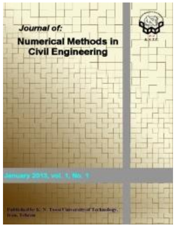
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The effects of friction coefficient on the nonlinear behavior of an arch dam with jointed foundation

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Abstract:

This study aims at determining the influences of the friction coefficient on both the safety factor of the wedge based on the Londe method and the nonlinear behavior of an arch dam with a jointed foundation according to the finite element analysis. Two separate finite element models of the Bakhtiari arch dam (with integrated and jointed foundations) are developed as a case study. Four values are taken for the friction coefficient to study the effect of the joint's parameters; the mentioned values are 0.25, 0.5, 0.75, and 1. The results indicate that considering the joints in the foundation has a prominent role in the nonlinear response of the arch dam. Moreover, the maximum displacements and quantity of tensile damage on the dam body having a jointed foundation reduces when the friction coefficient increases.

1. Introduction

Generally, concrete arch dams are regarded as paramount infrastructures constructed with disparate usages from flood control and irrigation purposes to generating power. Along with their wide usages, the safety of such structures is also of greatest importance on the ground of their enviro-economic values. Experiencing various seismic loading, such dams have been vulnerable to some failures such as tensile cracking, abutment displacement due to the discontinuities in rocks, and also the excessive contraction joint opening. Moreover, considering the vertical contraction joints as the discontinuities in their construction, such joints could be subjected to opening and closing cycles during an earthquake and consequently cause different stress distribution.

Since the critical failure mode occurs with the displacement in abutments, finding a proper analysis to investigate dam abutments appears to be indispensable. In the literature, there are different methods proposed for calculating the stability of dams with regard to the abutment rock wedges.

Some researchers numerically investigated the effect of contraction joints on the seismic response of arch dams. Accounting the thrust and uplift forces along with simplifying the mechanics and displacements, a limit equilibrium was developed by Londe [1] to evaluate the abutment stability in arch dams. Dowling and Hall [2] determined the tensile stresses in the upper part of the arch dam by using the finite element method for linear elastic analysis subjected to seismic loadings. More to their study, the obtained tensile stresses were found to be larger than the strength of grouted contraction joints, by which different patterns in cracking and openings in dams were engendered. Sohrabi et al. [3] studied the left abutment stability of the Luzzone dam resulted in the safety factor time history of a wedge using the Londe conventional method. As for delving into an optimized shape, Takalloozadeh and Ghaemian [4] carried out a research on concrete arch dams with regard to their abutment stability. It is worth mentioning that they assumed the wedges in contact with the dam body. Eventually, they concluded that compared to the tensile stresses, the optimum shape of the arch dam was mostly affected the abutments stability. Mirzabozorg et al. [5] drew a comparison between the finite element and the Londe methods on the stability of a rock wedge. Based on their results, the calculated wedge displacement by the Londe

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method was turned out to be larger than the one calculated by the finite element method. The effect of foundation nonlinearity on the seismic behavior of an arch dam was scrutinized by Mahmoudi et al. [6]. Based on their outcomes, owing to the dam's particular shape, the consideration of foundation nonlinearity had a marginal effect on the obtained results. Mostafaei et al. [7, 8] investigated the probable wedge displacements of the Luzzone dam subjected to seismic loading. Conducting another investigation, they highlighted the considerable influence of the uplift pressure on the abutment safety factor [9]. Pan and Wang et al. [10] investigated the nonlinear response of arch dams undergone abutment movements. Moreover, as a result of the movements, some damaging cracks were engendered at dam's mid-height (the downstream face) and also in the surface outlets. Mostafaei and Behnemfar investigated the effects of the vertical components of an earthquake on both the safety factor of the wedge and the nonlinear behavior of the dam with a jointed foundation [11, 12]. Their results illustrated that taking the vertical component of the earthquake into account reduced the safety factors of the wedges significantly. Furthermore, the vertical component of the earthquake had an important role in the nonlinear behavior of the dam with a jointed foundation. Liang et al. studied the seismic fragility of an arch dam based on the instability mode [13]. They obtained the seismic fragility curves for the different damage levels based on the different engineering demand parameters-based rules. The influences of the foundation rigidity, presence of the contraction joints, material nonlinearity on the abutment stability were scrutinized by Mostafaei et al. [14]. They found that the material nonlinearity had a weak effect on the safety factor of the wedges, and it can be neglected for calculating the safety factor.

As reviewed so far, the effect of friction coefficient on the wedge stability and the nonlinear response of concrete arch dam having jointed foundation was not scrutinized earlier. Thereby, the present paper is aimed at investigating different friction coefficients on the dam behavior. To have this done, in the first place, the critical wedges are determined using the Londe method. Thereafter, some joints will be taken into consideration in the identified wedges, and finally, the effect of friction coefficients on the nonlinear behavior of the dam is meticulously studied.

Throughout this paper, the Bakhtiari dam, built as a double-curvature arch dam in Iran, has been analyzed. The dam is supposed to store compressible water in this model. More about the modeling, an enormous medium accompanied by viscous boundaries at the far side (truncated part of the foundation) has been considered. It should also state that the concrete damaged plasticity (CDP) is assumed in the nonlinear analyses to have the nonlinear behavior of concrete material.

