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Research Article

EARTHQUAKE PERFORMANCE OF CONCRETE SLAB ON CONCRETE FACED ROCKFILL DAM INCLUDING HYDRODYNAMIC EFFECTS

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ABSTRACT

Concrete faced rockfill (CFR) dams are usually designed ignoring hydrodynamic pressures and also friction between the concrete slab and the rockfill. In this study, this combination is considered under seismic excitations. The main goal of the study is to investigate earthquake performance of concrete slab on CFR dam comprehensively. For this purpose, two dimensional finite element model of Torul CFR Dam is employed. Concrete slab-rockfill interface is considered as including welded contact (Case 1) and friction contact (Case 2) in finite element analyses. Earthquake performance of the concrete slab is determined according to empty and full reservoir cases. Hydrodynamic pressure of reservoir water is considered using fluid finite elements based on the Lagrangian approach. In the materially nonlinear time-history analyses, the Drucker-Prager model is utilized for concrete slab and multi-linear kinematic hardening model is utilized for rockfill zones and foundation rock. East-west component of 1992 Erzincan earthquake is used in seismic analyses. Earthquake record with peak ground acceleration (pga) of 0.496 g is scaled to 0.1 g, 0.2 g, 0.3 g and 0.4 g in time-history analyses. It is seen that earthquake performance of the concrete slab is depended on the magnitude enormity of the earthquake. As the pga of the earthquake increase, earthquake performance of the concrete slab decrease. Although hydrodynamic pressure has fairly less effect on earthquake performance of the concrete slab in Case 1, it has apparent influence in Case 2.

Keywords: Concrete faced rockfill dam, Drucker-Prager model, friction contact, lagrangian approach, multi-linear kinematic hardening model.

1. INTRODUCTION

Concrete-faced rockfill (CFR) dams are known to be safe under seismic excitations because they do not suffer porewater development. The main concern with CFR dams is the earthquake performance of the concrete slab [1-8]. If friction contact in the concrete slab-rockfill interface is considered instead of welded contact, the earthquake performance of the concrete slab can be determined more realistically. There is little study concerning seismic analyses of CFR dams in which friction between the concrete slab and rockfill is considered [5,9-10].

Though CFR dams involve fluid-structure-foundation interaction problems, hydrodynamic pressures on the concrete slab have not been taken into account in the preceding studies. However, hydrodynamic pressure effects on the dynamic response of dams have been investigated since the 1930's [11-21].

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In the recent years, the r esponse of CFR dams is still research matter for the researchers. The deformations in CFR dams are investigated according to linear and non-linear behaviour under ground motion effect. Besides deformation behavior is also determined for various joints including welded and friction contact for empty and full reservoir condition [22]. Abedian et al. [23] evaluated the long-term stability of a concrete faced rockfill dam. Their study showed that the number of construction layers used in the modeling of the dam had an important effect on the maximum deformation. Kartal [24] also investigated the horizontal accelerations and peak accelerations amplification coefficients occurred in a CFR dam to deconvolved ground motion considering viscous boundary conditions. His study indicates that horizontal accelerations and peak acceleration amplification coefficients increase when the rockfill is linear and welded contact existed in the joints.

There is an obvious necessity to assess the earthquake performance of concrete slab on CFR dams considering friction in the concrete slab-rockfill interface and hydrodynamic pressures under seismic excitations. In this study, welded contact and friction contact in the concrete slab-rockfill interface are considered in two dimensional finite element models of the Torul CFR Dam located in Torul, Gumushane. Empty and full reservoir cases are also taken into account in the seismic analyses. The hydrodynamic pressure of the reservoir water is considered by the Lagrangian approach. Linear and nonlinear time-history analyses are performed to determine the earthquake performance of the concrete slab. The Drucker-Prager model is used for the concrete slab and multi-linear kinematic hardening model is used for rockfill and foundation rock in nonlinear analyses. The East-West component of 1992 Erzincan earthquake acceleration record with peak ground acceleration (pga) of 0.496 g is utilized in performance analyses by scaling the pga to 0.1 g, 0.2 g, 0.3 g and 0.4 g.

2. FORMULATION OF FLUID-STRUCTURE-FOUNDATION INTERACTION BY THE LAGRANGIAN APPROACH

The formulation of the fluid system based on the Lagrangian approach is presented as follows [25]. In this approach, the fluid is assumed to be linearly elastic, inviscid and irrotational. For a general two-dimensional fluid, the stress-strain relationships can be written in matrix form as follows,

$$\begin{Bmatrix} P \\ P_z \end{Bmatrix} = \begin{bmatrix} C_{11} & 0 \\ 0 & C_{22} \end{bmatrix} \begin{Bmatrix} \varepsilon_v \\ w_z \end{Bmatrix} \tag{1}$$

where P, C_{11}, and ε_v are respectively, the pressure which is equal to the mean stress, the bulk modulus and the volumetric strain of the fluid. P_z, is the rotational stresses; C_{22}, is the constraint parameter and w_z is the rotation about the z Cartesian axis. Since irrotationality of the fluid is considered like penalty methods [26,27], rotations and constraint parameters are included in the stress-strain equation (Eq. (1)) of the fluid.

In this study, the equations of motion of the fluid system are obtained using energy principles. Using the finite element approximation, the total strain energy of the fluid system may be written as,

$$\pi_e = \frac{1}{2} \mathbf{U}_f{}^T \mathbf{K}_f \mathbf{U}_f \tag{2}$$

where $\mathbf{U}_f$ and $\mathbf{K}_f$ are the nodal displacement vector and the stiffness matrix of the fluid system, respectively. $\mathbf{K}_f$ is obtained as the sum of the stiffness matrices of the fluid elements as follows,

$$\mathbf{K}_{\mathrm{f}} = \sum \mathbf{K}_{\mathrm{f}}^{\mathrm{e}}$$
$$\mathbf{K}_{\mathrm{f}}^{\mathrm{e}} = \int_{V} \mathbf{B}_{\mathrm{f}}^{\mathrm{e}^{T}} \mathbf{C}_{\mathrm{f}} \mathbf{B}_{\mathrm{f}}^{\mathrm{e}} \mathrm{dV}^{\mathrm{e}} \tag{3}$$

where $\mathbf{C}_{\mathrm{f}}$ is the elasticity matrix consisting of the diagonal terms in Eq. (1) and $\mathbf{B}_{\mathrm{f}}^{\mathrm{e}}$ is the strain-displacement matrix of the fluid element.

If the Lagrange's equations [28] are considered the following equations of motions are obtained,

$$\mathbf{M}_{\mathrm{f}} \ddot{\mathbf{U}}_{\mathrm{f}} + \mathbf{K}_{\mathrm{f}}^{*} \mathbf{U}_{\mathrm{f}} = \mathbf{R}_{\mathrm{f}} \tag{4}$$

where $\mathbf{K}_{\mathrm{f}}^{*}$, $\ddot{\mathbf{U}}_{\mathrm{f}}$, $\mathbf{U}_{\mathrm{f}}$ and $\mathbf{R}_{\mathrm{f}}$ are, respectively, the system stiffness matrix including the free surface stiffness, the nodal acceleration and displacement vectors, and nodal force vector for the fluid system. In the formation of the fluid element matrices, reduced integration orders are used [25].

The equations of motion of the fluid system, Eq. (4), have a form similar to those of the structural system. To obtain the coupled equations of the fluid-structure system, the determination of the interface condition is required. Since the fluid is assumed to be inviscid, only the displacement in the normal direction to the interface is continuous at the interface of the system. Assuming that the positive face corresponds to the structure and the negative face is assigned the fluid, the boundary condition at the fluid-structure interface is,

$$\mathrm{U}_{\mathrm{n}}^{-} = \mathrm{U}_{\mathrm{n}}^{+} \tag{5}$$

where U_{n} is the normal component of the interface displacement [29]. Using the interface condition, the equations of motion of the coupled system subjected to a ground motion with damping effects included are given by,

$$\mathbf{M}_{\mathrm{c}} \ddot{\mathbf{U}}_{\mathrm{c}} + \mathbf{C}_{\mathrm{c}} \dot{\mathbf{U}}_{\mathrm{c}} + \mathbf{K}_{\mathrm{c}} \mathbf{U}_{\mathrm{c}} = \mathbf{R}_{\mathrm{c}} \tag{6}$$

in which $\mathbf{M}_{\mathrm{c}}$, $\mathbf{C}_{\mathrm{c}}$, and $\mathbf{K}_{\mathrm{c}}$ are the mass, damping and stiffness matrices for the coupled system, respectively. $\mathbf{U}_{\mathrm{c}}$, $\dot{\mathbf{U}}_{\mathrm{c}}$, $\ddot{\mathbf{U}}_{\mathrm{c}}$ and $\mathbf{R}_{\mathrm{c}}$ are the vectors of the displacements, velocities, accelerations and external loads of the coupled system, respectively.

3. STRUCTURAL PERFORMANCE AND DAMAGE CRITERIA FOR DAMS

Linear time-history analysis is used to formulate a systematic and rational methodology for qualitative estimate of the level of damage. In linear time-history analysis, where acceleration time-histories are the seismic input, deformations, stresses and section forces are computed in accordance with the elastic stiffness characteristics of various components in time domain. A systematic evaluation of these results in terms of the demand-capacity ratios (D/C), cumulative duration, spatial extent of overstressed regions, and consideration of possible failure modes comprise the basis for approximation and appraisal of probable level of damage. The damage for structural performance amounts to cracking of the concrete, opening of construction joints, and yielding of the reinforcing steel. If the estimated level of damage falls below the acceptance curve for a particular type of structure, the damage is considered to be low and linear time-history analysis will be sufficient. Otherwise the damage is considered to be severe in which case nonlinear time-history analysis would be required to estimate damage more accurately [30].

3.1. Performance Criteria for Linear and Nonlinear Analysis

The dam response to the maximum design earthquake is considered to be within the linear elastic range of behavior with little or no possibility of damage if the computed demand-capacity ratios are less than or equal to 1.0. The stage of nonlinear response or opening and cracking of joints is considered acceptable if demand-capacity ratio is less than 2 and the cumulative duration falls below the performance curve given in Fig. 1. The earthquake performance curves are developed for the concrete gravity dams and arch dams. This study considers earthquake performance curve belong to the concrete gravity dams [31]. If the cumulative duration for the concrete slab of the concrete faced rockfill dam is determined, the earthquake performance of the concrete faced rockfill dams can be obtained more realistically.

3.2. Demand-Capacity Ratios

The demand-capacity ratios for CFR dams are defined as the ratio of the computed principal tensile stresses to the tensile strength of the concrete. As discussed previously demand-capacity ratio is limited to 2.0, thus permitting stresses double up to the static or the level of dynamic tensile strength of the concrete. The cumulative duration beyond a certain level of demand-capacity ratio is obtained by multiplying the number of stress values exceeding that level of tensile strength by the time-step of the time-history analysis. The cumulative duration in Figure 1 refers to the total duration of all stress excursions beyond a certain level of demand-capacity ratio. Although tensile strength of concrete is affected by the rate of seismic loading, the acceptance criteria employ stable tensile strength in the computation of the demand-capacity ratios. The reason for this is to account for the lower strength of the lift lines and to provide some level of conservatism in the estimation of damage using the results of linear elastic analysis.

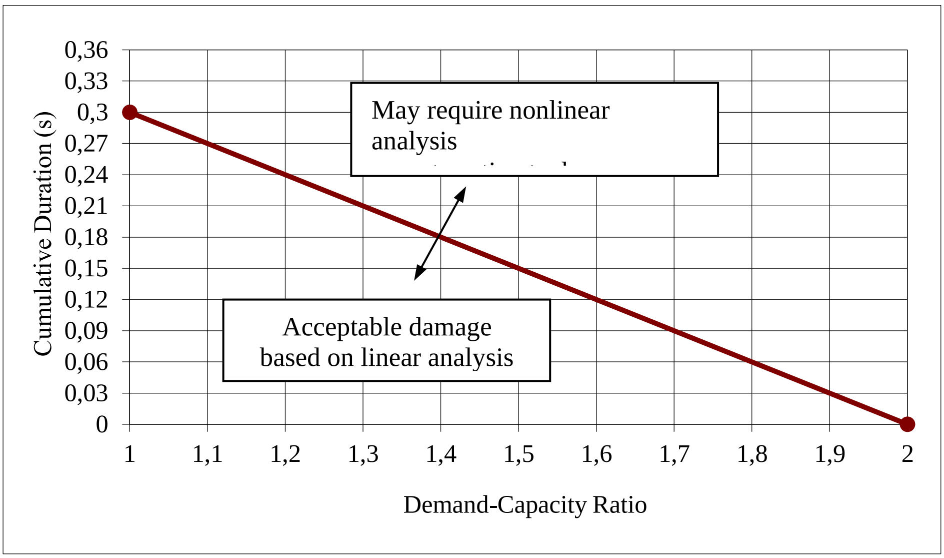


Figure 1. Assumed performance curve [31].

4. MATHEMATICAL MODEL OF THE TORUL CFR DAM

4.1. The Torul Dam

Torul CFR Dam (Fig. 2) is sited on the Harsit River and approximately 14 km northwest of Torul, Gumushane, Turkey. Torul Dam was built by General Directorate of State Hydraulic Works in 2007 [32]. The reservoir is used for power generation. The volume of the dam body is 4.6 hm^3 and the lake area of the dam at the normal water level is 3.62 km^2. The annual total power generation capacity is 322.28 GW. The length of the dam crest and its width are 320 m and 12 m, respectively. The maximum height and base width are 142 m and 420 m, respectively. The thickness of the concrete slab is 0.3 m at the crest level and 0.7 m at the foundation level. The concrete slab has high seepage resistance. The dimensions of the dam at the largest cross section are shown in Fig. 3.

Figure 2. Torul CFR Dam.

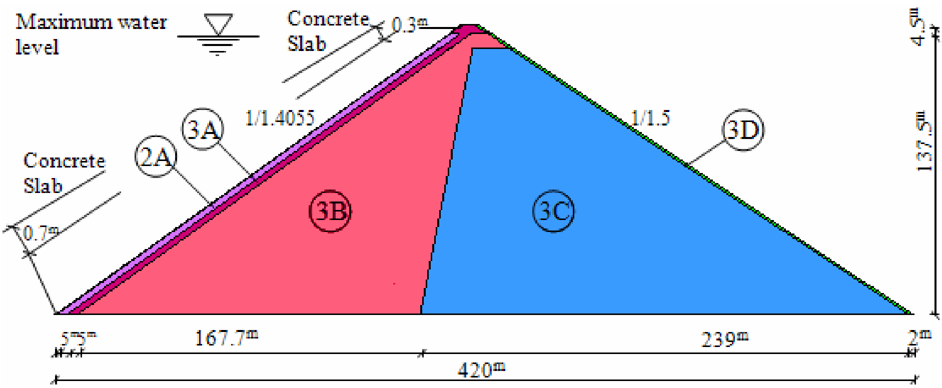


Figure 3. The two dimensional largest cross section of Torul dam body [32].

