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Evaluation of structural safety reduction due to water penetration into a major structural crack in a large concrete project

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Abstract. Structural damage to an arch dam is often of major concern and must be evaluated for probable rehabilitation to ensure safe, regular, normal operation. This evaluation is crucial to prevent any catastrophic or failure consequences for the life time of the dam. If specific major damage such as a large crack occurs to the dam body, the assessments will be necessary to determine the current level of safety and predict the resistance of the structure to various future loading such as earthquakes, etc. This study investigates the behavior of an arch dam cracked due to water pressure. Safety factors (SFs), of shear and compressive tractions were calculated at the surfaces of the contraction joints and the cracks. The results indicated that for cracking with an extension depth of half the thickness of the dam body, for both cases of penetration and non-penetration of water load into the cracks, SFs only slightly reduces. However, in case of increasing the depth of crack extension into the entire thickness of the dam body, the friction angle of the cracked surface is crucial; however, if it reduces, the normal loading SFs of stresses and joints tractions reduce significantly.

Keywords: arch concrete dams; cracking; safety and performance evaluation; stage construction; Morrow Point dam

1. Introduction

While having large dams is considered as a big asset to a country and its people, dangers of their rupture are big and significant, too. Operability of these dams can be influenced by flooding, earthquake, rock mass slides, deterioration of foundation, worsening of concrete used in the body of dam, etc. Due to the mentioned importance and sensitivity, designing and evaluation of dam safety against destroying factors are of high importance. A concrete dam may experience different types of damage due to different phenomena. Therefore, dams need to be assessed for all possible modes of damage, failure, and cracking and the impact of these modes on each other. Dam well-being must be inspected continuously, and existent damage and problems need to be corrected so that the structure well-being and, consequently, people's health and national asset remain preserved (Hariri-Ardebili and Mirzabozorg 2013, Mata *et al*. 2014, Salazar *et al*. 2015, Pisaniello and Tingey-Holyoak 2016, Omidi and Lotfi 2017). Arch concrete dams with high elevations store water resources in high volumes and produce energy (Akkose *et al*. 2008, Abaqus 2009, Perera *et al*. 2010). On the other hand, this big asset can put society under probable dangers when rupture and failure occur in it. Despite the point that arch dam failures have occurred rarely, these failure experiences have expressed this point that we cannot flee from catastrophe if we ignore dam working status and do not become assured from the safety of dam in utilization time (Akbari *et al*. 2011, Chopra 2012, Alembagheri and Ghaemian 2013, Chen *et al*. 2016). Crack in arch dams may appear due to various reasons, and there are a number of crack intensifying factors such as thermal loads, seismic loads, abutment impact, etc. (Altarejos-García *et al*. 2012, Hariri-Ardebili and Saouma 2016). Although, this research aims at evaluation of water penetration into fractures made by cracking and assessment of crack development risk induced by this problem.

The first effect of water penetration into crack or joint is the application of a large load in compressional form onto crack or joint wall and, consequently, increment of stress intensity ratio in first mode of failure on the crack tip (see Fig. 1). This effect of water pressure in crack is called "wedge split effect". This wide pressure does not have equal and monotonous load effect, and it can be affected by different features such as permeability of structure's concrete and opening of crack along the crack's length. On

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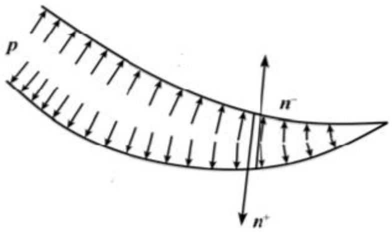


Fig. 1 Penetration of water inside the crack and applied pressure on cracked walls

the other hand, redistribution cycle and improvement of water pressure profile in the crack with advancement of crack will continue increasingly to reach stability condition (Sevim *et al*. 2013, Amina *et al*. 2015, Hariri-Ardebili *et al*. 2016). Experiments conducted on many mortar samples have shown that the effect of water pressure on creation and expansion of crack is 80%, which increases with the length of the crack (Valliappan and Chee 2009, Hariri-Ardebili and Seyed-Kolbadi 2015, Dias *et al*. 2016, Wang 2016, Wang *et al*. 2017, Chen *et al*. 2019, Hu and Wu 2019, Lin *et al*. 2019). However, in this research, penetration or non-penetration means it is occurring inside concrete body or toward cracked wall, respectively, and it differs with discussion of penetration in crack opening.