2. Details on seismic stability of the wedge

Fig. 1 demonstrates the dam structure, the foundation and the reservoir along with the wedge and its supportive planes. In accordance with the Londe method elaborated in [1], the rigid behavior is assumed for the wedge. It is necessary to state that the studied wedge is surrounded by three sliding probable planes of the sub-horizontal plane (P1), the sub-vertical plane (P2) and the grout curtain (P3), which intersect each other as shown in Fig. 1. To have the problem simplified, the tensile strength on the wedge surfaces and also the moments of reaction force are both disregarded in the equilibrium equations. Afterward, the equilibrium equations are solved.

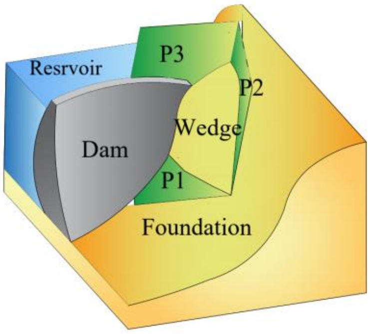


Fig. 1: Dam-reservoir-foundation, wedge, and its supporting planes.

As for the stability of the given wedge, the effective forces are the thrust force ($\boldsymbol{F}_{\boldsymbol{TH}}^{\boldsymbol{D}}$), the uplift force ($\boldsymbol{F}_{up}^{W}$), the wedge weight force ($\boldsymbol{F}_{w}^{w}$), and the seismic inertia force ($\boldsymbol{F}_{Eq}^{w}$). The thrust forces were determined by developing a three-dimensional FEM modeling of the dam, reservoir and foundation. Through the water seepage into the planes' cracks, an uplift water force was applied to them, which could be simply calculated with regard to water height, the area and the geometry of the plane. With regard to the Londe method and the mentioned forces, the sum of the exerted forces is written as follows:

$$\mathbf{F}_{\mathbf{Res}}^{\mathbf{W}} = \mathbf{F}_{\mathbf{W}}^{\mathbf{W}} + \mathbf{F}_{\mathbf{Up}}^{\mathbf{W}} + \mathbf{F}_{\mathbf{EQ}}^{\mathbf{W}} + \mathbf{F}_{\mathbf{TH}}^{\mathbf{D}} \tag{1}$$

The exploitation of the equilibrium equations would yield to three normal forces of N_1, N_2 and N_3. Based on the Londe method, the planes can only experience compressive forces. Therefore, in the case of a normal force as tensile, the occurrence of either overturning or sliding instability is probable. As tabulated in Table. **1**, there are eight disparate sliding modes affecting wedge stability that are possible to take place.

Table. 1: Possible sliding modes [7]

Case	Definition	Result
1	All of the normal forces on the planes are compressive.	Wedge is completely stable.
2	Normal force on the first plane is compressive.	Wedge detaches from the two other planes.
3	Normal force on the second plane is compressive.	Wedge detaches from the two other planes.
4	Normal force on the third plane is compressive.	Wedge detaches from the two other planes.
5	Normal force on the first plane is tensile.	Wedge detaches from the first plane.
6	Normal force on the second plane is tensile.	Wedge detaches from the second plane.
7	Normal force on the third plane is tensile.	Wedge detaches from the third plane.
8	All of the normal forces on the planes are tensile.	Wedge is unstable.

As one can notice from the given table, the stable case will occur if the planes are subjected to compression normal reactions. On the other hand, a friction force (*F*) is imposed along the plane's intersection line for cases 2, 3 and 4. Moreover, two normal forces and the single friction force are calculated using three translational equilibrium equations. For instance, in the case of tension in the third plane, the wedge safety factor could be written as follows:

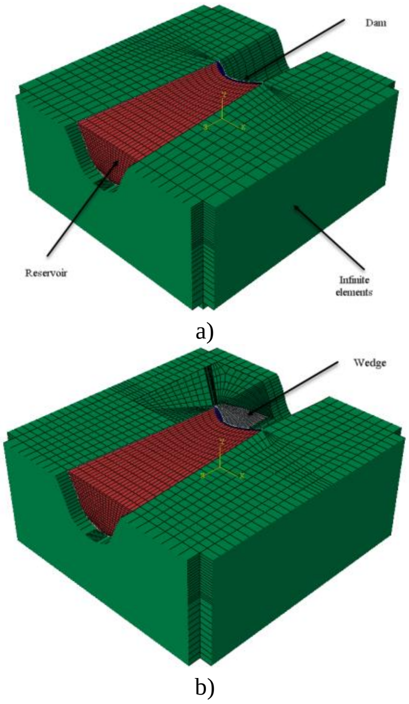
$$SF = \frac{N_1\mu_1 + c_1A_1 + N_2\mu_2 + c_2A_2}{F_{12}} \qquad (2)$$

In which μ refers to the friction coefficient, c is cohesion, and A is the plane area. Note that the written index shows the number of planes; *e.g.* F_{12} highlights the shear force exiting at the intersection line of planes 1 and 2. Considering cases 5, 6 and 7, two normal components related to the friction force are taken into account instead of the tensile reactions. Afterwards, solving the equilibrium equations in the case of N_2 and N_3 as tensile components result in the *SF* against the sliding as follows:

$$SF = \frac{N_1\mu_1 + c_1A_1}{F_1} \qquad (3)$$

3. Case study

For this purpose, the highest double-curvature arch dam in the world, which is still under construction (Bakhtiari Dam), is chosen as a case study. The Bakhtiari dam is located on the Bakhtiari river within the Zagros Mountains. The main purpose of the dam is hydroelectric power production and trapping sediment. The height of the dam is 325m, with various thicknesses range from 5m (crest) to 54m (base) [12]. In addition to its configuration, the normal water level is designed to be at 320m. Through the usage of the eight-node brick isoparametric element (C3D8R), two unique finite element models have been developed. The C3D8R elements are used for modelling the concrete dam and its surrounding foundation. The difference between models is the foundation which is once modeled as the integrated foundation and once as a jointed foundation. With the purpose of inhibiting the truncated boundary conditions on the dam response, it is assumed that the truncated reservoir length is two times of the dam height as suggested by FERC [15] and USACE [16, 17]. Moreover, modeling the reservoir water is based on the acoustic element AC3D8R. As for wave radiation simulation, infinite elements are utilized at the boundaries of the foundation. At the far-ends of the reservoir, the transmitting boundary condition is applied. This boundary condition is used to absorb pressure waves going away from the domain. In addition, the bottom of the reservoir is assumed to obey a non-absorbing boundary condition. Using these elements vanishes the displacement and the stress at infinity. The current finite element model consists of 1,360, 21,982 and 5,440 elements for the dam, the foundation rock, and the water, respectively. Fig 2 illustrate the dam geometry and its finite element modeling, respectively.



a)

b)

Fig. 2: The finite element model of the Bakhtiari dam with a) Integrated foundation, b) Jointed foundation

Table. 2: The characteristics of the WL6 wedge at the left abutment [19]

Plane	unit normal vector	Area (m^2)	Cohesion	Uplift force
Sub-horizontal plane ($P1$)	(0, 0, 1)	23514	0.6	11432
Sub-vertical planes ($P2$)	(0.752, -0.606, 0.259)	54974	0.1	39453
Grout curtain ($P3$)	(0.752, -0.606, 0.259)	9720	0.3	14042

The material properties of the dam are tabulated in Table 3. Moreover, the mass density and Bulk modulus of water are taken to be $\rho_w = 1000\,kg/m^3$ and $K_w = 2.2GPa$, respectively [14]. The stress-strain behavior of the concrete is not available; therefore, the Kent and Park model is utilized to model the tension and compression stress-strain responses. The constitutive relations under tensile and compressive loadings are shown in Fig. 3.

Table. 3: Material properties of the concrete and the rock [11]

Materials	Elastic modulus (GPa)	Poisson 's ratio	Density (kg/m^3)
Dam	24	0.18	2400
Rock	12	0.25	2600

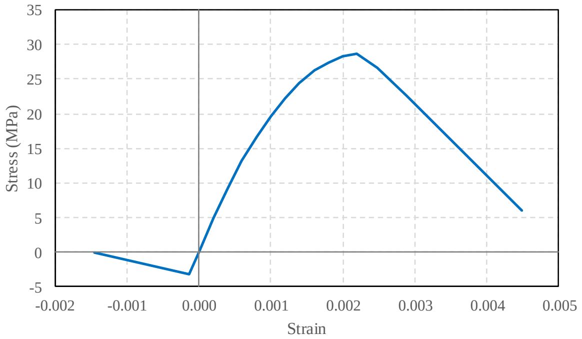


Fig. 3: The Stress-strain model for the tensile and compressive loadings of concrete [14]

The concrete damage plasticity is employed for modeling the nonlinear behavior of concrete. In this approach, the tensile cracking and compressive crushing of concrete are taken into account by using two damage variables, d, in tension (t) and compression (c). The aforementioned variables are assumed to be functions of inelastic strain ratio that changes from zero to one showing the undamaged material and total loss of strength, respectively [1]. The stress-strain relations under uniaxial tension and compression can be written as follows:

$$\begin{aligned} \sigma_t &= (1-d_t)\,E_0\left(\varepsilon_t - \tilde{\varepsilon}_t^{pl}\right) \\ \sigma_c &= (1-d_c)\,E_0\left(\varepsilon_c - \tilde{\varepsilon}_c^{pl}\right) \end{aligned} \tag{4}$$

where E_0, σ, ε and $\varepsilon^{\sim pl}$ stand for the initial (undamaged) modulus of elasticity, the stress, strain, and inelastic strain of concrete, respectively.

Geometric nonlinearity

The contact force between two surfaces includes tangential and normal components [18]. By the Coulomb friction model, the stresses transmitted across the interfaces can be obtained as follows:

$$\tau_u = \mu\sigma \tag{5}$$

where τ_u, μ and σ denote the ultimate shear stress, the coefficient of friction and the normal stress. It should be noted that for modeling the normal behavior of contact, hard contact condition is taken into account.

Definition of the wedges

The WL6 wedge at the left abutment is defined by three discontinuity planes. The geometrical and mechanical characteristics of these discontinuity planes are presented in Table 2. The wedge volume has been estimated at 2.396 $\times 10^6$ m^3.