4.2. Material Properties

The Torul Dam body consists of a concrete face slab and five rockfill zones: 2A, 3A, 3B, 3C, 3D, respectively, from upstream toward downstream. These zones are arranged from thin granules to thick particles in upstream-downstream direction. The material properties of the dam and the reservoir water used in linear and nonlinear analyses are presented in Tab. 1. The concrete slab has high resistance to water penetration. In addition, the tensile and compression strengths of the concrete are 1.6 MPa and 20 MPa, respectively. Besides, the cohesion and angle of internal friction of the concrete is 2500 kN/m² and 30°, respectively

Table 1. Material properties of Torul CFR Dam [32].

Material	Material Properties				
	Modulus of Elasticity $\times 10^7$ kN/m^2	Poisson's Ratio	Mass per unit Vol. kg/m^3	Cohesion kN/m^2	Angle of internal friction
Concrete	2.800	0.20	2395.5	2500	30
2A (sifted rock or alluvium)	0.040	0.36	1880.0	-	-
3A (filling with selected rock)	0.030	0.36	1870.0	-	-
3B (filling with quarry rock)	0.025	0.32	1850.0	-	-
3C (filling with quarry rock)	0.020	0.32	1850.0	-	-
3D (filling with selected rock)	0.040	0.26	1800.0	-	-
Foundation Soil (volcanic tufa)	1.036	0.17	-	-	-
Foundation Soil (limestone)	1.206	0.18	-	-	-
Reservoir	0.207	-	1000	-	-

4.3. Finite Element Model

In this study, ANSYS program is used in the finite element analyses. ANSYS has capability of computing non-linear response of the structures and fluid-structure-foundation interaction. The two dimensional dam-reservoir-foundation finite element model used in analyses is shown in Fig. 4. In this model, the dam body has 592 solid finite elements (Plane42), the foundation soil has 656 solid finite elements (Plane42) and the reservoir water has 495 fluid finite elements (Fluid

79). In addition to these elements, 16 interface elements (Inter192) are defined between the concrete slab and the rockfill. The numbers of nodal points of the dam body, foundation soil and reservoir water are 663, 747 and 544, respectively. The solid finite elements used in the analyses have four nodes and 2x2 integration points and the fluid finite elements have four nodes and 1x1 integration point. The element matrices are computed using the Gauss numerical integration technique [25]. The Rayleigh damping model is considered in all finite element analyses with a 5% damping ratio.

Foundation soil is assumed as massless and its damping effects are ignored in all analyses since the earthquake acceleration record acquired from the ground surface. Therefore, soil affects the earthquake response of the dam with its rigidity. The length of the reservoir and the foundation soil in the upstream direction is taken three times of the dam height to represent infinite reservoir condition. In addition, the total height of the soil layers and the foundation length at downstream side are taken into account as the dam height. In the finite element models, all degrees of freedom at boundary of the foundation soil are fixed. Besides, at the end of the reservoir only the horizontal degrees of freedom are restrained to allow sloshing waves.

When the Lagrangian approach is used to model reservoir water, interface condition of the fluid-structure interaction system requires a different sensitivity. At the interface of the fluid-structure interaction system, only the displacements in normal direction to the interface are considered to be compatible in the structure as well as in the fluid. Therefore, the displacements in normal direction to the reservoir-dam and reservoir-soil interface are coupled. Coupling length in these interfaces is chosen as 1 mm and 50 numbers of couplings were defined in the dam-soil-reservoir model.

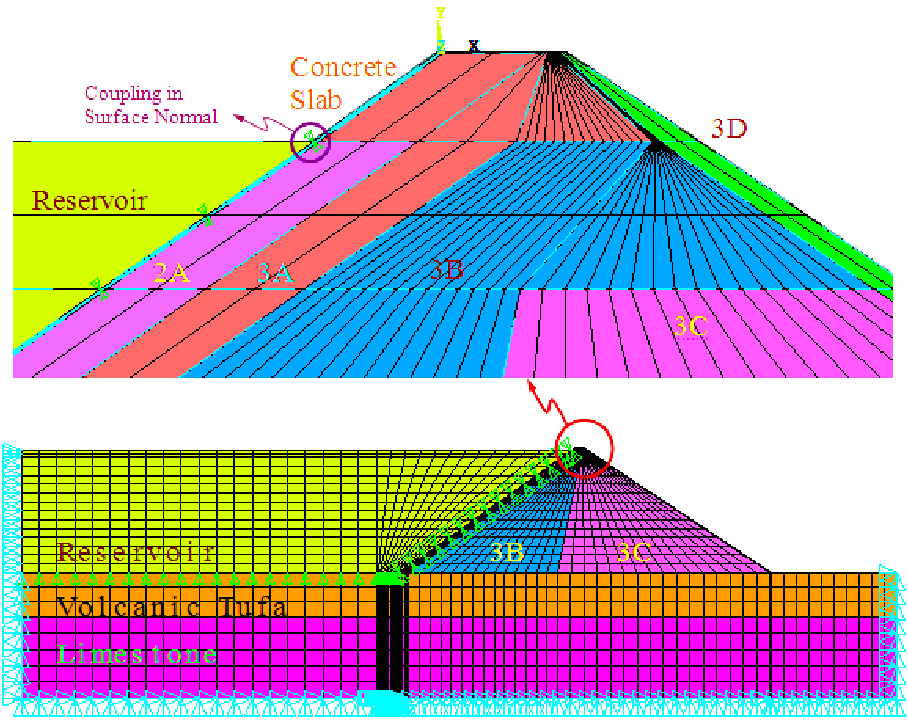


Figure 4. The two dimensional finite element model of Torul Dam.

4.4. Concrete Slab - Rockfill Interface

The earthquake response of the concrete slab mostly depends upon its contact to the rockfill. The joint can be modeled as welded contact and friction contact (Fig. 5). Because concrete slab is not directly in contact with the rockfill, using interface elements in the finite element analysis can produce more rational results. By means of this element, the concrete slab may slide over the rockfill. In this study, the concrete slab and rockfill are assumed as independent deformable bodies and they can also be considered as dependent deformable bodies by considering welded contact. The interface element used in this study has four nodes and two integration points.

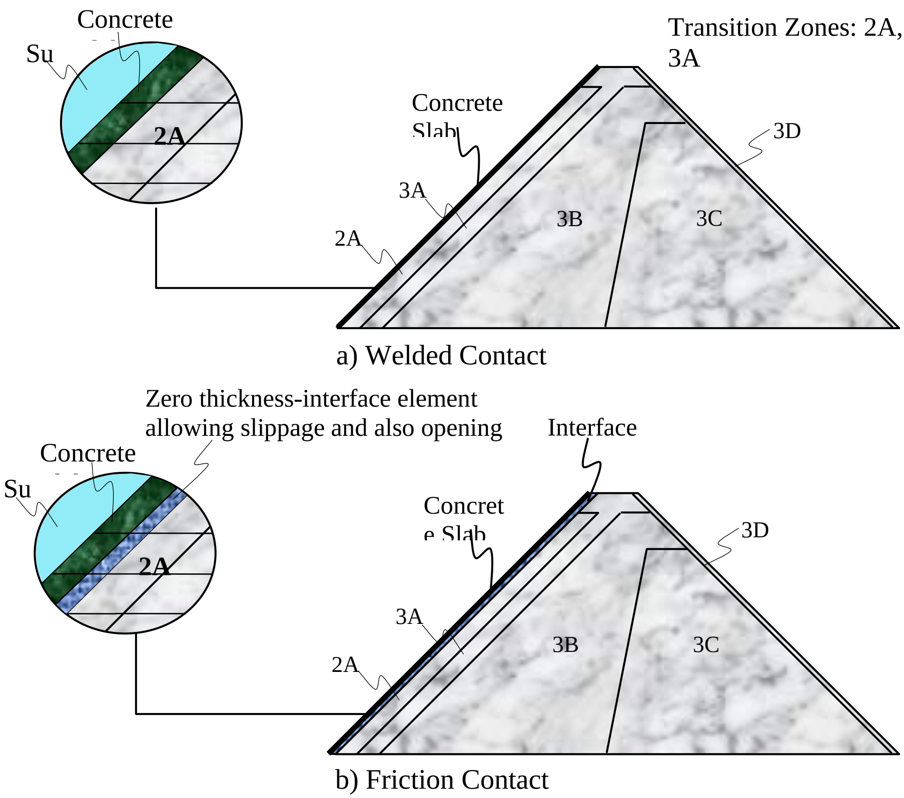


Figure 5. Schematic representations of contact types: a) welded contact and b) friction contact.

The interface element used in this study has four node and two integration points [33]. The element width was considered only 1 mm in this study. The stable stiffness, maximum tension stress allowed and transverse shear stiffness of the joint material were assumed as 2×10^7 kN/m, 2×10^8 kN/m^2 and 1.8×10^3 kN/m respectively.

4.5. Non-linear Response of CFR Dams

The Drucker-Prager model is used for concrete slab in the materially non-linear analysis. Non-linear response of rockfill and foundation soil is determined by the multi-linear kinematic hardening model. In this method, uniaxial stress-strain curve of the non-linear material is required. This curve can be determined by shear modulus-shear strain relationship for rock and rockfill materials. Rollins et al. [34] produced the best-fit hyperbolic curve defining G/G_{max} versus cyclic shear strain relationship for gravelly soils based on testing by 15 investigators (Fig. 6). This study considers the best curve produced by Rollins et al. [34] for rockfill. In addition, shear modulus-shear strain relation for rock soils obtained from experimental studies by Schnabel et al. [35] is used for rock foundation (Fig. 7). Using these curves, the uniaxial stress-strain curves for rockfill and foundation soil are determined as shown in Figs. 8 and 9.

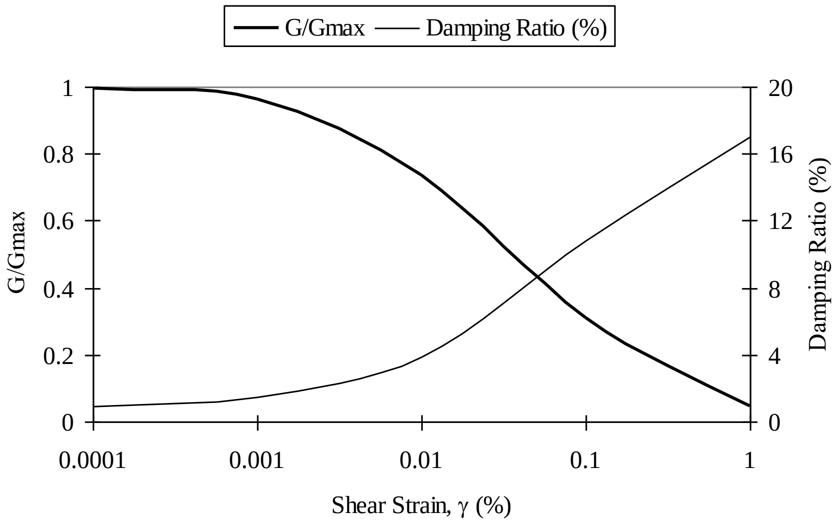


Figure 1. Normalized shear modulus-shear strain and damping ratio relationships for gravels [34].

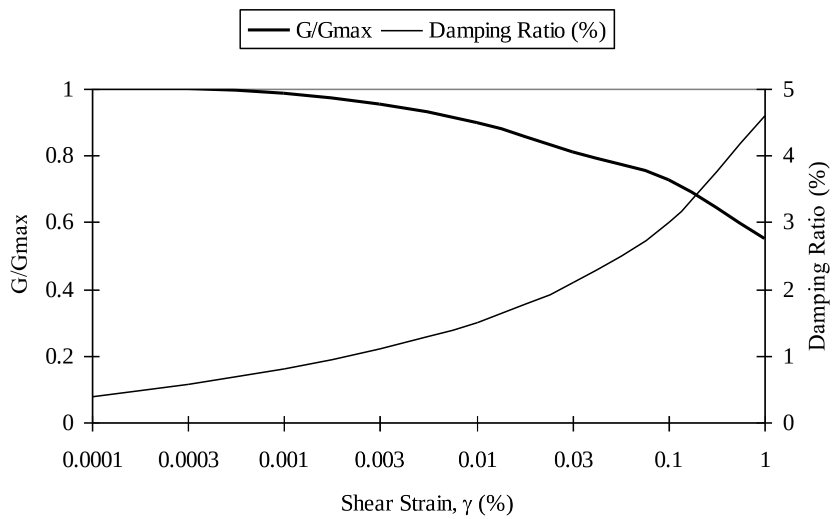


Figure 2. Normalized shear modulus-shear strain and damping ratio relationships for rocks [35].

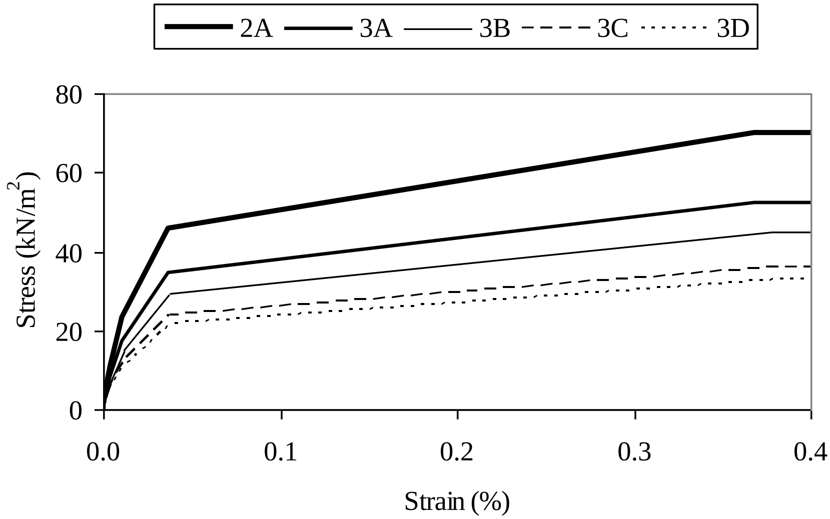


Figure 3. The uniaxial stress-strain relationship for rockfill.

