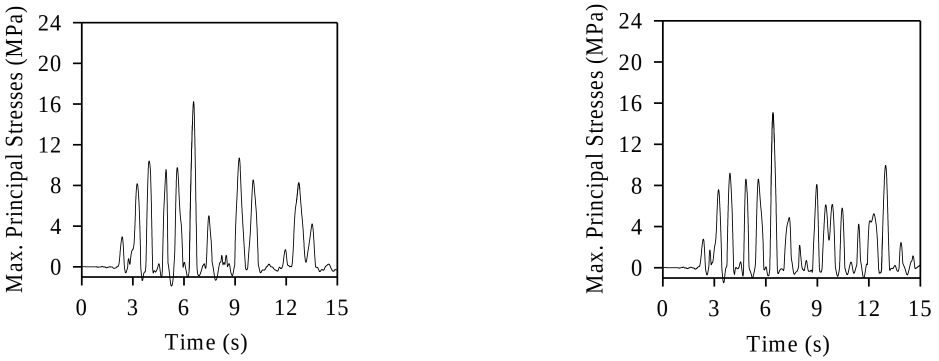
so suitable model when representing the seismic response of gravity dams.

The peak values of the maximum and minimum principal stresses are listed in Table 4 for each model. As is seen in Table 4 that, the minimum principal stresses (compressive stress) are lower than compressive strength of concrete material of gravity dam models. But the maximum principal stresses (tensile stress) are more than tensile strength of concrete material of gravity dam for each model. Such results are obtained due to earthquake forces existed from negative accelerations. So all dam models have to be designed according to these tensile stresses and all models have to be analyzed nonlinearly to consider plastic behavior of concrete.

The time-histories of maximum principal stresses (tensile stress) for the most representative



(a) Model 1 (b) Model 2 (c) Model 3



(d) Model 4 (e) Model 5

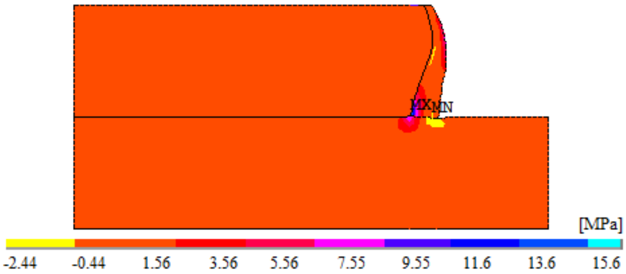
Fig. 7 The time-histories of maximum principal stresses for the most representative point of gravity dams

point of each dam model, which is base of downstream side of the dam for Model 1 and Model 2, and base of upstream side of the dam for Model 3, Model 4 and Model 5 are displayed in Fig. 7 (a)-(e), respectively. It is clearly seen from Fig. 7 that the frequency contents of the stresses are different compared to Model 1, Model 2 and Model 3 together. On the other hand the frequency contents of the stresses of Model 4 and Model 5 are different compared to those of Model 1, Model 2, and Model 3, but they are similar to Model 4 and Model 5. The results show that the Model 4 is so desirable for finite element modeling like the displacements results.

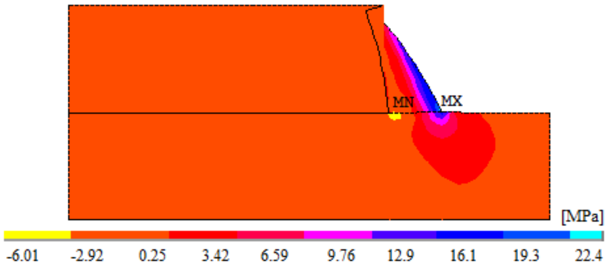
The maximum principal stresses contour through the lateral direction at the instant at which the maximum stresses occur are shown in Fig. 8 (a)-(e) for) for each model. It can be seen in Fig. 8 that the maximum stresses occur at the base point on downstream face of the dam except Model 2. The maximum principal (tensile) stresses obtained for each model are more than those of the limited tensile stress capacity of dam concrete. These may cause local damage on the dams. So more realistic representation, nonlinear time history analyses may be performed.