2. Similar incident in history of dam construction

In 1977, horizontal and progressive cracking appeared in all El Atazar arch dam head water covering in elevation of 30 meters higher than foundation (i.e., in worst possible point of arch dam body), due to over limit displacement of weak left-side abutment (Bruce and De Porcellinis 1991). Cracking spread into middle layer of the dam rapidly and finally was observed with the length of 45 meters inside the gallery. With growth of crack opening from 3 to 8 millimeters, water leakage reached to 9000 liters per minute from 1500 l/m. The crack was grouted with special resin using the Rodour method with a lot of effort in 90 m head water of reservoir and simultaneously with intense water flow. Nevertheless, abutment movement continued and resulted in smashing of contact location between the body and foundation of the dam. With severe increase of water flow in foundation, serious grouting in foundation was performed to stabilize its movement subsequently in following year (Visser 1999). This structure, which is considered a concrete dam with medium elevation, was an important case that was treated without discharging reservoir water (due to serious dependency of Spain's capital drinking water to the reservoir), with exceptional and unprecedented structural grouting. This grouting was performed with accepting higher-than-normal risks by an American-Spanish group made of most experienced experts in dam grouting. Nonetheless, this grouting did not result in permanent treatment, and the foundation behaviour was in need of excess measures such as water tight and consolidation grouting in coming years.

Table 1 Properties of rock and concrete materials

Elastic modulus (GPa)	20.68
υ	0.2
Density (Kg/m^3)	2403

3. Study method

The Morrow Point arch dam was selected for case study in this research. Two rows of 20 knots iso-parametric elements for the dam and 8 knots of iso-parametric elements for the foundation were used. Then, complete integrations were applied to both sets of elements. Analyses were done in two main sections. The first section included linear materials analyses on dam and foundation, and the second one involved analyses on non-linear behaviour of dam materials. The properties of rock and concrete materials are presented in Table 1.

The purpose of analyses in the first section was measuring the sensitivity of parameters that may impact dam safety and its working conditions from the researchers' point of view. These parameters included friction angle of cracking surface, depth of crack penetration in dam crust thickness, penetration and non-penetration of water, and length of the crack in section parallel to contraction joint in arch dam. The first three parameters were indeterminate for applied cracking, but the last parameter, which was determinate somewhat, was considered for the prediction of changes to cracked arch dam behaviour with the cracking length increment.

In this research, compressional and shear behaviour of dam contraction joints was modeled, and no tensile strength was assumed. For modeling joints behaviour in compression mode, eight node joint elements were analysed by means of penalty solution method, and in shear mode by coulomb frictional solution method. In each joint location, two surfaces, i.e., slave surface and master surface, were defined, which had surface-to-surface contact (Hibbitt *et al*. 2011). Characteristics of contraction joint element are given in Table 2.

Geometry of applied cracking to the Morrow Point dam included the cracking length and its thickness in the body of the arch dam. The cracking length had two parts: (1), Perpendicular to abutment; and (2), Parallel to contraction joint; their properties can be seen in Figs. 2(a)-(b). In addition, Figs. 2(c)-(d), (e), and (f), demonstrate the cracks 44, 35, full, and half penetration crack surface, respectively. This cracking was applied to dam thickness, and it was similar to contraction joints modeled by compressional-shear joint element (Momenzadeh *et al*. 2018, Koopialipoor *et al*. 2018).

Table 2 Characteristics of joint element in contraction joints

φ	τ_{max}	Elastic slip (mm)	$K_n(GPa/m)$
50°	8	2	Stiffness of adjacent volume element × 130