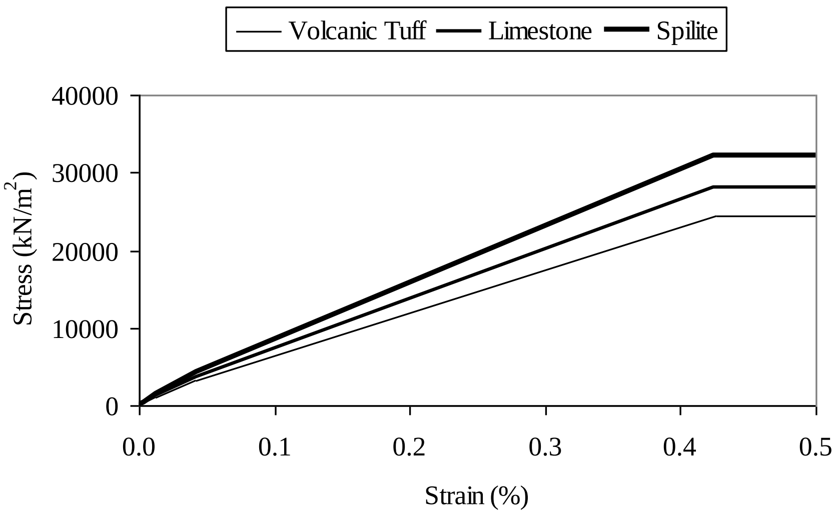


Figure 4. The uniaxial stress-strain relationship for foundation rock.

Structural connections of the finite element model built for friction contact consider Coulomb’s friction law. Contact elements realize it. Those are the contact pairs defined mutually as contact element and target element. Friction coefficient is used as 0.7 for concrete slab-rockfill, rockfill-foundation and plinth-foundation. In these interfaces, “no separation” contact model is preferred. The friction coefficient is used as 0.6 in concrete slab-plinth interface and “standard” contact model is preferred in this interface. In the standard contact model, the structural element behind the contact element may slide over and leaves from the structural element behind the target element. However, though the contact surface does not separate from the target surface, it may slide over the target surface in the no separation contact model.

5. EARTHQUAKE PERFORMANCE OF THE TORUL CFR DAM

The earthquake performance of the Torul CFR Dam under strong ground motion including dam-reservoir-foundation interaction is investigated using ANSYS [33]. Because the Torul CFR Dam is close to the North Anatolian Fault, the East-West component of the 1992 Erzincan earthquake acceleration record with an original pga of 0.496 g, scaled to 0.1 g, 0.2 g, 0.3 g and 0.4 g, is used in performance analyses. The acceleration record used in the numerical analyses is given in Fig. 10 [36]. The time interval of the acceleration record is chosen as 0.005 second in the analyses. The Newmark time-integration algorithm is used in the numerical solutions.

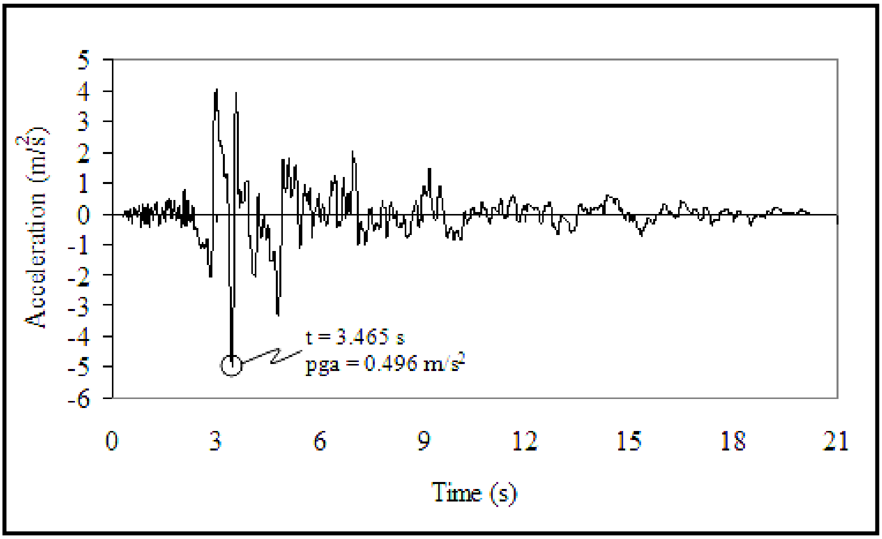
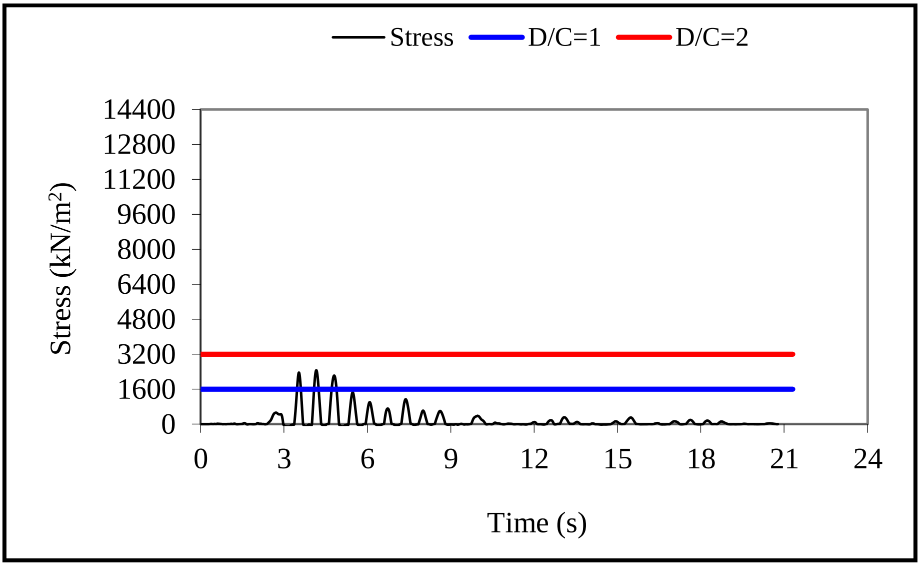
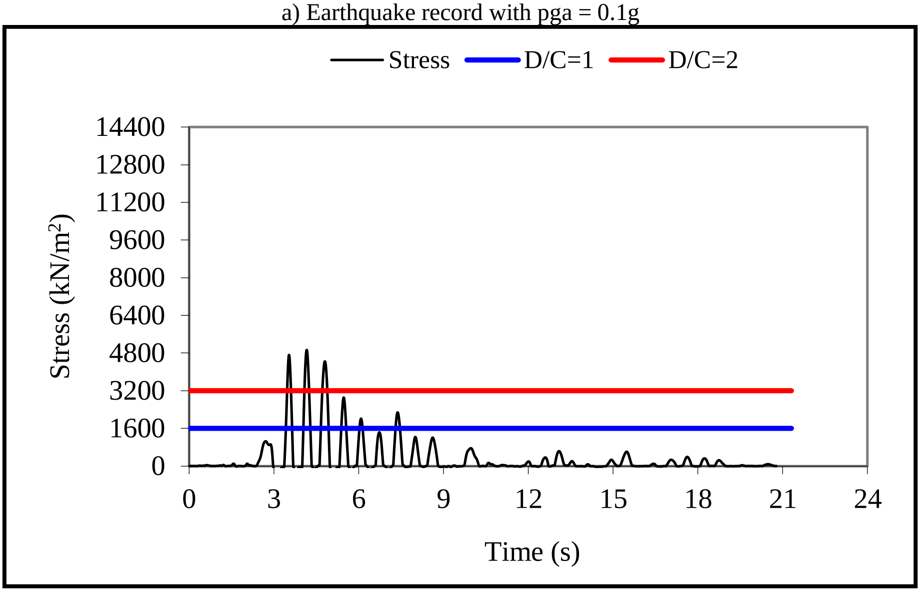


Figure 10. East-West component of the 1992 Erzincan earthquake [36].

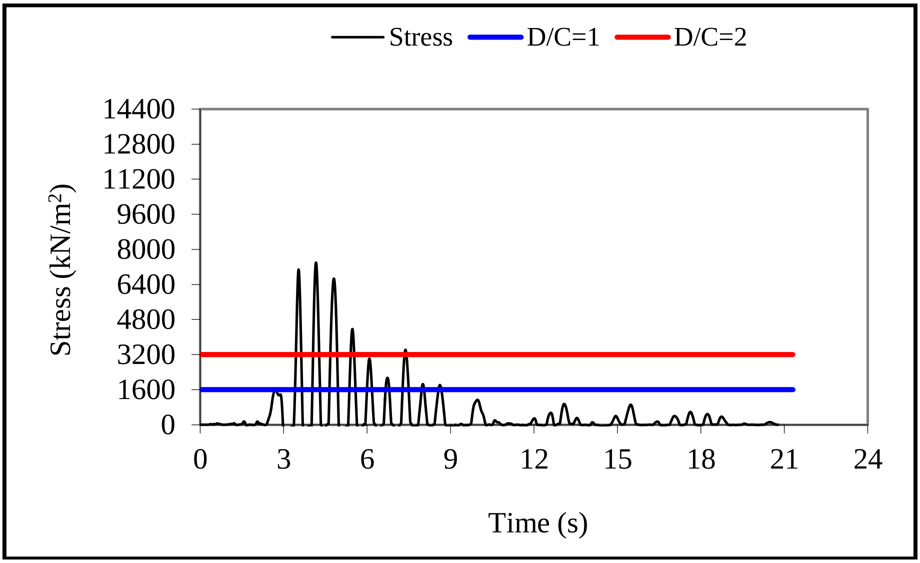
The maximum principal stresses that occurred in the concrete slab are evaluated for demand-capacity ratios which vary between 1 and 2. The maximum principal stress cycles obtained from linear time-history analyses are drawn considering welded and friction contact in the concrete slab-rockfill interface for both reservoir conditions (Figs. 11-14). According to the analyses performed, principal tensile stresses that occurred in the concrete slab increase when the hydrodynamic pressure is accounted for. This increase is more evident if friction in the concrete slab-rockfill interface is considered. Tensile strength of the concrete is exceeded for all scaled earthquake records. As the pga of the earthquake record increases, the duration of exceeding tensile strength of the concrete increases. Therefore, the earthquake performance evaluation should be realized considering performance curves.