4. Conclusions

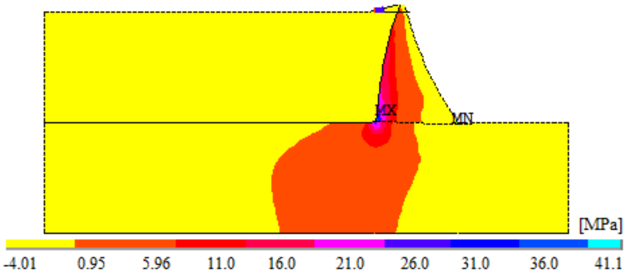
In this study, effects of geometrical dimensions of dam body on the seismic response of gravity dams are investigated. For the purpose, five gravity dam-reservoir-foundation systems are modelled considering different dam base width (L)-height (H) ratios. The ratios are assumed as



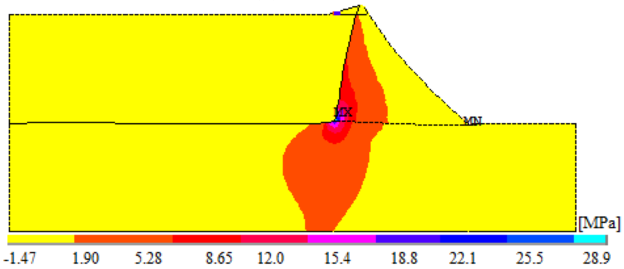
(a) Model 1



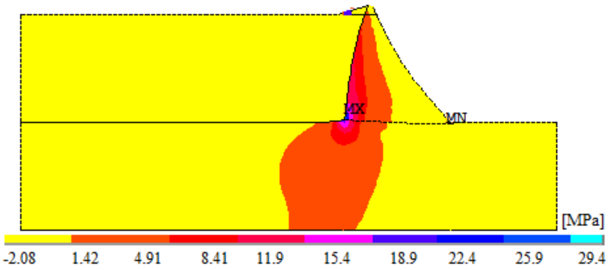
(b) Model 2



(c) Model 3



(d) Model 4



(e) Model 5

Fig. 8 Maximum principal stress contours obtained for each model

0.25, 0.5, 0.75, 1.00, 1.25. All gravity dams are modeled in ANSYS software and the models are titled as Model 1, Model 2, Model 3, Model 4 and Model 5 for each ratio, respectively. 1989 Loma Prieta earthquake records are applied to models in upstream-downstream direction and linear time history analyses are performed. In this study, the following observations and suggestion can be made:

- Natural frequencies are obtained between 0-5 Hz for all models. Also the natural frequencies are generally increased from Model 1 to Model 5 when compared to five models together. Results show that Model 5 is more rigidity than others, however natural frequencies of Model 4 are near to these of Model 5.
- The frequency contents of the displacements are different compared to Model 1, Model 2 and Model 3 together. On the other hand the frequency contents of the displacements of Model 4 and Model 5 are different compared to those of Model 1, Model 2, and Model 3, but they are similar to for Model 4 and Model 5.
- The displacements increase by the height of dams and maximum displacement occurs at the top of the dams for each model. The maximum displacements obtained on Model 1 are % 22 more than Model 2 results, % 33 more than Model 3 results, % 61 more than Model 4 results and % 65 more than Model 5 result. Although all models provide the displacements limit criteria such a kind height (200 m), Model 4 is so desirable for finite element modeling when considered volume of concrete used construction or payment.
- The maximum and minimum principal stresses are obtained at the downstream side of the dam for Model 1 and Model 2. Those are obtained at the upstream side of the dam for Model 3, Model 4, and Model 5. Model 1, Model 2 and Model 3 do not reflect a good response, however the seismic response of Model 4 and Model 5 are so appropriate under 1989 Loma Prieta Earthquake.
- Maximum and minimum principal stresses obtained at the bottom section of the dam are higher at the side of section, however the stresses are decreased on the middle of the section for all models. Maximum principal (tensile) stresses obtained for each model are more than tensile strength of concrete material of dam. Also the most suitable values are obtained for Model 4 and Model 5.
- The frequency contents of the stresses are different compared to Model 1, Model 2 and Model 3 together. On the other hand the frequency contents of the stresses of Model 4 and Model 5 are different compared to those of Model 1, Model 2, and Model 3, but they are similar to Model 4 and Model 5.
- According the results of the study, Model 4 and Model 5 have good seismic responses. But Model 4, where base width (L) - height (H) ratio is 1.0, has more suitable response. Because the displacement and stresses results are near to Model 5 results. Model 4 has nearly % 25 lower concrete volume. Such a difference provides more economy during construction.
- Although the maximum tensile stresses occurred on local points for each model and due to tensile stress exceed strength material, it is suggested performing nonlinear analyses which are consider concrete plastic behavior for more realistic representation.