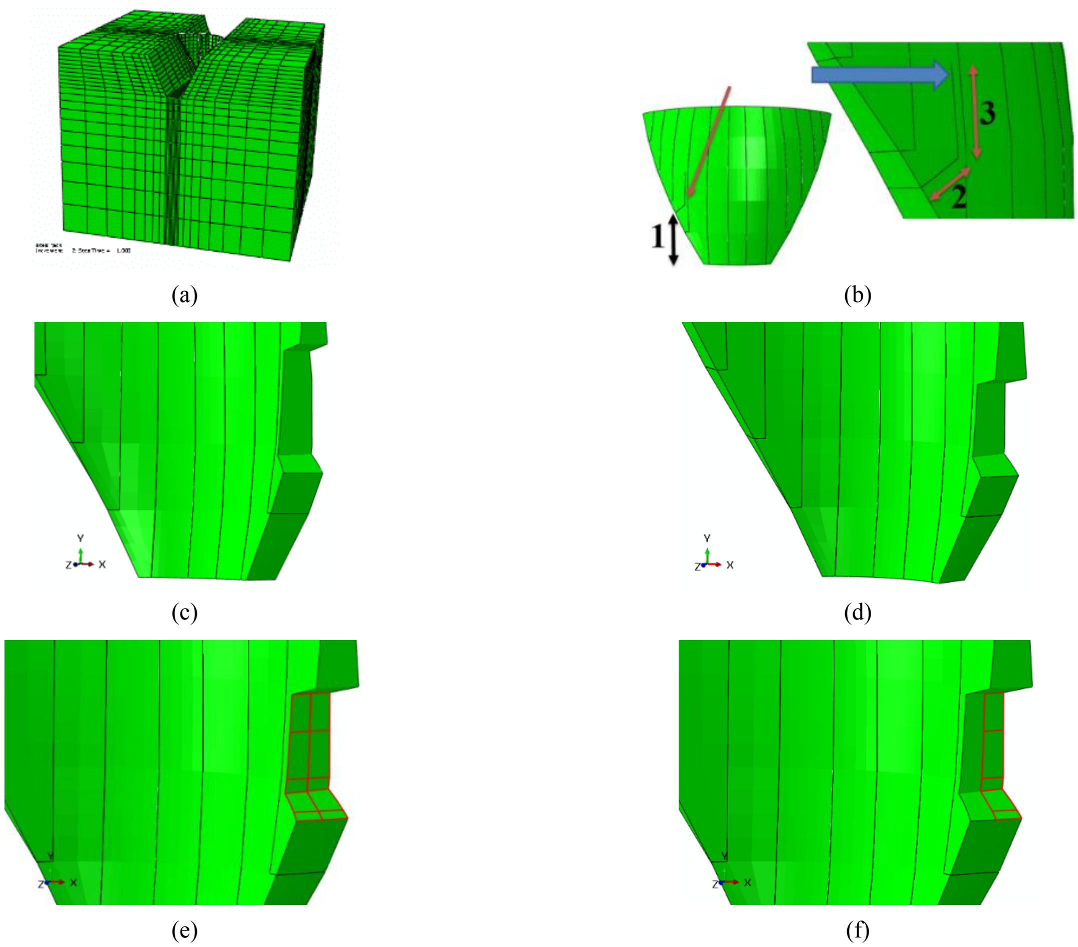


Fig. 2 Geometrical properties of dam, environment, and crack modeling (a) Finite element model of dam-foundation; (b) Geometry of cracking applied to the Morrow Point dam; (c) and (d) the crack 44 and 35 m, respectively; (e) and (f) the full and half penetration crack surface, respectively

The crack grew in two branches. Branch 1 was parallel to contraction joint, which is used and modeled in this research. Branch 2 was stopped by colliding to contraction joint. Branch 1, which has reached the upper section of the dam, would see water penetration into itself. This branch has a growth potential in the body of the dam; therefore, it is necessary to evaluate its growth and safety conditions.

4. Analyses

4.1 Under service loads, without crack

To clarify the dam working level in normal conditions and the displacements and structural stresses, and also to monitor the opening of contraction joints, it is needed to evaluate the dam under water weight and pressure (i.e., the main loads of the early utilization of a dam). The obtained results can be used in next comparisons.

4.2 Conditions for typical crack existence

There is not clear information about the amount of cracking and cracking properties such as thickness of crack, mechanical characteristics of crack planes, opening status of crack planes, etc. To cope with this challenge in this research, several groups of cracking were evaluated by considering different probable states. In the first group, in lieu of mechanical characteristics of crack plane, friction angles of planes were evaluated. Four friction angles of 0, 15, 25, and 50 degrees were evaluated. The zero-degree friction angle means the opening and separation of roughness from crack's both sides, which is probable in water presence. Other friction angles are common in the engineering field.

In the second group of analyses, the amount of crack penetration in the dam body thickness and its effect on dam working condition were evaluated. For this purpose, evaluations were performed in two sections: crack in half thickness of the dam body, and crack in the whole thickness of the dam body. The third group of analyses was about the impact of the crack's length on dam working conditions. In this group, the impact of crack's length was evaluated in two sections.