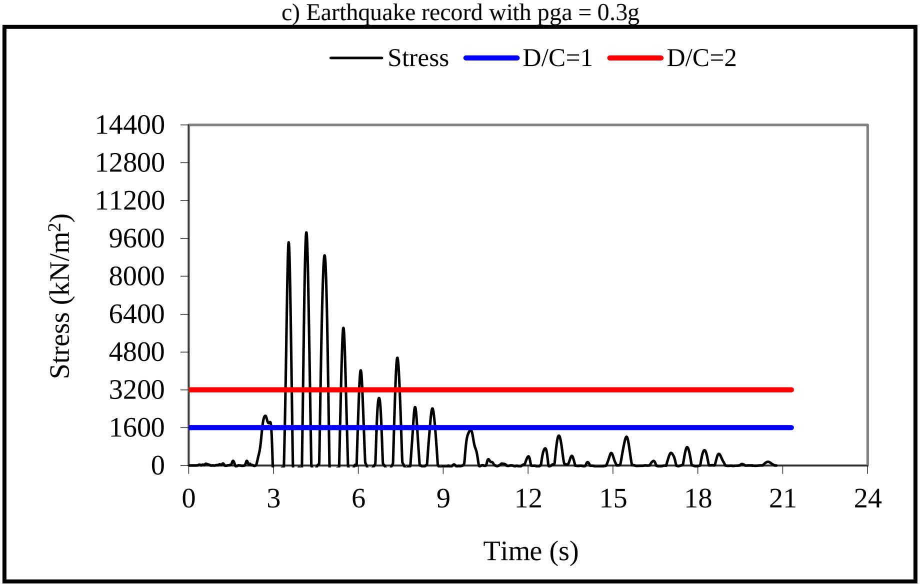
a) Earthquake record with pga = 0.1g



b) Earthquake record with pga = 0.2g

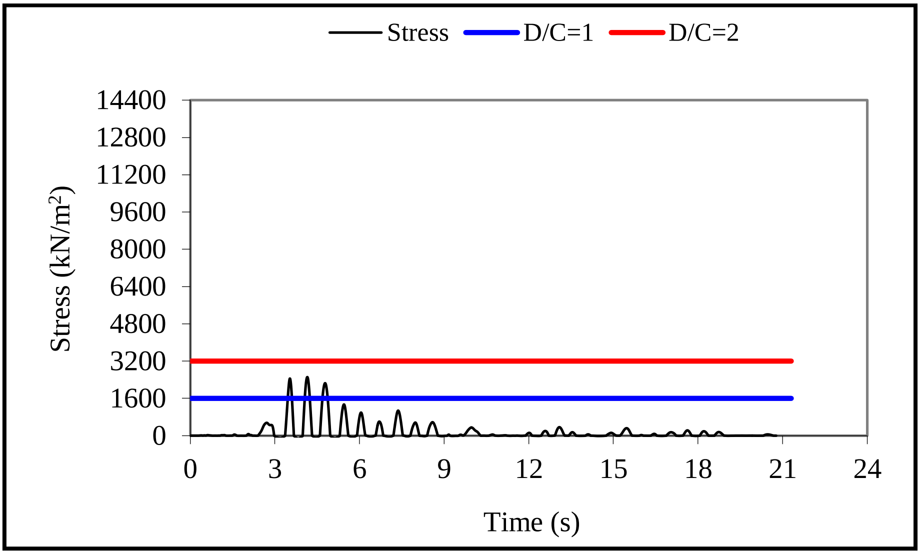


c) Earthquake record with pga = 0.3g

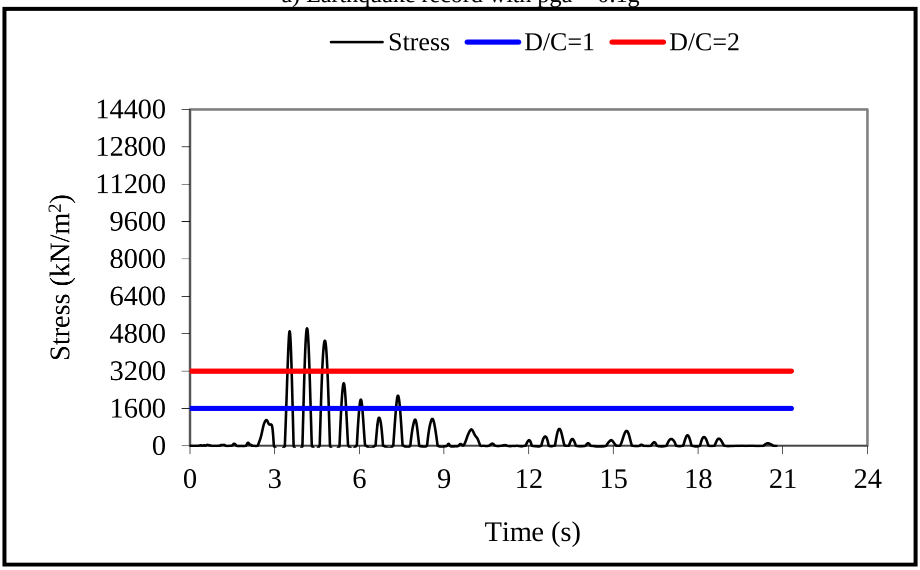


d) Earthquake record with pga = 0.4g

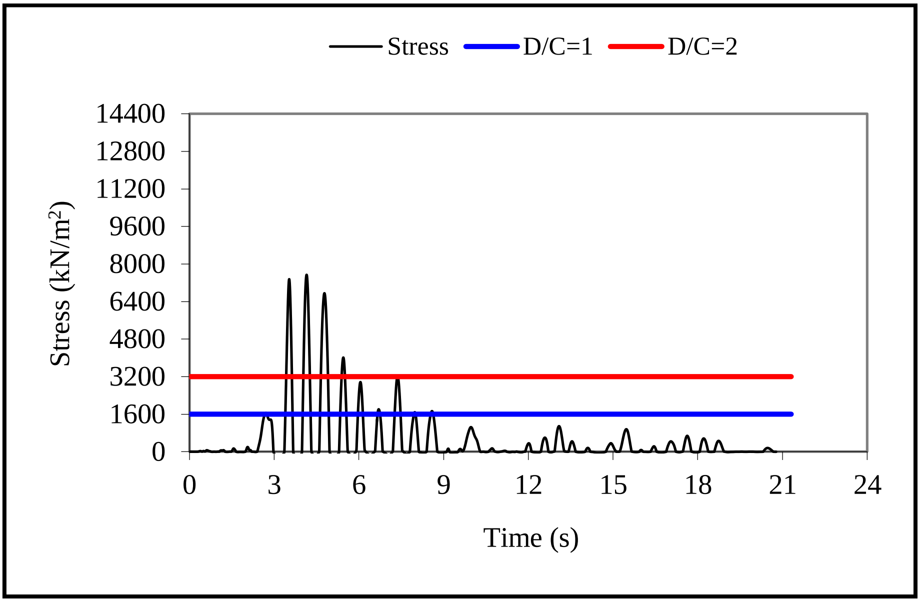
Figure 11. Maximum principal stress cycles for empty reservoir case and welded contact according to linear analyses.



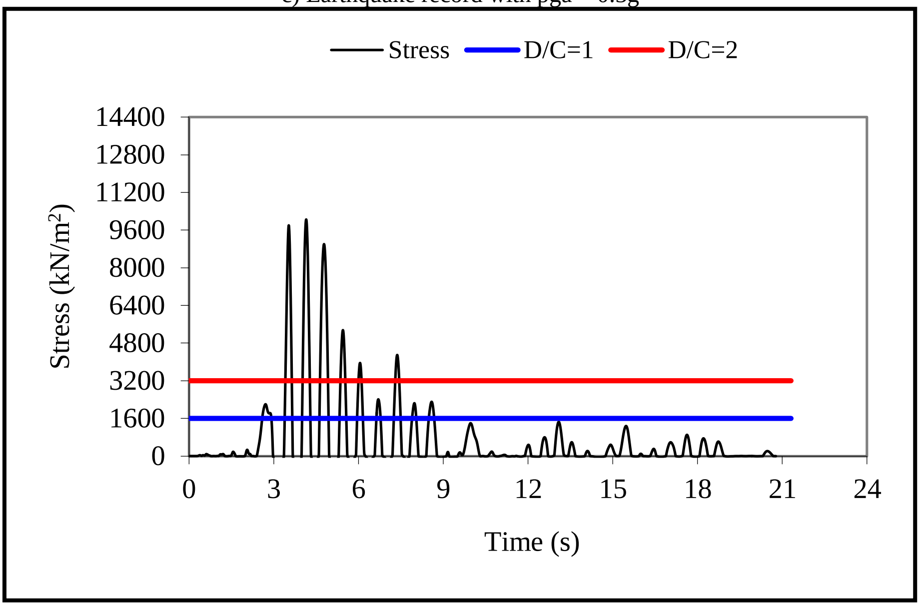
a) Earthquake record with pga = 0.1g



b) Earthquake record with pga = 0.2g

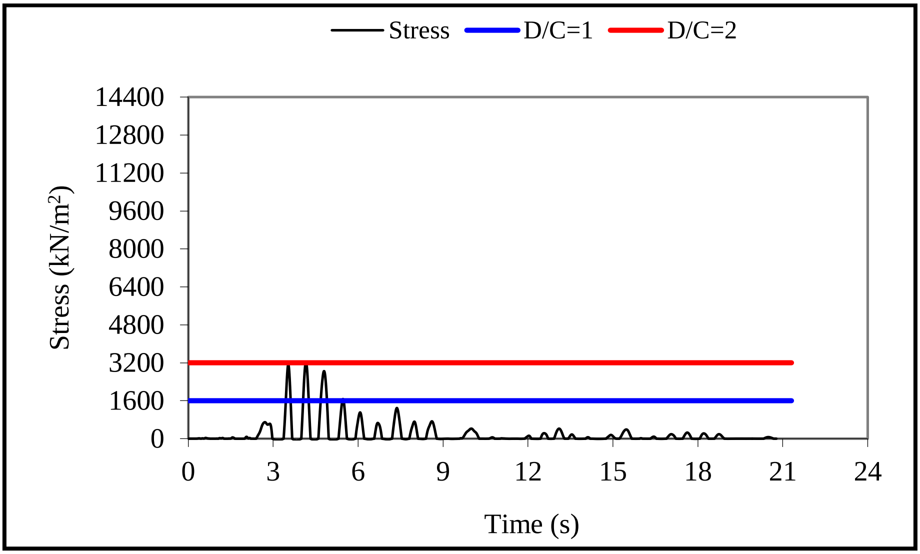


c) Earthquake record with pga = 0.3g

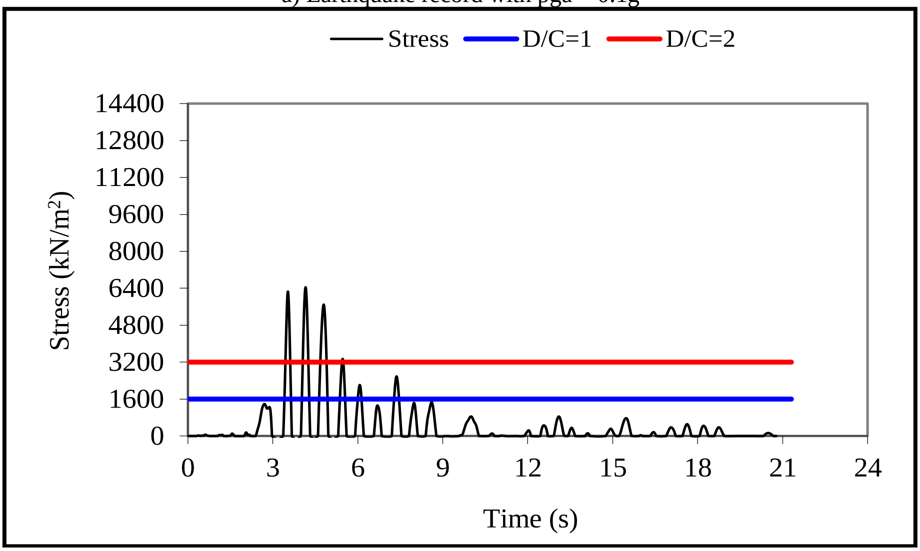


d) Earthquake record with pga = 0.4g

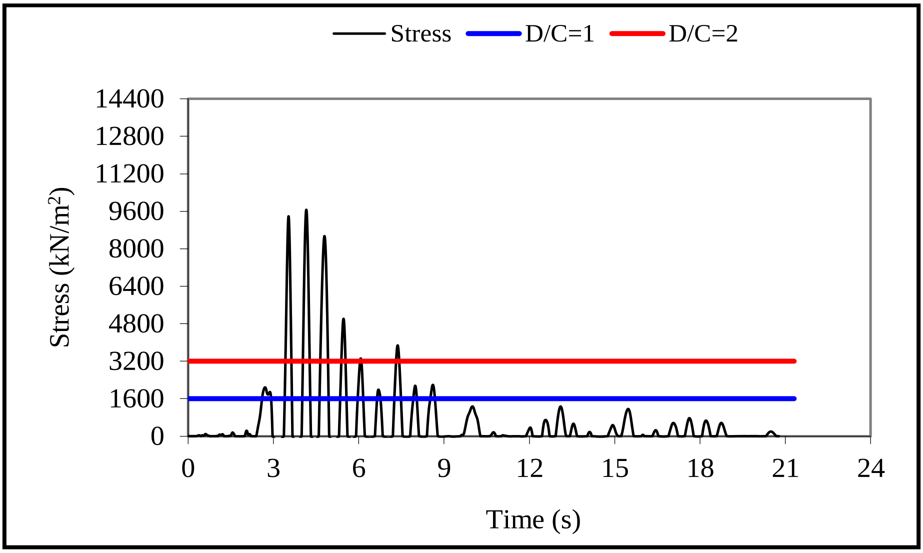
Figure 12. Maximum principal stress cycles for empty reservoir case and friction contact according to linear analyses.



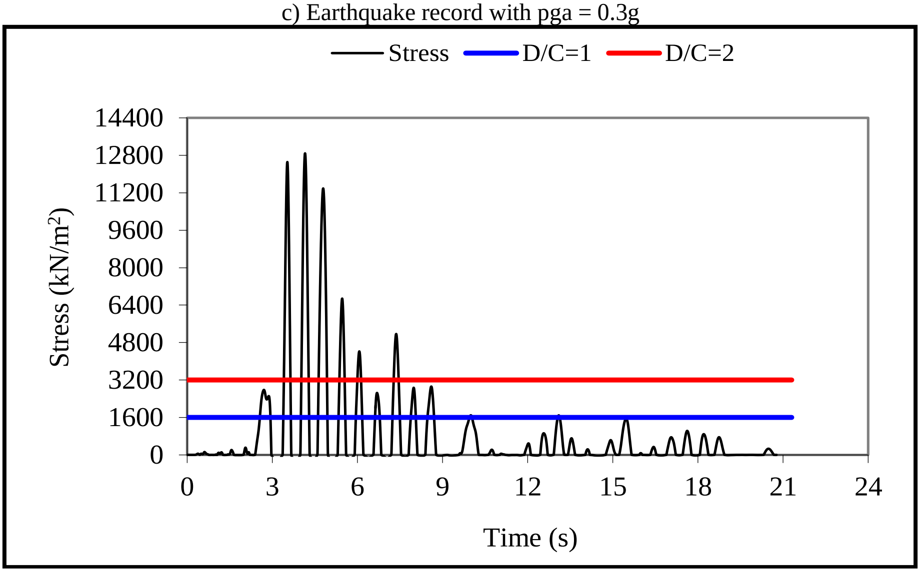
a) Earthquake record with pga = 0.1g



b) Earthquake record with pga = 0.2g

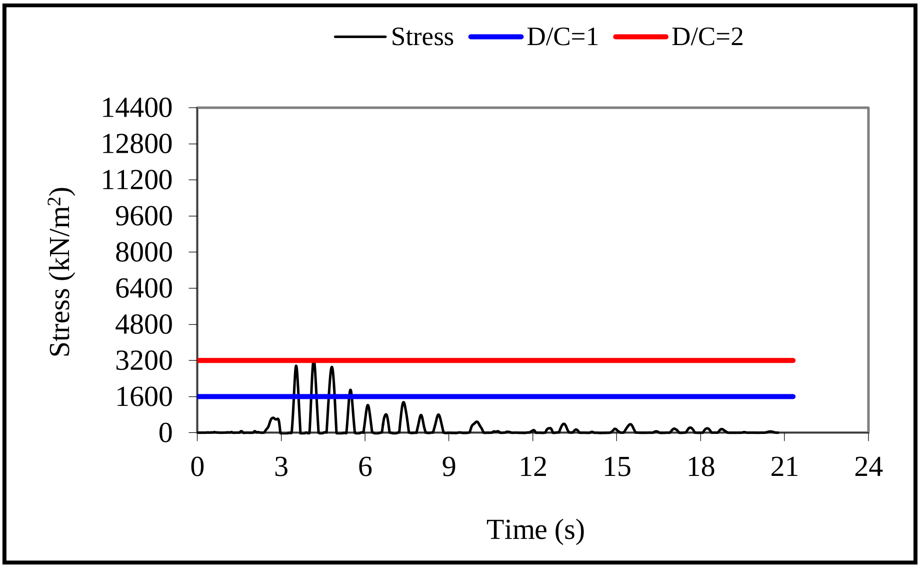


c) Earthquake record with pga = 0.3g

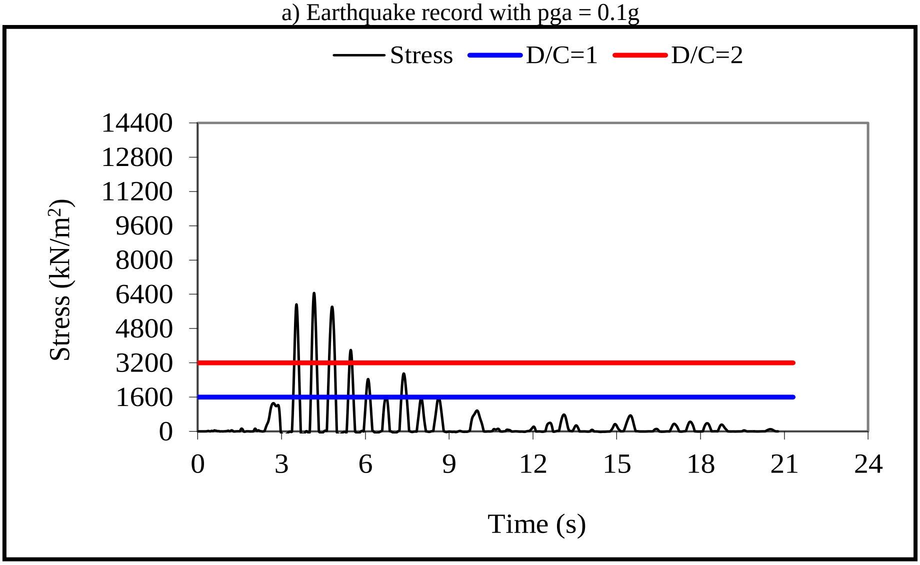


d) Earthquake record with = 0.4g

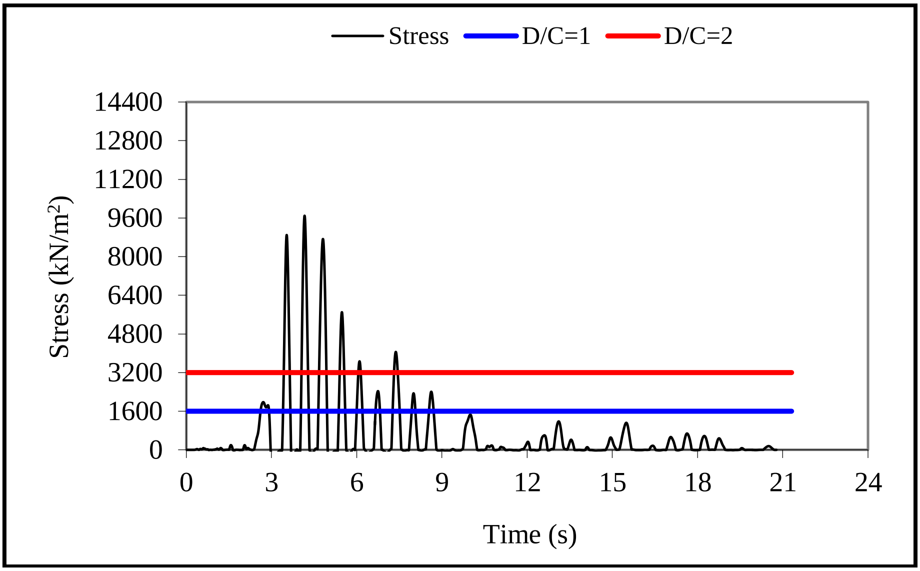
Figure 13. Maximum principal stress cycles for full reservoir case and welded contact according to linear analyses.