References

Akpinar, U., Binici, B. and Arici, Y. (2014), “Earthquake stresses and effective damping in concrete gravity dams”, *Earthq. Struct.*, **6**(3), 251-266.

Alembagheri, M. (2016), “Earthquake damage estimation of concrete gravity dams using linear analysis and empirical failure criteria”, *Soil Dyn. Earthq. Eng.*, **90**, 327-339.

Altunisik, A.C. and Sesli, H. (2015), “Dynamic response of concrete gravity dams using different water modelling approaches: Westergaard, Lagrange and Euler*”, Comput. Concrete*, **16**(3), 429-448.

ANSYS (2017), Swanson Analysis System, US.

Arabshahi, H. and Lotfi, V. (2008), ‘‘Earthquake response of concrete gravity dams including dam-foundation interface nonlinearities’’, *Eng. Struct.*, **30**(11), 3065-3073.

Ardebili, M.A.H., Kolbadi, S.M.S. and Mirzabozorg, A. (2013), “Smeared crack model for seismic failure analysis of concrete gravity dams considering fracture energy effects”, *Struct. Eng. Mech.*, **48**(1), 17-39.

Bathe, K.J. (1996), *Finite Element Procedures in Engineering* Analysis, Englewood Cliffs, NJ, US, Prentice Hall.

Bayraktar, A., Altunışık, A.C., Sevim, B., Kartal, M.E., Türker, T. and Bilici, Y. (2009), “Comparison of near and far fault ground motion effects on the nonlinear response of dam-reservoir-foundation systems”, *Nonlin. Dyn.*, **58**(4), 655-673.

Bayraktar, A., Türker, T., Akköse, M. and Ateş, Ş. (2010), “The effect of reservoir length on seismic performance of gravity dams to near- and far-fault ground motions”, *Nat. Hazard.*, **52**, 257-275.

Bilici, Y. and Bayraktar, A. (2012), “Site-response effects on the transient stochastic seismic response of concrete dam-reservoir-foundation systems by the Lagrangian approach”, *Arab. J. Sci. Eng.*, **37**(7), 1787-1800.

Calayır, Y. and Karaton, M. (2005), “A continuum damage concrete model for earthquake analysis of concrete gravity dam-reservoir systems”, *Soil Dyn. Earthq. Eng.*, **25**(11), 857-869.

Calayır, Y., Dumanoğlu, A.A. and Bayraktar, A. (1996), “Earthquake analysis of gravity dam-reservoir systems using the Eulerian and Lagrangian approaches”, *Comput. Struct.*, **59**,877-890.

Dungar, R. (1978), “An efficient method of fluid-structure coupling in the dynamic analysis of structures”, *Int. J. Numer. Meter. Eng.*, **13**, 93-107.

Ghaemian, M. and Ghobarah, A. (1999), “Nonlinear seismic response of concrete gravity dams with dam-reservoir interaction”, *Eng. Struct.*, **21**(4), 306-315.