Loading conditions of these analyses groups are similar to non-damage dam conditions. The only difference is that an additional step was considered for observing the cracking impact. At this step, a new loading condition was added to current loading conditions on the dam.

4.3 Conditions for typical crack existence and water penetration

In this section, the process of water penetration into cracks is examined. For all analyses explained in the previous section, the effect of water penetration, in the form of water pressure equal to hydrostatic head of dam, which is applied to crack planes under study, was investigated.

5. Results and discussion

For simplification and abbreviation of each case evaluated, a label consisting of three numerical sections (digits), for each of the studied sections is considered. In this label, the first digit represents the presence of water (1), or non-presence of water (0), the second digit shows the depth of penetration of cracking plane in the dam body thickness, which includes: full-penetration depth in the dam body thickness (1), or half-penetration depth (0.5). Finally, the third digit represents the length of cracking parallel to contraction joint for evaluation of crack's length on safety of the dam, which includes 35 and 44 m lengths. For example, the study case of "1-0.5-44" means a 44 meter-crack parallel to contraction joint with the crack penetration depth of half of the dam body in the presence of water. First, the maximum compressional and tensile stresses in the dam were evaluated.

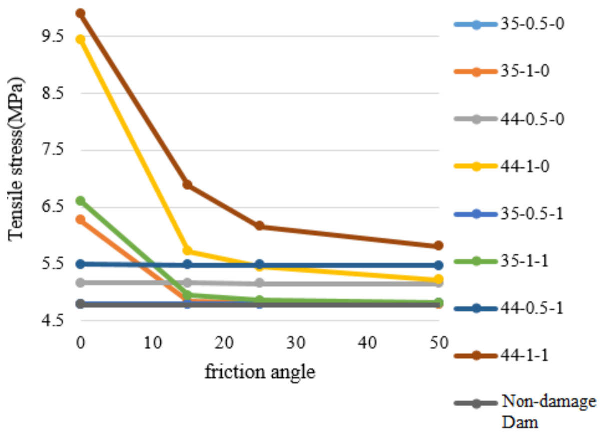


Fig. 3 Maximum tensile stress produced in the dam for different proposed friction angles in the cracking plane

In the cracked cantilever for two sides of crack plane (upper and lower inclined sections of the cracking perpendicular to the abutment), the lower section tolerates higher water pressure (due to great value of water pressure on upstream of the dam), and this higher water load causes more movement of lower plane relative to the upper plane. More movement of the lower plane and, consequently, movement of lower part of cracked cantilever and bounding of this section in junction location of the abutment and its griping effect, all will result in increment of rotation of this section. This brings increment of the bending moment in this location. As a result, the tensile stresses in upper section of this location (Fig. 3), and the compressional stresses in lower section of this location (Fig. 4), which are the cantilever spring location, will increase.

However, it is necessary to mention that this increasing trend occurs for the full depth of the crack penetration in the dam thickness; and in the half depth crack penetration, the mentioned movements do not occur or occur only at a limited level. The increase of tensile or compressional stresses cannot be seen in the dam in this state.

Another factor that amplifies stresses in this section is opening of the crack spout (Fig. 5), which is in the conjunction location of the dam abutment. As it was seen in the first section, this region, in its upper section, has tensile stress that is the maximum amount of tensile stress in the dam. With non-linear acting of the crack plane and inability of tolerating the tensile stress in this plane, the stress produced in this region in location of plane goes away and tensile stress is divided into two sides. But after the division, it can be seen that the stress share in lower section increases; therefore, the location of maximum tensile stress in dam would be in this section. On the other hand, the tensile stress increment will appear and alert the appropriate increment of these two stresses. This increasing trend of the stress in full penetration depth is not too much; it is up to the value of 15 degrees in friction angle (0.5 MPa for tensile stress and 1 MPa for compressional stress). However, for reduction (drop), of friction ratio to zero value, which is