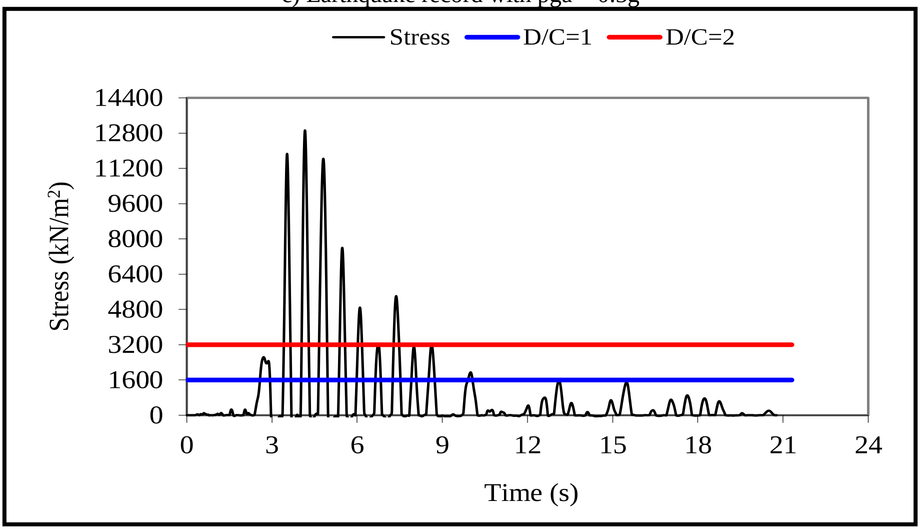
a) Earthquake record with pga = 0.1g



b) Earthquake record with pga = 0.2g



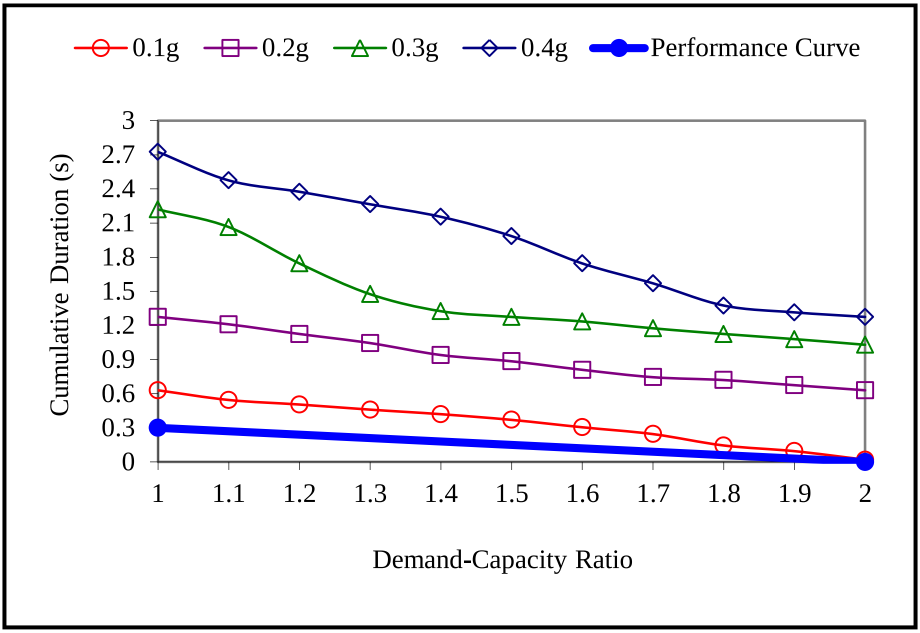
c) Earthquake record with pga = 0.3g



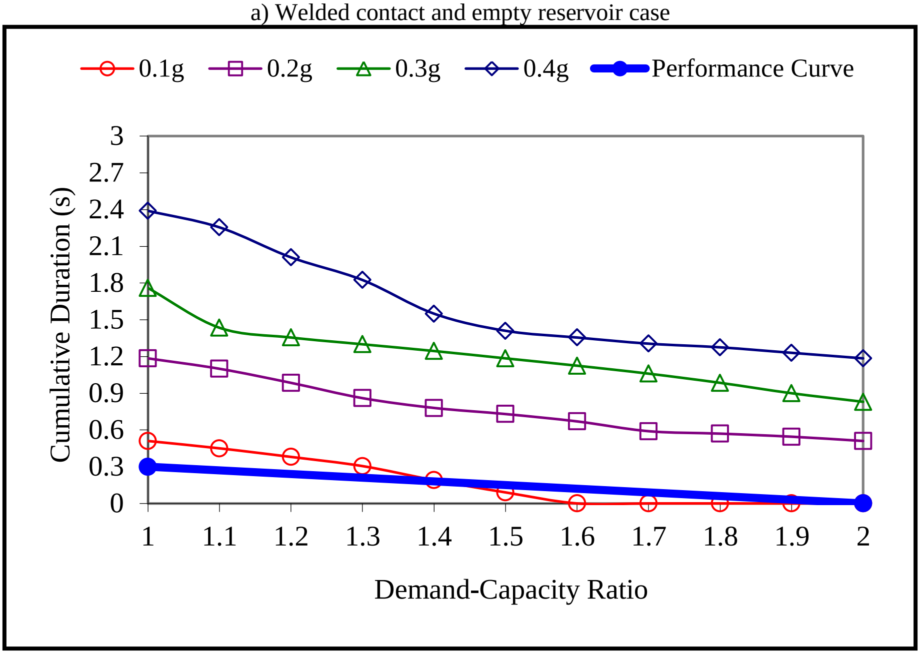
d) Earthquake record with pga = 0.4g

Figure 14. Maximum principal stress cycles for full reservoir case and friction contact according to linear analyses.

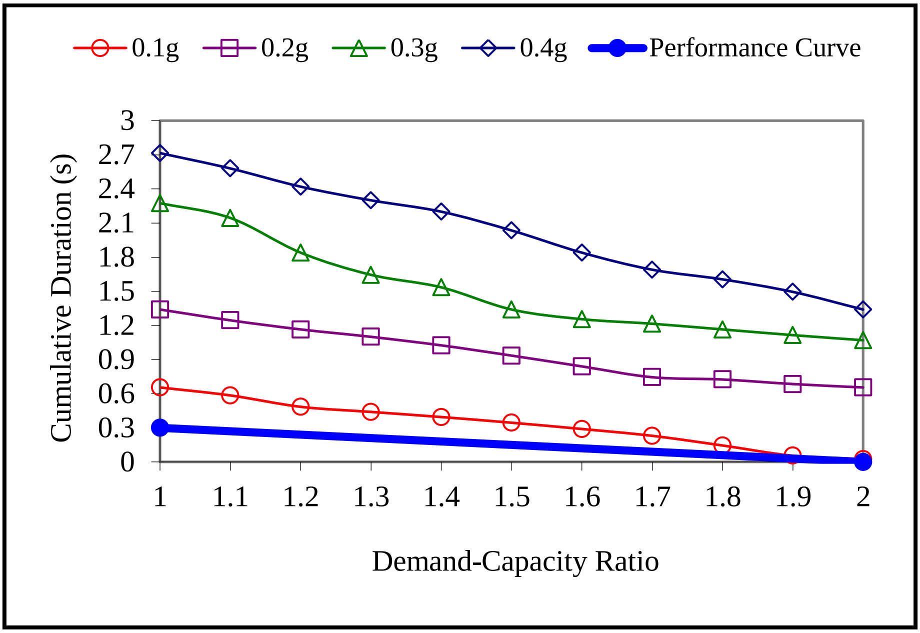
The earthquake performance curves are drawn in Fig. 15 for welded and friction concrete slab-rockfill interface and empty and full reservoirs. It can clearly be concluded from Fig. 15 that earthquake performance of the concrete slab decreases by the effect of the hydrodynamic pressure. This is more evident for the case of friction contact in the concrete slab-rockfill interface. As the pga of the scaled earthquake record increases, the earthquake performance of the dam decreases in all cases. Evaluation of the earthquake performance of the dam indicates that crack forming seems inevitable for all the scaled earthquake records.



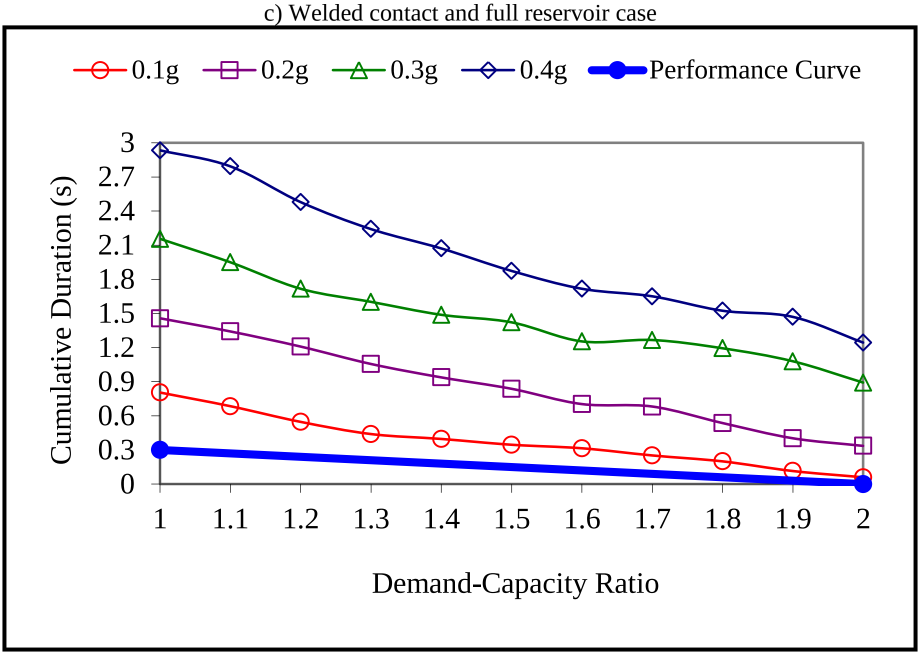
a) Welded contact and empty reservoir case



b) Friction contact and empty reservoir case



c) Welded contact and full reservoir case

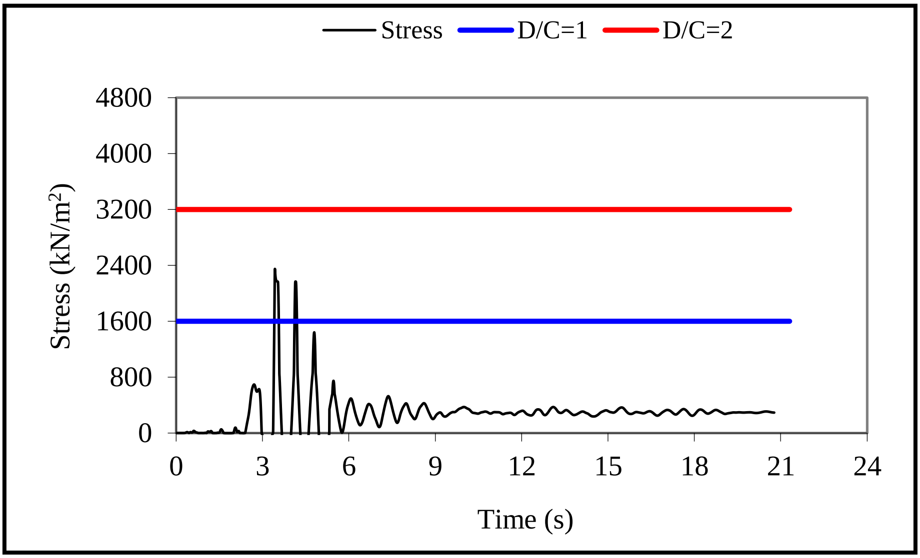


d) Friction contact and full reservoir case

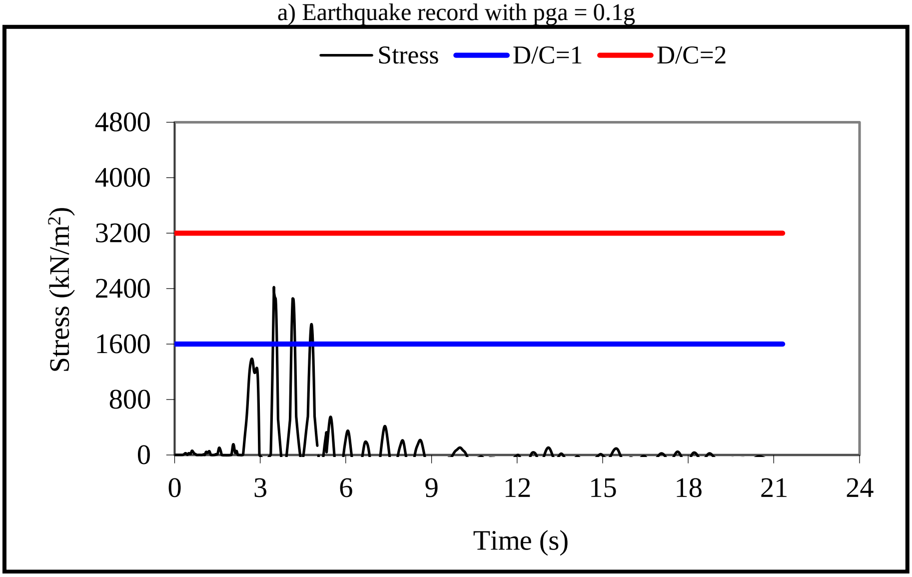
Figure 15. Earthquake performance curves of the dam according to linear analyses.