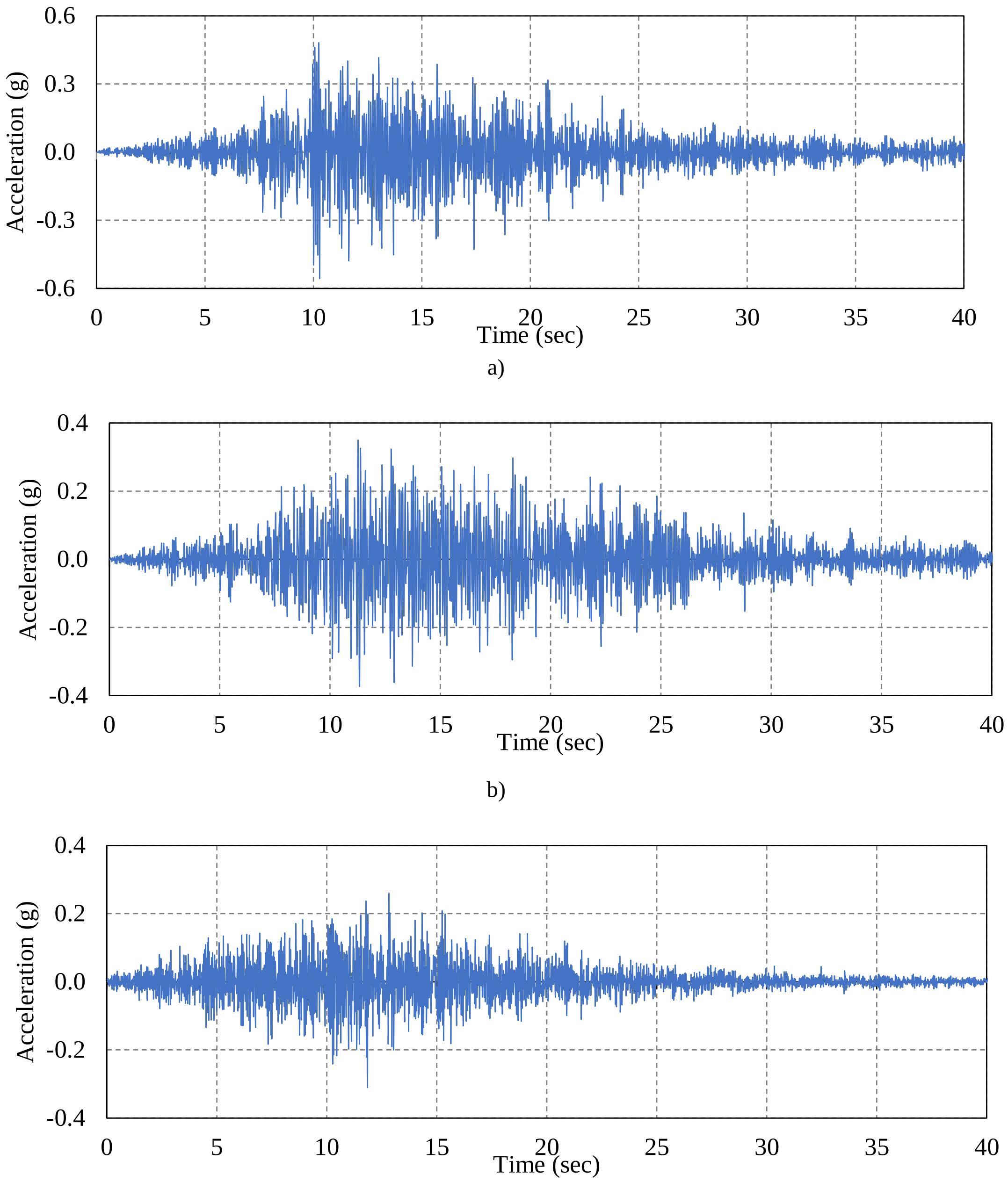
4. Numerical results and discussion

In this section, the influence of the friction coefficient on the safety factor of the wedge and the nonlinear behavior of the dam having a jointed foundation are studied. ABAQUS is a commercial finite element software package used in the present study. Moreover, the safety factor of the wedges is calculated by using a procedure developed in MATLAB. For the purpose of seismic analysis, the ground acceleration of the Iwate earthquake is considered. The ground acceleration earthquakes are applied in cross-stream (x-direction), stream (y-direction), and vertically upward (z-direction) directions. The ground accelerations of the Iwate are shown in Fig. 4.

The time history of the thrust forces applied on WL6 wedge is presented in Fig. 5.

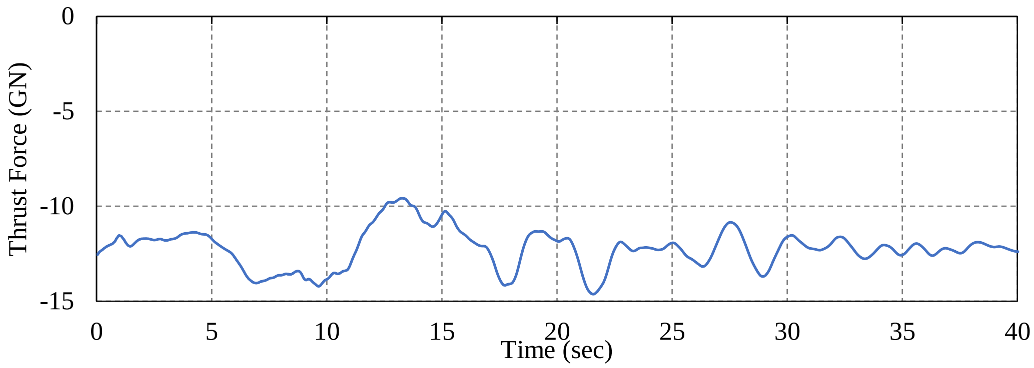
The time histories of the safety factor of the WL6 wedge for different values of the friction coefficient are illustrated in Fig. 6.

According to the results presented in Fig. 6, the effect of the friction coefficient on the minimum of the safety factor of wedges is shown in Fig. 7. The results demonstrate that the minimum of the safety factor has an ascending trend with respect to increasing the friction coefficient.



c)

Fig. 4: Time histories of the ground acceleration in the Iwate earthquake. a) Stream direction; b) Cross-stream direction; c) Vertical direction.