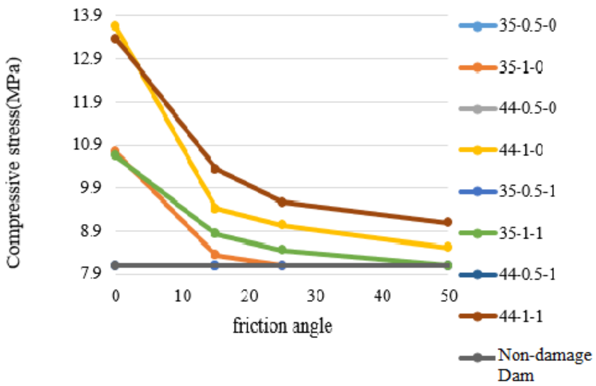


Fig. 4 Maximum compressional stress produced in the dam for different proposed friction angles in the cracking plane

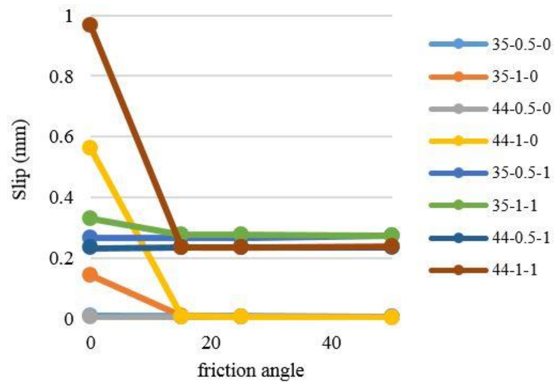


Fig. 5 Maximum opening of crack plane spout for different friction angles considered on the cracking surface

related to zero friction angle, the increasing trend of stress would be significant.

It seems that in the most of crack plane points, shear stress tolerance of the crack plane in friction angles of more than zero is higher than shear stress produced in the plane. Thus, slips in these crack plane points were limited in the range of elastic slips (with slip values of less than 2 mm). As a result, only a small increment of tensile stress of crack plane was observed (around 0.5 MPa), in the angles between 15 to 50 degrees, and no special difference was seen in changing pattern of the crack plane movement except the slip value of lower plane that increased in smaller angles. However, with getting close to zero shear stress in the crack plane, slips increased greatly in this plane, which resulted in two phenomena. The first one was related to intense increment of tensile and compressional stresses in the cantilever spring, which reduced the safety factors of tensile and compressional stresses of concrete in this region, and even introduced it to the destruction zone. The second one was related to the increment of tensile stress in crack tip in a section parallel to contraction joint. With adding the force of penetrated water into the crack, tensile stress increment in the crack tip will be tangible.

But in other cantilevers, the dam stress pattern and stress values and also contraction joint movement have not changed sensibly considering the friction angle between contraction joints was stable and in 50 degrees value. The stress values in all the cases of sensitivity measurement were almost equal and they did not change considerably by decreasing friction angle of the crack plane and increasing of stresses in the cracked cantilever spring. This means that the cracking has less impact on other dam cantilevers even with having a probable nature, including different friction angles of the crack plane, water penetration into it, crack penetration depth in the body of dam, and also length of perpendicular section of crack that is parallel to the contraction joints. Cracking impact on other dam cantilevers is low and can be neglected in the worst case. More events of opening of the crack plane cause cracked cantilever to lose its curvature (arch), effect, and bearing capacity mechanism of cantilever gets activated. This point causes unusual increments of stresses in the cracked cantilever.

With decreasing friction angle of the crack surface, critical shear stress value τ_{cri} decreases for slip of crack plane, hence slipping more points of crack plane. This happens due to stable shear stresses originated from loading on the crack plane. These slips provide suitable ground for openings in more points, and bearing capacity mechanism of cantilever overcomes this cracked cantilever and, consequently, stresses in spring location of cantilever will increase.

Nevertheless, investigations show that this section is under pressure before cracking happens, and with inducing of crack plane, it causes more pressure in the crack planes. This pressure is the main obstacle to growth of the crack in its tip located above the vertical section of the crack.

In cases where crack penetration depth is half of the dam thickness, openings of the crack plane do not intervene in bearing capacity of the curvature (arch), in this region (even with penetration of water into the crack and application of pressure on it). This is because in lower section of the crack, dam preserves its solidarity state, while compressional stresses still exist in the body of dam. The openings in upper section of the crack do not add considerable stress to stresses of the cracked cantilever spring.

5.1 Stress safety factor against concrete failure

Failure criteria of Kupfer-Gerstle (1973), was used to calculate the safety factors of the dam body (Fig. 6), (Kupfer and Gerstle 1973).