For a more rational estimation of the earthquake performance of the dam, materially nonlinear analyses are needed. For the nonlinear analyses the Drucker-Prager constitute model is preferred for the concrete slab and multi-linear kinematic hardening model is preferred for rockfill zones and foundation rock. Therefore, nonlinear analyses are performed to estimate the essential performance of the dam for all the scaled ground excitations.

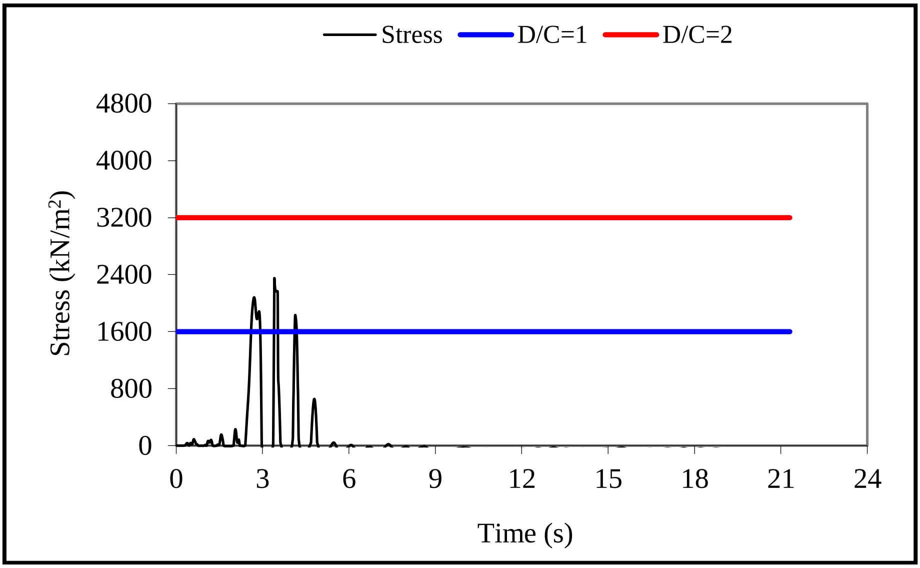
The maximum principal tensile stresses obtained from nonlinear analyses are given in Figs. 16-19. The principal tensile stresses resulted from nonlinear analyses are quite smaller than the linear ones. In addition, the hydrodynamic pressure raised the principal tensile stresses in nonlinear analyses for both contact conditions. Moreover, as expected, as the pga of the scaled earthquake record increases, principal tensile stresses and the duration of exceeding demand-capacity ratios are also increased.



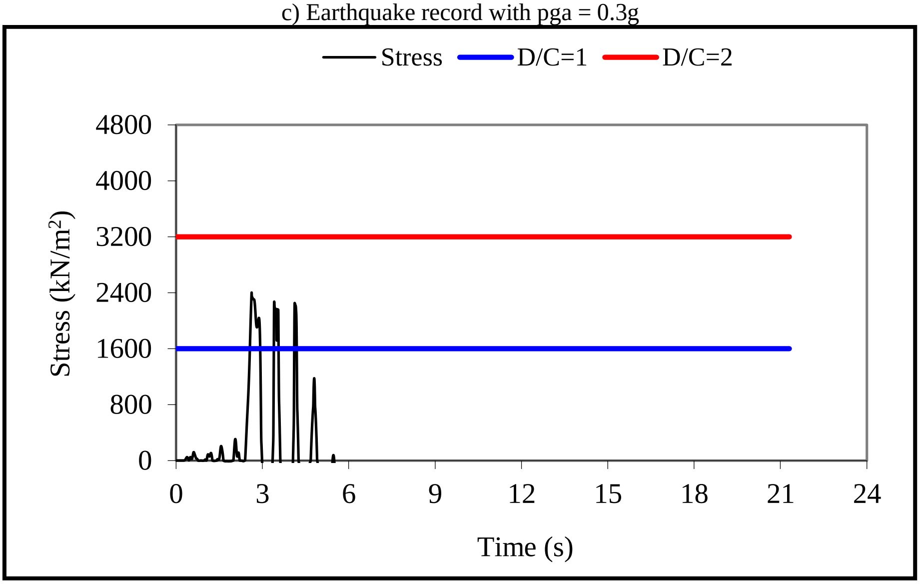
a) Earthquake record with pga = 0.1g



b) Earthquake record with pga = 0.2g

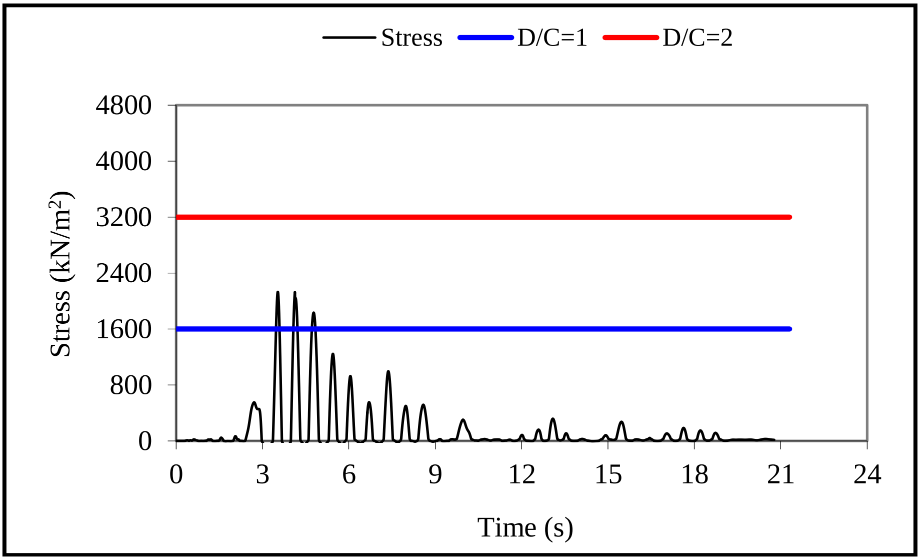


c) Earthquake record with pga = 0.3g

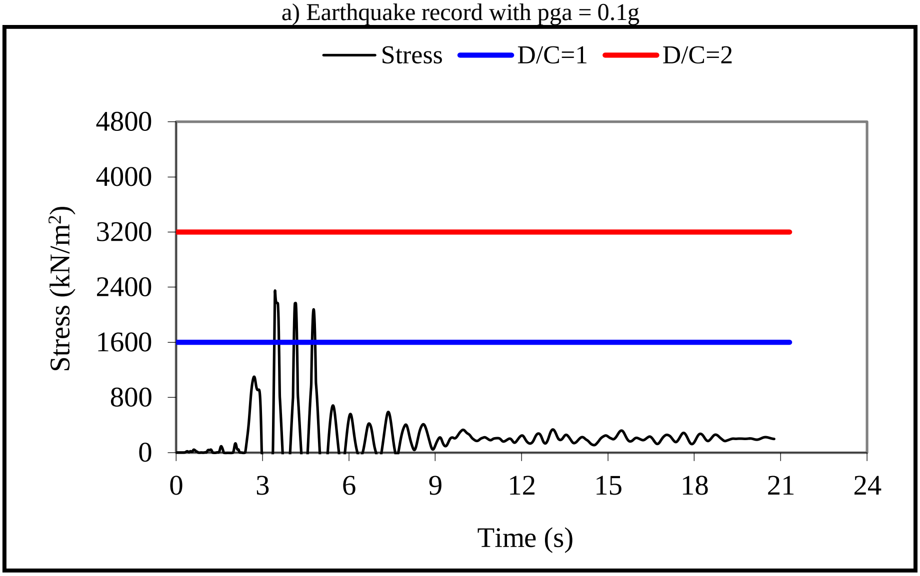


d)Earthquake record with pga = 0.4g

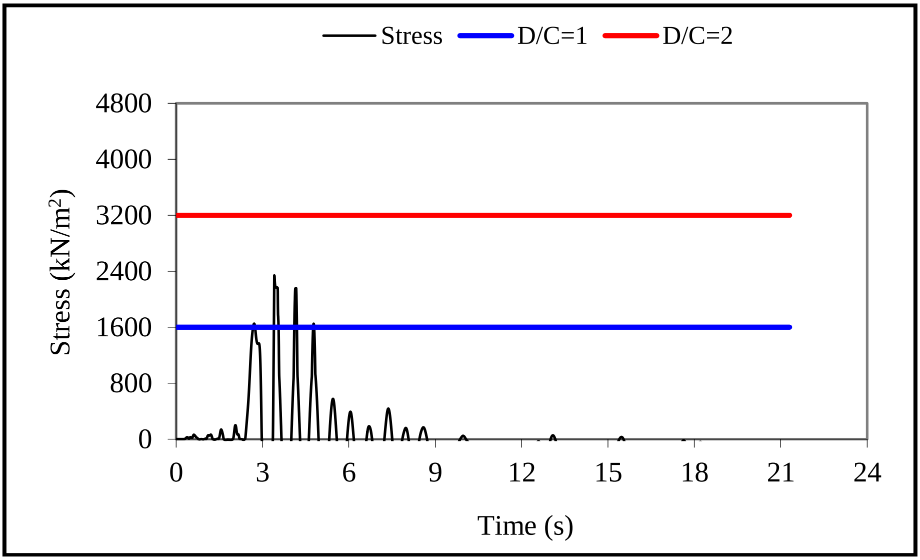
Figure 16. Maximum principal stress cycles for empty reservoir case and welded contact according to nonlinear analyses.