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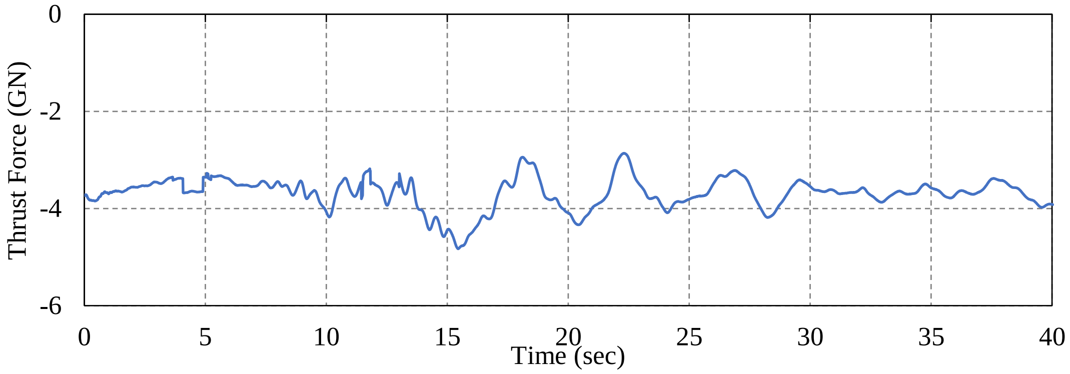

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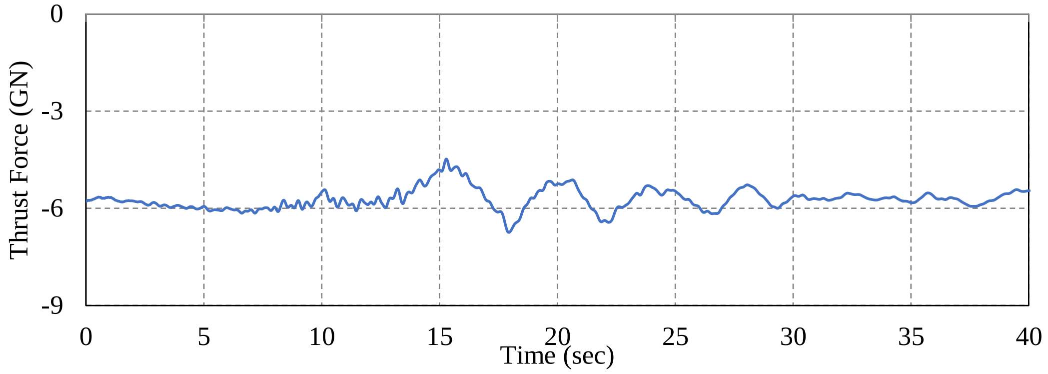
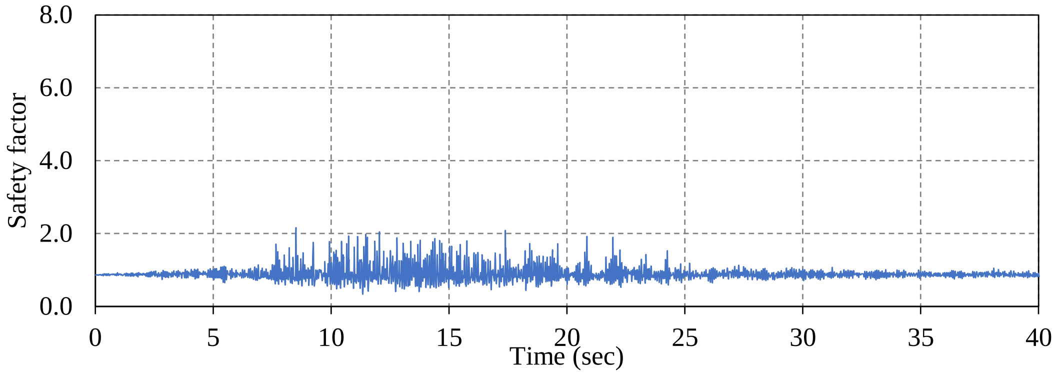


c)

Fig. 5: Time histories of the thrust force of WL6 wedge. a) Stream direction; b) Cross-stream direction; c) Vertical direction.



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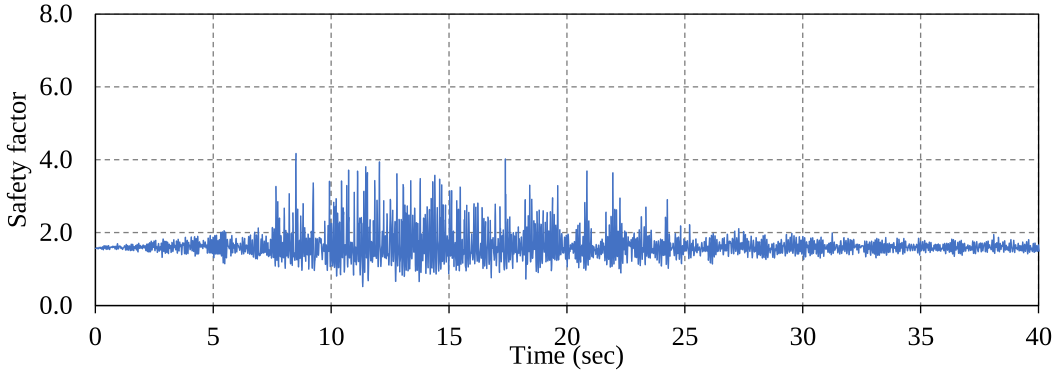