Ghanaat, Y., Patev, R. and Chudgar, A. (2015), “Seismic fragility for risk assessment of concrete gravity dams”, *35th Annual USSD Conference*, Kentucky, USA, April.

Guanglun, W., Pekau, O.A., Chuhan, Z. and Shaomin, W. (2000), “Seismic fracture analysis of concrete gravity dams based on nonlinear fracture mechanics”, *Eng. Fract. Mech.*, **65**(1), 67-87.

Khosravi, S. and Heydari, M.M. (2015), “Design and modal analysis of gravity dams by ANSYS parametric design language”, *Walailak J. Sci. Tech.*, **12**(2), 167-180.

Lotfi, V. and Samii, A. (2012), “Dynamic analysis of concrete gravity dam-reservoir systems by wavenumber approach in the frequency domain”, *Earthq. Struct.*, **3**(3-4), 533-548.

Lupoi, A. and Callari, C. (2012), “A probabilistic method for the seismic assessment of existing concrete gravity dams”, *Struct. Infrastr. Eng.*, **8**, 985-98.

Millan, M.A., Young, Y.L. and Prevost, J.H. (2007), “The effect of reservoir geometry on the seismic response of gravity dams”, *Earthq. Eng. Struct. Dyn.*, **36**, 1441-1459.

PEER (Pacific Earthquake Engineering Research Centre), http://peer.berkeley.edu/smcat/data.

Proulx, J. and Paultre, P. (1997), “Experimental and numerical investigation of dam-reservoir-foundation interaction for a large gravity dam”, *Can. J. Civil Eng*., **24**(1), 90-105.

Shariatmadar, A. and Mirhaj, A. (2011), “Dam-reservoir-foundation interaction effects on the modal characteristic of concrete gravity dams”, *Struc. Eng. Mech*., **38**(1), 65-79.

Tekie, P. and Ellingwood, B. (2003), “Seismic fragility assessment of concrete gravity dams”, *Earthq. Eng. Struct. Dyn.*, **32**, 2221-2240.

Url-1 (2017), http://www.strongmotioncenter.org.

USACE (2003), “Time-history dynamic analysis of concrete hydraulic structures”, Engineering Manual, EM 1110-2-6051, US Army Corps of Engineers, USA.

Valamanesh, V., Estekanchi, H.E., Vafai, A. and Ghaemian, M. (2011), “Application of the endurance time method in seismic analysis of concrete gravity dams”, *Scientia Iranica*, **18**(3), 326-337.

Wang, M., Chen, J., Fan, S. and Lv, S. (2014), "Experimental study on high gravity dam strengthened with reinforcement for seismic resistance on shaking table", *Struct. Eng. Mech.*, **51**(4), 663-683.

Westergaard, H.M. (1933), "Water pressure on dams during earthquakes", *Tran.*, ASCE, **98**(2), 418-433.

Wilson, E.L. and Khalvati, M. (1983), "Finite elements for the dynamic analysis of fluid-solid systems", *Int. J. Numer. Meter. Eng.*, **19**, 1657-1668.

Zeidan, B.A. (2015), "Effect of foundation flexibility on dam-reservoir-foundation interaction", *18th International Water Technology Conference (IWTC18)*, Sharm ElSheikh, March.

Zhu, H.H., Yin, J.H., Dong, J.H. and Zhang, L. (2010), "Physical modelling of sliding failure of concrete gravity dam under overloading condition", *Geomech. Eng.*, **2**(2), 89-106.

Ziaolhagh, S.H., Goudarzi, M. and Sani, A.A. (2016), "Free vibration analysis of gravity dam-reservoir system utilizing 21 node-33 Gauss point triangular elements", *Coupl. Syst. Mech.*, **5**(1), 59-86.

Zienkiewicz, O.C. and Nath, B. (1963), "Earthquake hydrodynamic pressures on arch dams-an electric analogue solution", *Proc. Int. Civil Eng.*, **25**(2), 165-176.

JK