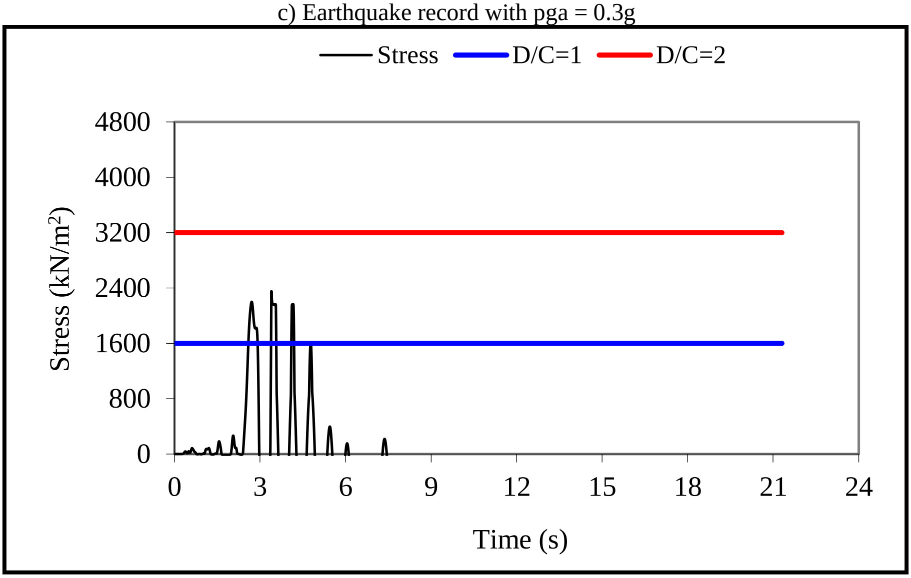
a) Earthquake record with pga = 0.1g



b) Earthquake record with pga = 0.2g

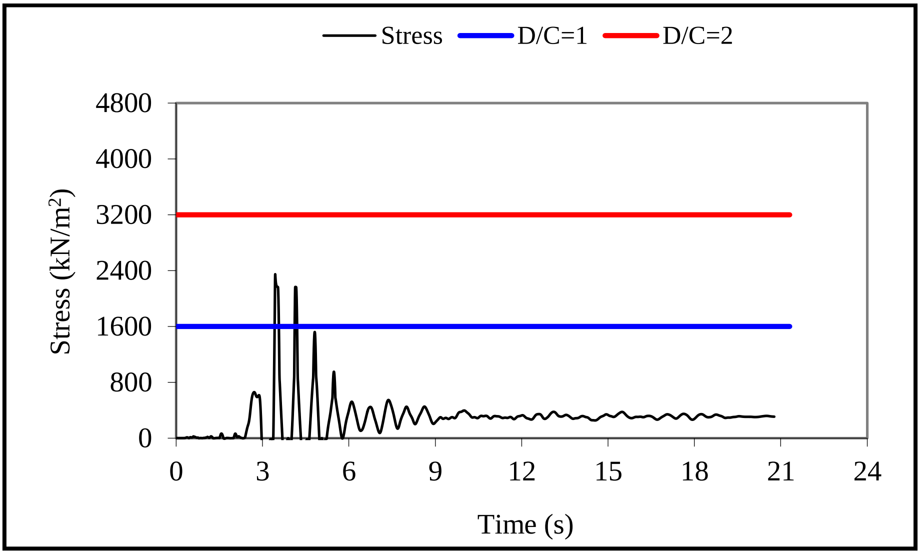


c) Earthquake record with pga = 0.3g

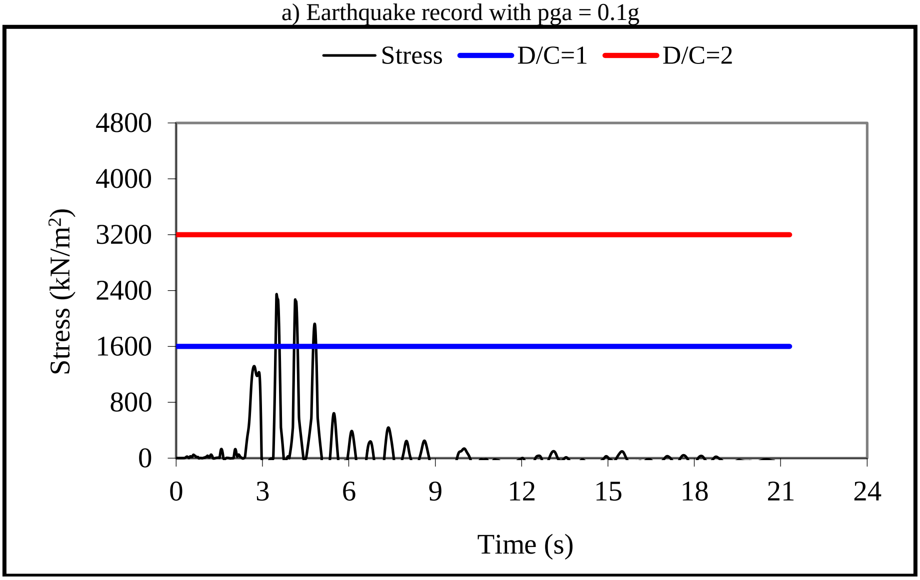


d)Earthquake record with pga = 0.4g

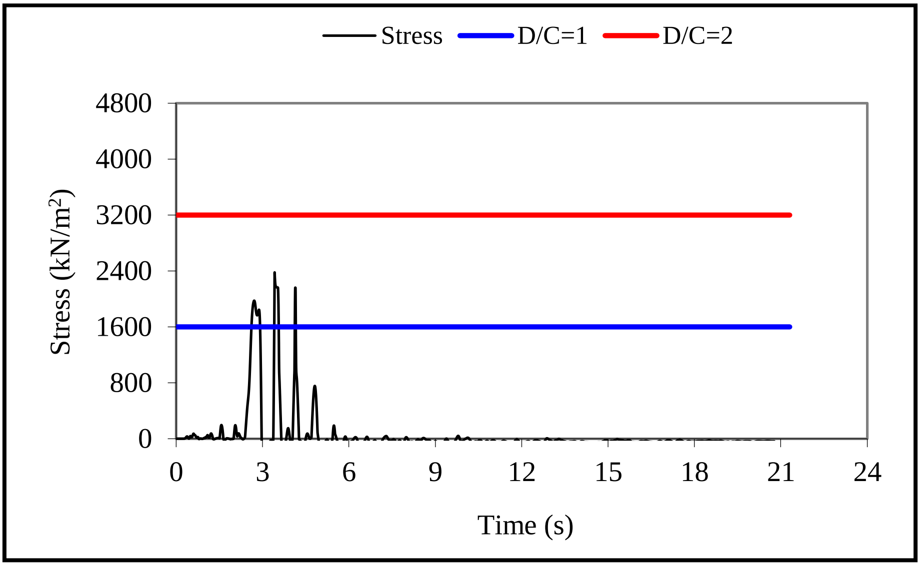
Figure 17. Maximum principal stress cycles for empty reservoir case and friction contact according to nonlinear analyses.



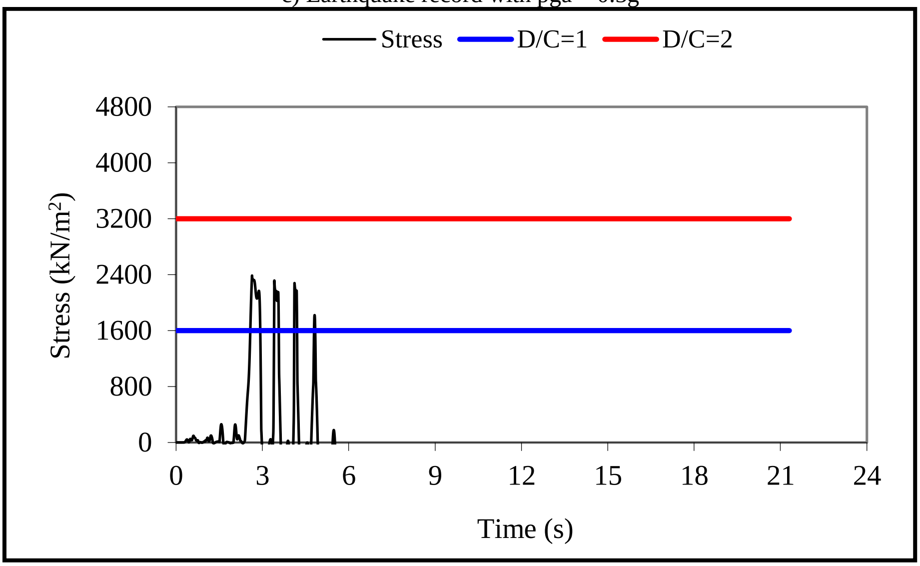
a) Earthquake record with pga = 0.1g



b) Earthquake record with pga = 0.2g

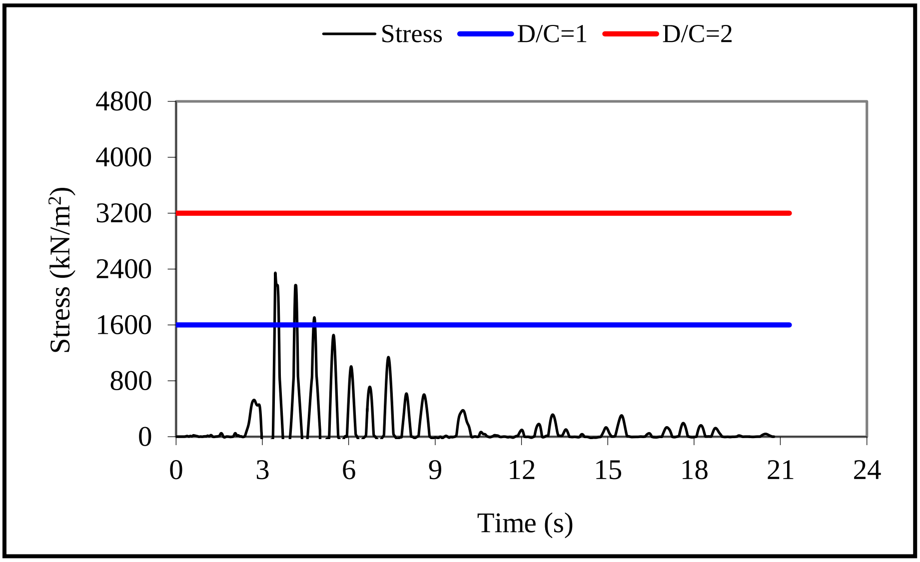


c) Earthquake record with pga = 0.3g

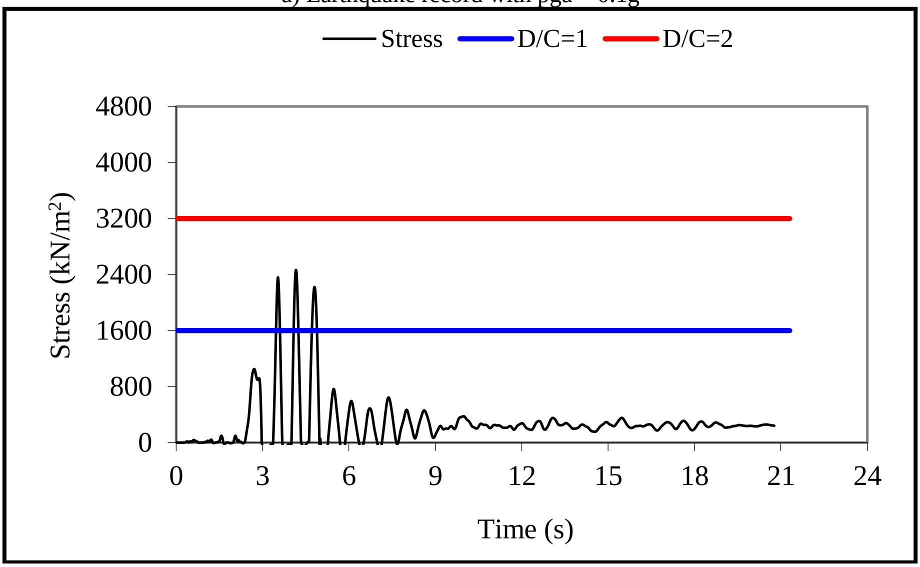


d) Earthquake record with pga = 0.4g

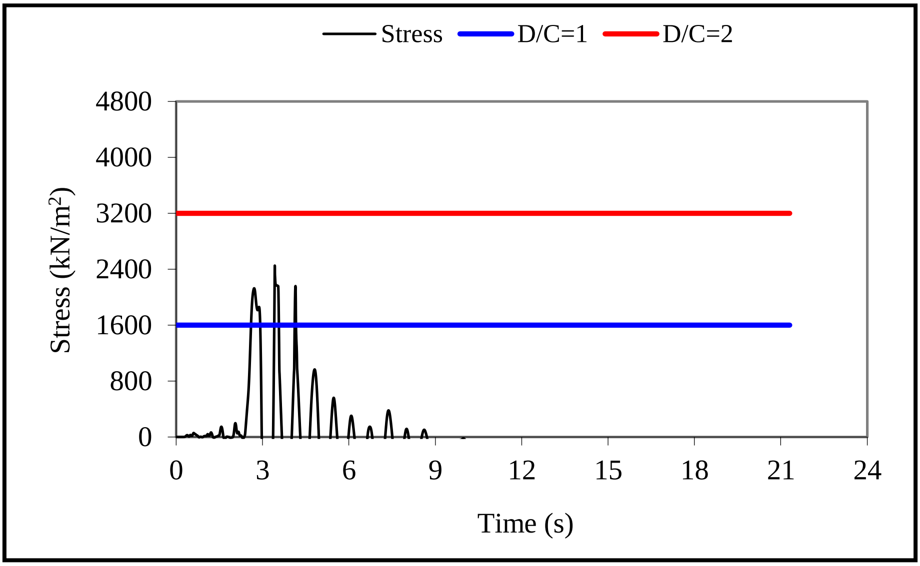
Figure 18. Maximum principal stress cycles for full reservoir case and welded contact according to nonlinear analyses.



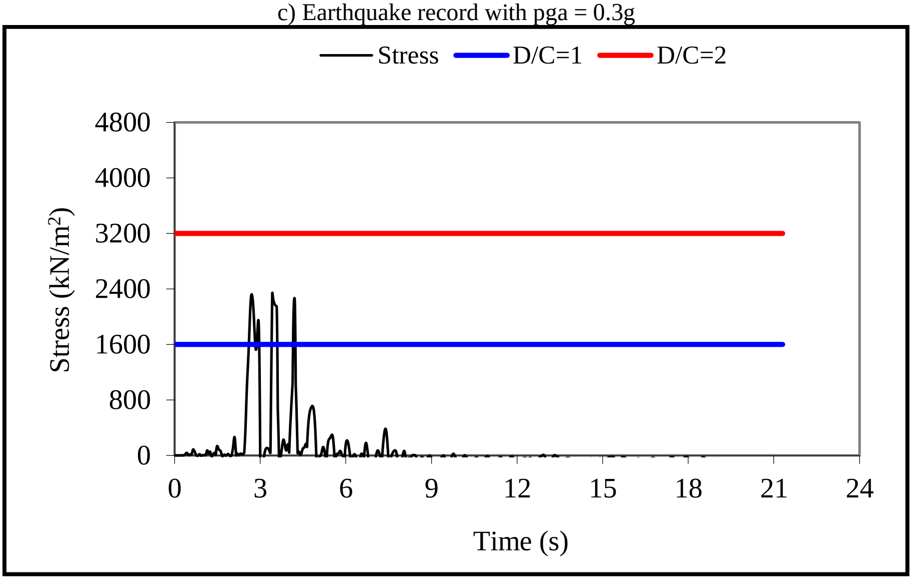
a) Earthquake record with pga = 0.1g



b) Earthquake record with pga = 0.2g



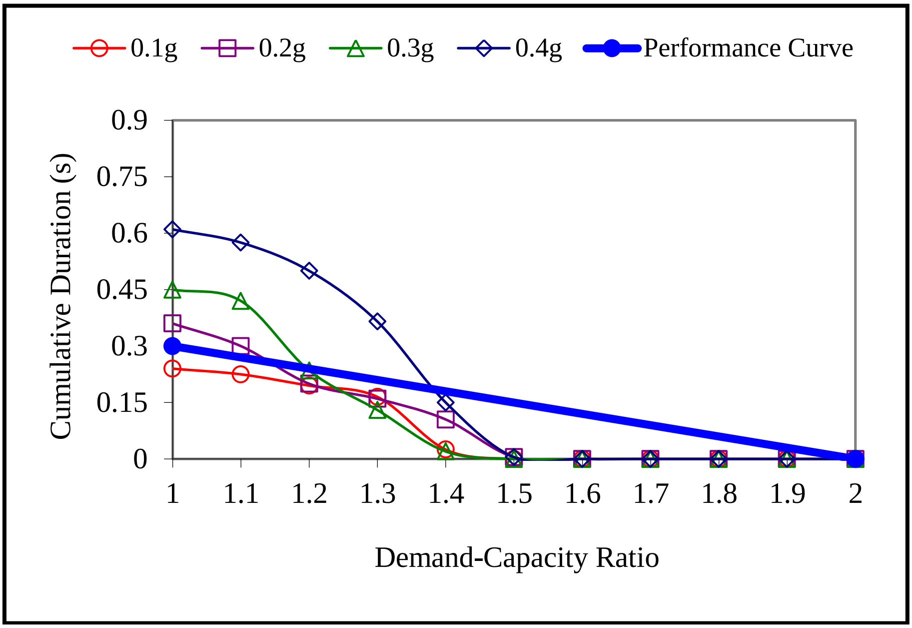
c) Earthquake record with pga = 0.3g



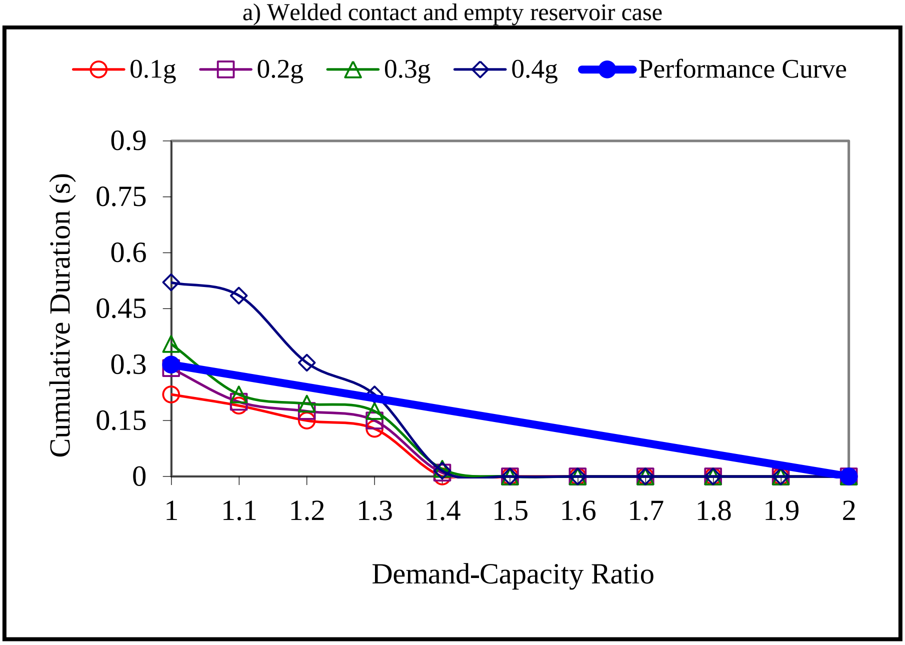
d)Earthquake record with pga = 0.4g

Figure 19. Maximum principal stress cycles for full reservoir case and friction contact according to nonlinear analyses.