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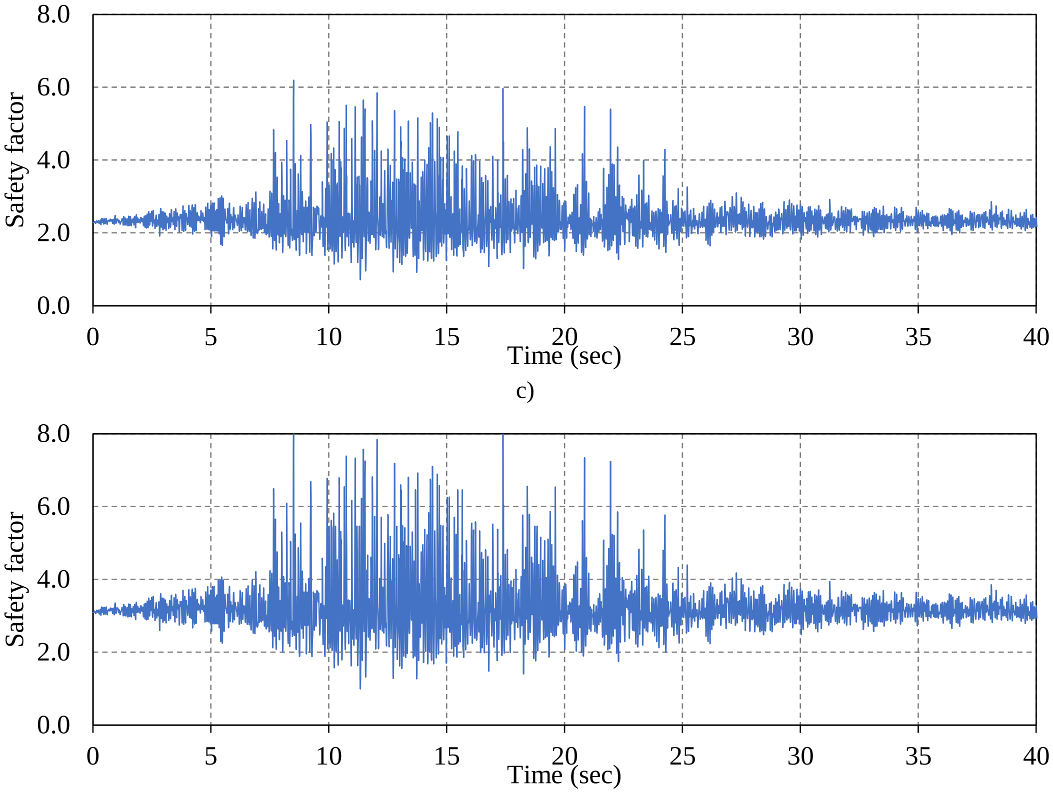


c)

d)

Fig. 6: The time histories of safety factors of WL6 wedge at the left abutment for different values of the friction coefficient. a) μ = 0.25 b) μ = 0.50 c) μ = 0.75 d) μ = 1.00

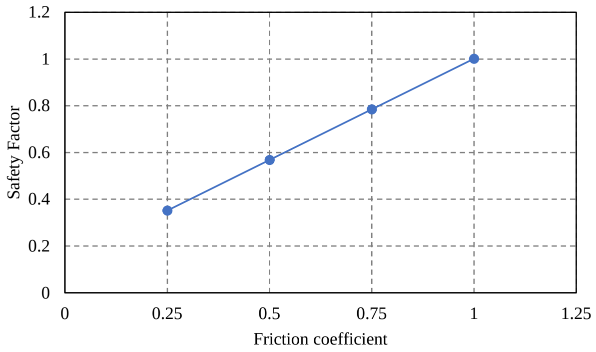


Fig. 7: The minimum safety factor of wedge for different values of the friction coefficient

Afterwards, a separate finite element model of the dam having a foundation with the wedge joints is developed, and the seismic behavior of the dam is obtained. Furthermore, the effects of the friction coefficient on the nonlinear response of the dam are investigated.

Moreover, Fig. 8 shows the effects of the friction coefficient on the tensile damage contours of the dam with jointed foundations. Owing to the considering the wedge joint, the higher tensile damages observed in the dam body, while the consideration of integrated foundation causes the marginal cracks spread near the dam heel. In cases of jointed foundation, the tensile cracks initiate from the intersection between the dam body and the wedge and propagate to the middle of the dam crest. Moreover, it can be concluded that the quantity of the tensile damages in the dam body has a descending trend with respect to the friction coefficient.

Fig. 9 shows the displacement contours of the dam at the moment that the safety factor of the wedge calculated based on the Londe method attains its minimum. It can be inferred that taking the wedge joints into account results in the dam leans on the left bank. It can also be concluded that when the friction coefficient increases, the maximum displacement of the dam with jointed foundations reduces. For example, the maximum displacement of the dam with integrated foundation is 0.277m, while this value is 3.322, 1.352, 0.888 and 0.834m when μ=0.25, 0.5, 0.75 & 1.00 respectively.