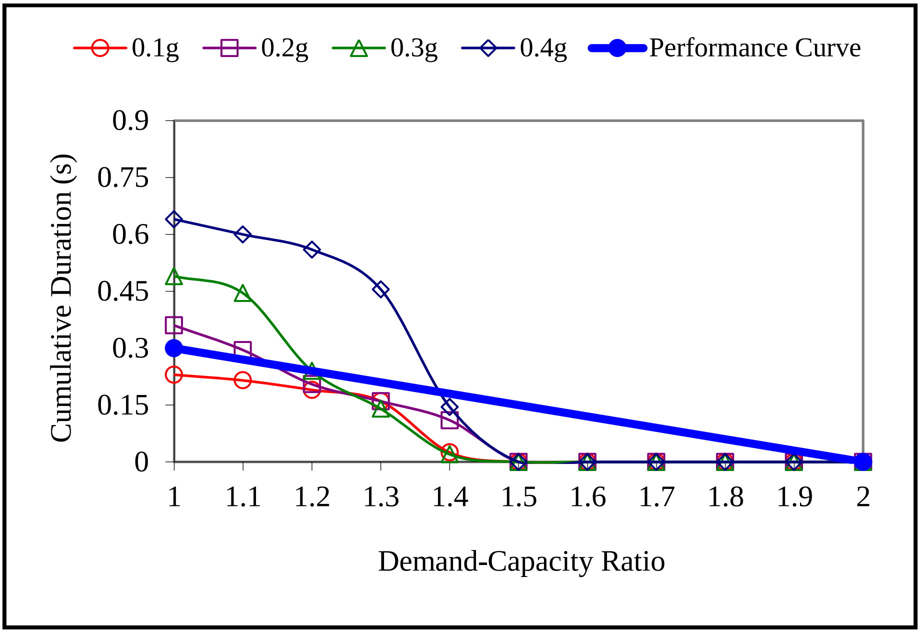
Earthquake performance curves for nonlinear time-history analyses are given in Fig. 20 to clarify earthquake performance of the dam. Performance evaluation is done for D/C ratios between 1 and 2. According to Fig. 20, crack formation and major damages is not possible for D/C ratios larger than 1.4. However, damage forming might be assessed for D/C less than 1.4. The numerical analyses reveal that damage does not occur in the concrete slab for the earthquake record with pga of 0.1g. However, the concrete slab is damaged for the earthquake record with pga of 0.4g in both cases of reservoir condition. The earthquake performance of the concrete slab calculated with nonlinear analyses decreases when the hydrodynamic pressure is considered. It also decreases when the peak ground accelerations of the earthquake record increases and this is more apparent for the dam with friction contact in concrete slab-rockfill interface.



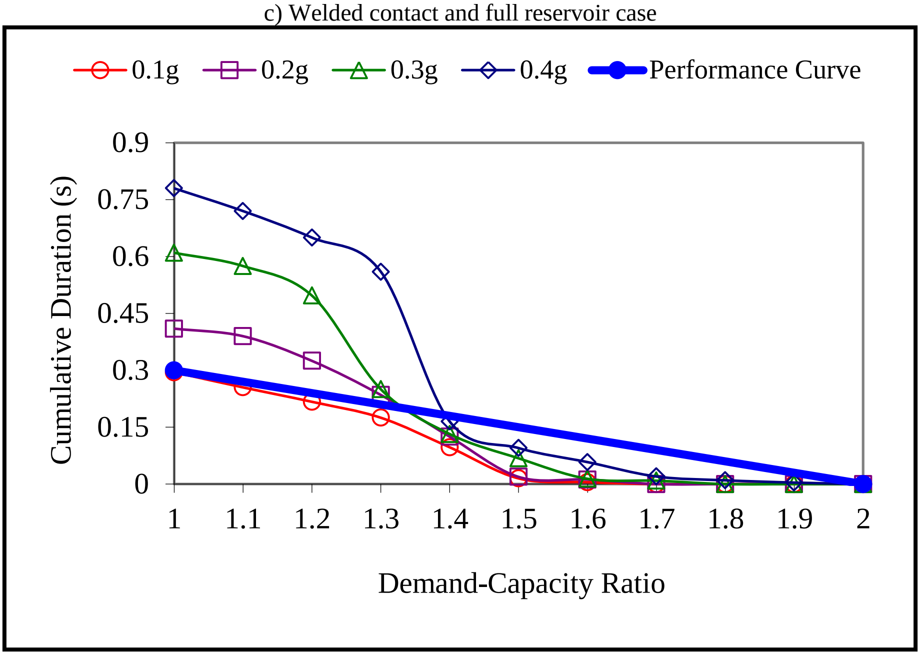
a) Welded contact and empty reservoir case



b) Friction contact and empty reservoir case



c) Welded contact and full reservoir case



d) Friction contact and full reservoir case

Figure 20. Earthquake performance curves of the dam according to nonlinear analyses.

6. CONCLUSIONS

In this paper, the effect of hydrodynamic pressure on concrete face slab is investigated considering friction contact and welded contact in concrete slab-rockfill interface. In the numerical analyses, the East-West component with 0.496 pga of the 1992 Erzincan earthquake record is used. This accelerogram is scaled to 0.1g, 0.2 g, 0.3g and 0.4g. For this purpose, linear and nonlinear time-history analyses are performed. In the materially nonlinear time history analyses, the Drucker-Prager model is used for the concrete slab and multi-linear kinematic hardening model, rockfill zones and also the foundation soil. The, hydrodynamic effect of the reservoir water is modeled using two dimensional fluid finite elements based on the Lagrangian approach.

According to the earthquake performance evaluation of the Torul CFR Dam, damage formation seems inevitable in the concrete slab based upon linear time-history analyses for empty and full reservoir and the two interface conditions. Also, according to linear analyses the earthquake performance decreases by considering hydrodynamic pressure on the face slab. Thus, materially nonlinear time-history analyses are performed for a rational assessment of earthquake performance. In this case, damage also occurs in the concrete slab but for lower degree of demand-capacity ratio cracks occur in the concrete slab and damage level increase by increasing pga of earthquake. On the other hand, no damage occurs in the concrete slab for the earthquake with a 0.1 g pga. This study indicates that the lowest earthquake performance occurs for full reservoir case. In addition, the highest earthquake performance is achieved with empty reservoir and with friction contact in the concrete slab-rockfill interface. For the welded contact in the concrete slab-rockfill interface, the hydrodynamic pressure effect on the earthquake performance of the concrete slab is less important than in the friction contact case.

As a consequence of the results of the study, the following are recommendations are put forward:

- In earthquake performance evaluation of a CFR dam, friction contact should be considered in the concrete slab-rockfill interface.
- Hydrodynamic pressure on face slab should be considered in earthquake performance analyses.
- Nonlinear earthquake analyses should be performed to obtain reliable earthquake performance of a CFR dam.
- Using more than one earthquake record may provide comprehensive knowledge about earthquake response of the CFR dam.

REFERENCES

[1] Seed H.B., Seed R.B., Lai S.S., Khamenehpour B., “Seismic Design of Concrete Faced Rockfill Dams”, Proceedings of the Symposium on Concrete Face Rockfill Dams – Design, Construction and Performance, ASCE, New York, 1985, 459-478.

[2] Priscu R., Popovici A., Stematiu D., Stere C., “Earthquake Engineering for Large Dams”, New York, Editura Academiei, Bucuresti and John Wiley & Sons, NY, 1985.

[3] Sherard J.L., Cooke J.B., “Concrete-Face Rockfill Dam – I. Assessment, and II. Design”, J.Geo.Eng., 113, 10, 1096-1132, 1987.

[4] Gazetas G., Dakoulas P., “Seismic Analysis and Design of Rockfill Dams – State of the Art.”, *Soil Dyn.Earth.Eng.*, 11, 27-61, 1992.

[5] Uddin N., “A Dynamic Analysis Procedure for Concrete-Faced Rockfill Dams Subjected to Strong Seismic Excitation”, Comp.&Struct., 72, 409-421, 1999.

[6] Bayraktar A., Kartal M.E., “Linear and Nonlinear Response of Concrete Slab on CFR Dam During Earthquake”, Soil Dyn.Earth.Eng., 30, 10, 990-1003, 2010.

[7] Kartal M.E., Bayraktar A., Başağa H.B., "Seismic Failure Probability of Concrete Slab on CFR Dams with Welded and Friction Contacts by Response Surface Method", Soil Dyn.Earth.Eng., 30, 11, 1383-1399, 2010.

[8] Bayraktar A., Kartal M.E., Adanur S., "The Effect of Concrete Slab-Rockfill Interface Behavior on the Earthquake Performance of a CFR Dam", Int.J.Non.Lin.Mech., 46, 1, 35-46, 2011.

[9] Uddin N., Gazetas G., "Dynamic Response of Concrete-Face Rockfill Dams to Strong Seismic Excitation", J.Geo.Eng., ASCE, 121, 2, 185-197, 1995.

[10] Bayraktar A., Altunişik A.C., Sevim B., Kartal M.E., Türker T., Bilici Y., "Comparison of Near- and Far-Fault Ground Motion Effect on the Nonlinear Response of Dam–Reservoir–Foundation Systems", Nonlin.Dyn., 58, 4, 655-673, 2009.

[11] Westergaard H.M., "Water Pressures on Dams During Earthquakes", Transactions, ASCE, 98, 418-433, 1933.

[12] Zangar C.N., Haefei R.J., "Electric Analog Indicates Effects of Horizontal Earthquake Shock on Dams", Civ.Eng., 54-55, 1952.

[13] Zienkiewicz O.C., Nath B., "Earthquake hydrodynamic pressures on arch dams-an electric analogue solution". Proceedings of International Civil Engineering Congress, 25, 165-176, 1963.

[14] Chopra A.K., "Earthquake Behavior of Reservoir-Dam Systems", J.Eng.Mech.Div., 94, 1475-1500, 1968.

[15] Finn W.D.L., Varoglu E., "Dynamics of Gravity Dam-Reservoir Systems". Comp.&Struct., 3, 913-924, 1973.

[16] Saini S.S., Bettess P., Zienkiewicz O.C., "Coupled Hydrodynamic Response of Concrete Gravity Dams Using Finite and Infinite Elements". Earth.Eng.&Struct.Dyn., 6, 363-374, 1978.

[17] Chopra A.K., Chakrabarti P., "Earthquake Analysis of Concrete Gravity Dams Including Dam-Water-Foundation Rock Interaction", Earth.Eng.&Struct.Dyn., 9, 363-383, 1981.

[18] Greeves E.J., Dumanoglu A.A., "The Implementation of an Efficient Computer Analysis for Fluid-Structure Interaction Using the Eulerian Approach Within SAP-IV", Department of Civil Engineering, University of Bristol, Bristol, 1989.

[19] Singhal A.C., "Comparison of Computer Codes for Seismic Analysis of Dams", Comp.&Struc., 38, 107-112, 1991.

[20] Calayır Y., Dumanoglu A.A., Bayraktar, A., "Earthquake Analysis of Gravity Dam–Reservoir Systems Using the Eulerian and Lagrangian Approaches". Comp.&Struct., 59, 877-890, 1996.

[21] Bayraktar A., Dumanoglu A.A., Calayır Y., "Asynchronous Dynamic Analysis of Dam-Reservoir-Foundation Systems by the Lagrangian Approach", Comp.&Struct., 58, 925-935, 1996.

[22] Kartal M.E., "Investigation of The Deformations in a Concrete Faced Rockfill Dam During Strong Ground Motion, Sigma J.Eng.&Nat.Sci, 36, 1, 207-230, 2018.

[23] Abedian M.A., Farrokhi F., Rasouli R., "Settlement Evaluation of a Concrete Face Rock-Fill Dam (CFRD) Using a Back-Analysis Method Based on Measurement Results (A Case Study of Siah-Bisheh Dam), J.Eng.&Tech.Sci., 50, 4, 516-533, 2018.

[24] Kartal M.E., "An Evaluation of Peak Acceleration Amplification Coefficients in A CFR Dam Considering Hydrodynamic Pressure, J.Struct.Eng.&App.Mech., 1, 2, 73-94, 2018.

[25] Wilson E.L., Khalvati M., "Finite Elements for the Dynamic Analysis of Fluid-Solid Systems", Int.J.Num.Meth.Eng., 19, 1657-1668, 1983.

[26] Zienkiewicz O.C., Taylor R.L., "The Finite Element Method", Mc Graw-Hill, 1989.

[27] Bathe K.J., "Finite Element Procedures in Engineering Analysis". New Jersey, Englewood Cliffs: Prentice-Hall, 1996.

[28] Clough R.W., Penzien J. "Dynamics of Structures" 2nd Ed., Singapore, McGraw-Hill, 1993.
[29] Akkas N., Akay H.U., Yılmaz C., "Applicability of General-Purpose Finite Element Programs in Solid-Fluid Interaction Problems", Comp.&Struct., 10, 773-783, 1979.
[30] Ghanaat Y., "Seismic Performance and Damage Criteria for Concrete Dams", In Proceedings of the 3rd US-Japan Workshop on Advanced Research on Earthquake Engineering for Dams, San Diego, California, 2002.
[31] USACE, US Army Corps of Engineers, "Time History Dynamic Analysis of Concrete Hydraulic Structures-Engineering and Design (Engineer Manual)", EM 1110-2-6051, 2003.
[32] DSI, General Directorate of State Hydraulic Works, 2018.
[33] ANSYS, Swanson Analysis Systems Inc., Houston PA, USA, 2017.
[34] Rollins K.M., Evans M.D., Diehl N.B., Daily III W.D., "Shear Modulus and Damping Relationships for Gravels". J.Geo.Geoenv.Eng., 124, 5, 396–405, 1998.
[35] Schnabel P.B,, Lysmer J., Seed H.B., "SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites", Report No. EERC-72/12, Earthquake Engineering Research Centre, University of California, Berkeley, 1972.
[36] PEER, Pacific Earthquake Engineering Research Centre, Available from http://peer.berkeley.edu/smcat/data/ath/erzikan/ERZ-EW.AT2, [accessed May 21,2005].