5. Conclusions

In the framework of the current study, the influences of the friction coefficient on the safety factor of dam abutment and nonlinear behavior of dam having a jointed foundation are investigated. In this regard, the developed framework was applied to the Bakhtiari arch dam, a doubly curved arch dam, as a case study. Two separate finite element models (dam with integrated foundation and foundation having discontinuities) were independently developed. By using the Londe method in conjunction with the time history analysis, the safety factor of the wedge against sliding instability was achieved for different values of the friction coefficient. The results indicated that the friction coefficient plays a prominent role in the wedge stability. Afterwards, wedge joints were modeled and influences of friction coefficient on the seismic behavior of the dam with a jointed foundation were investigated. The studies showed that the dam body undergoes more tensile damages when the foundation joints were taken into account. The peak of the dam displacements was inclined toward the abutment containing the wedge. Besides, the most important finding was that the friction coefficient had great influences on the severity of the tensile damages and the maximum displacements of the dam having a jointed foundation.

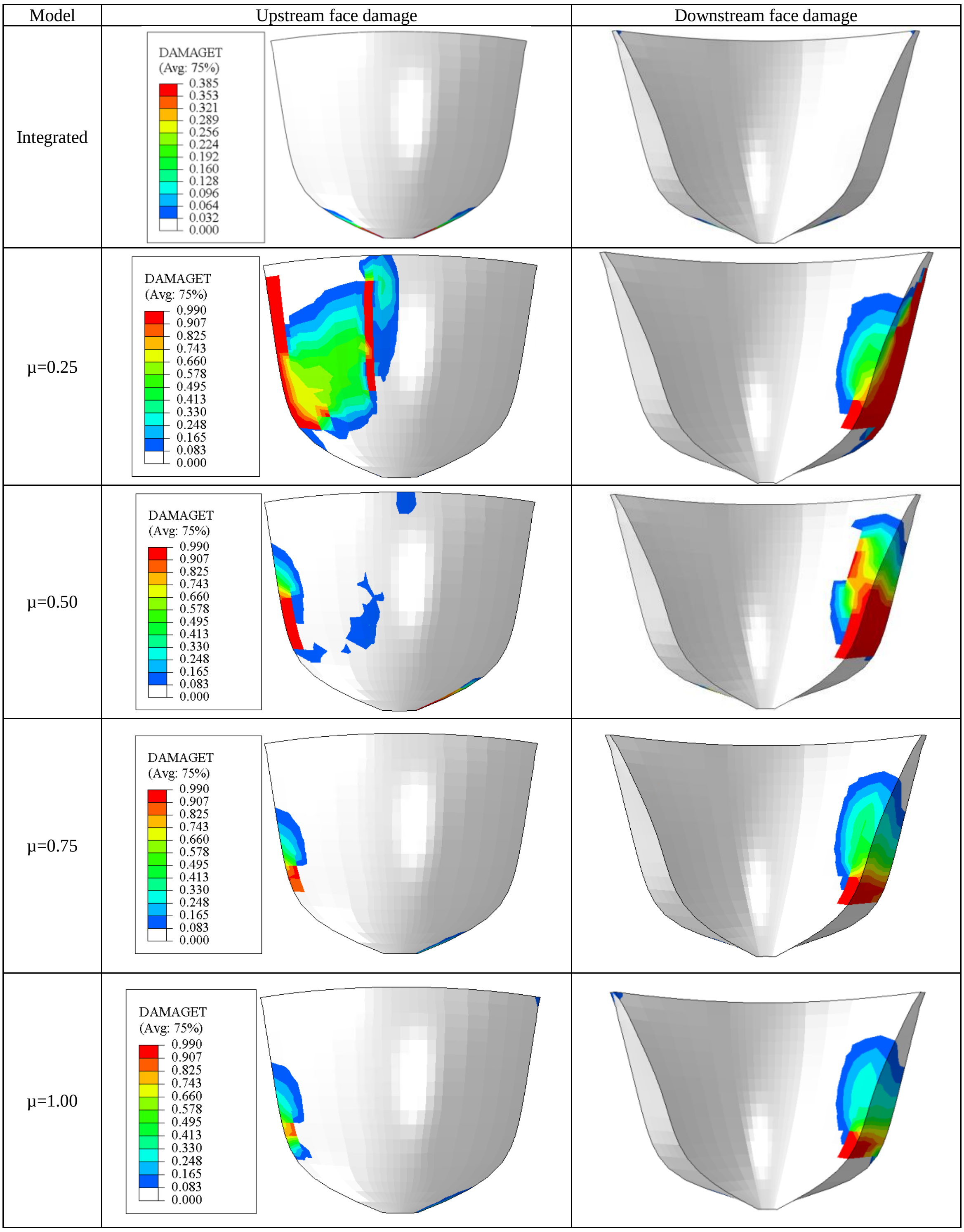


Fig. 8: Tensile damage contours of the dam for different values of the friction coefficient

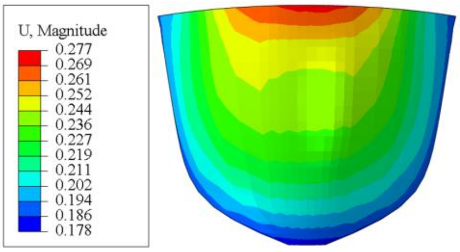
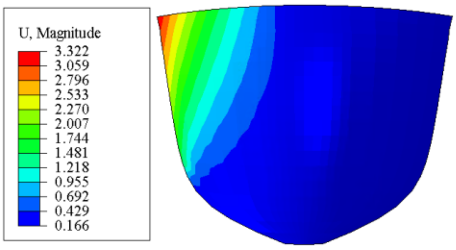
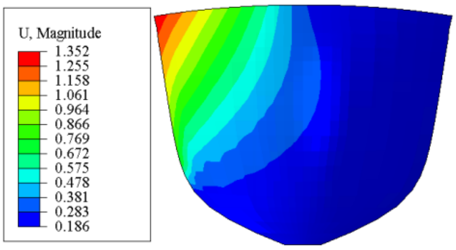
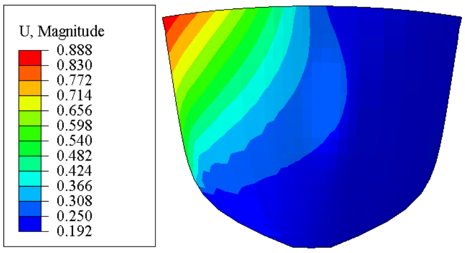
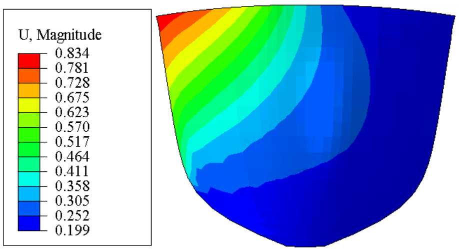
Model	Displacement contour
Integrated	
μ=0.25	
μ=0.50	
μ=0.75	
μ=1.00	

Fig. 9: Displacement contours of the dam for different values of the friction coefficient

Acknowledgments

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References:

[1] Londe, P., *Analysis of the stability of rock slopes.* Quartery Journal of Engineering Geology and Hydrogeology, 1973. 1: p. 93-127.

[2] Dowling, M.J. and J.F. Hall, *Nonlinear seismic analysis of arch dams.* Journal of Engineering Mechanics, 1989. 115(4): p. 768-789.

[3] Sohrabi Gilani, M., R. Feldbacher, and G. Zenz, *Stability of dam abutment including seismic loading*, in *10th ICOLD Benchmark Workshop*. 2009: Paris.

[4] Takalloozadeh, M. and M. Ghaemian, *Shape optimization of concrete arch dams considering abutment stability.* Scientia Iranica. Transaction A, Civil Engineering, 2014. 21(4): p. 1297.

[5] Mirzabozorg, H., et al., *A comparative study of rock wedge stability of an arch dam abutment subjected to static and seismic loading.* Soil mechanics and Foundation Engineering, 2015. 52(5).

[6] Mahmoudi, P.P., et al., *Effect of foundation nonlinearity on seismic response of an existing arch dam.* Civil engineering journal, 2016. **2**(5): p. 197-207.

[7] Mostafaei, H., M.S. Gilani, and M. Ghaemian, *Stability analysis of arch dam abutments due to seismic loading.* Scientia Iranica. Transaction A, Civil Engineering, 2017. 24(2): p. 467.

[8] Mostafaei, H., M.S. Gilani, and M. Ghaemian, *A Comparative Study between Pseudo-static and Dynamic Analyses on Rock Wedge Stability of an Arch Dam.* Civil Engineering Journal, 2018. 4(1): p. 179-187.

[9] Mostafaei, H., M.S. Gilani, and M. Ghaemian, *The Effect of Grout Curtain Efficiency on Abutments Stability of an Arch Dam*, in *4th International Conference on Long-Term Behavior and Environmentally Friendly Rehabilitation Technologies of Dams* 2017: Tehran,Iran.

[10] Wang, J.-T., F. Jin, and C.-H. Zhang, *Nonlinear Seismic Response Analysis of High Arch Dams to Spatially-Varying Ground motions.* International Journal of Civil Engineering, 2019. 17(4): p. 487-493.

[11] Mostafaei, H. and F. Behnamfar, *Effect of the vertical earthquake component on nonlinear behavior of an arch dam having a foundation with discontinuities.* International Journal of Numerical Methods in Civil Engineering, 2019. 4(2): p. 69-78.

[12] Mostafaei, H. and F. Behnamfar, *Stability Analysis of Arch Dam Abutments Due to Vertical Seismic Excitation*, in *8th International Conference on Seismology & Earthquake Engineering*. 2019: Tehran,Iran.

[13] Liang, H., et al., *Seismic fragility analysis of a High Arch Dam-Foundation System based on seismic instability failure mode.* Soil Dynamics and Earthquake Engineering, 2020. 130: p. 105981.

[14] Mostafaei, H., F. Behnamfar, and M. Alembagheri, *Nonlinear analysis of stability of rock wedges in the abutments of an arch dam due to seismic loading.* Structural monitoring and maintenance, 2020. **7**(4): p. 295.

[15] Commission, F.E.R., *Engineering guidelines for the evaluation of hydropower projects. Chapter 11-Arch Dams.* Washington DC, 1999. 20426: p. 11-18.

[16] USACE, *Engineering and design: arch dam design.* EM 1110-2-2201, 1994.

[17] USACE, *Earthquake design and evaluation of concrete hydraulic structures.* EM 1110-2-6053, 2007.

[18] Khaneghahi, M.H., M. Alembagheri, and N. Soltani, *Reliability and variance-based sensitivity analysis of arch dams during construction and reservoir impoundment.* Frontiers of Structural and Civil Engineering, 2019. 13(3): p. 526-541.

[19] Dam, B.H., *Preliminary Stability Analysis of Abutments*. 2012, Bakhtiary joint Venture Consultants, Doc. No. 4673/4258 Rev. 0, .