Safety factor was calculated as explained above for different behaviours of crack to which sensitivity measurement was applied in previous sections. For cantilevers in which cracks did not intervene, average reduction percentages of safety factors in integration points are very low (Fig. 7). Safety factors were obtained for cantilever that had cracking, and safety factors reduction

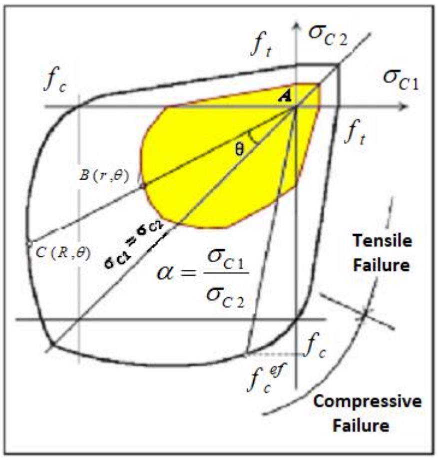


Fig. 6 Kupfer-Gerstle Failure envelope (Kupfer and Gerstle 1973)

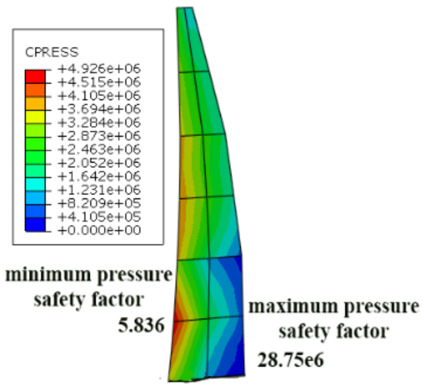


Fig. 7 Pressure distribution on the surface between the third and fourth cantilever around the central cantilever under weight loading, water pressure, and water penetration in the crack loading, and obtaining maximum and minimum of the compressional safety factor

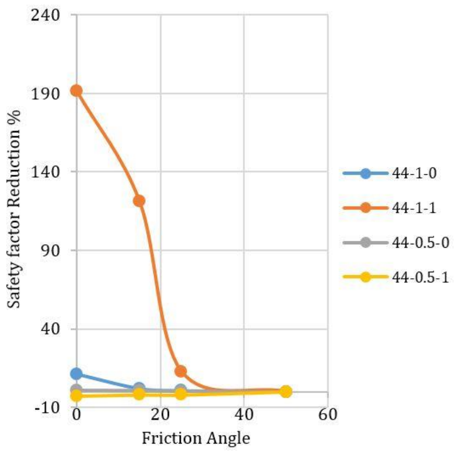


Fig. 8 Comparison of percentages of the safety factor reduction in the cantilever containing a 44-meter crack for different states of crack and water penetration in the first section of the cantilever

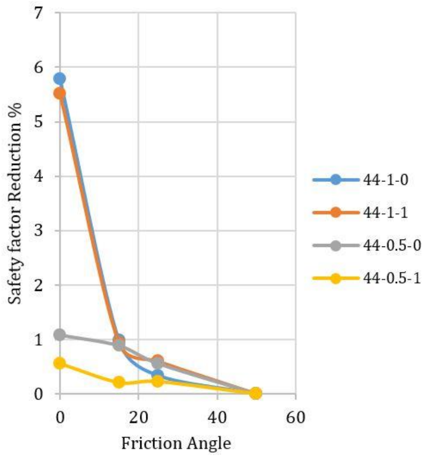


Fig. 9 Comparison of percentages of the safety factor reduction in the cantilever containing a 44-meter crack for different states of crack and water penetration in the second section of the cantilever

(Figs. 8-10), offered different explanations for other cantilevers. The cantilever was divided into two sections after the cracking. The lower section was called cracked cantilever and the upper section of cantilever crack plane was assigned with a name (label). For a crack of 44 m, safety factors of these two sections of cantilever for the upper and lower sections were calculated, and then the obtained results from averaging safety factors were compared to the state of the dam without crack. Results showed that in the crack penetration depth equal to the half of the dam body thickness, very low reductions even with low friction angle happened, and water penetration into the cracks did not occur. On the other hand, with the increase of the crack penetration to the whole thickness of the dam body, the reduction percentages increased in the first section of cantilever and reached to two or three times with adding water pressure inside the crack. It showed that these cracks were dangerous. Considerable reductions did not occur for the upper section of cantilever in the mentioned state. But negative reduction percentages showed increment of safety factor in the table due to decrement of stress level.

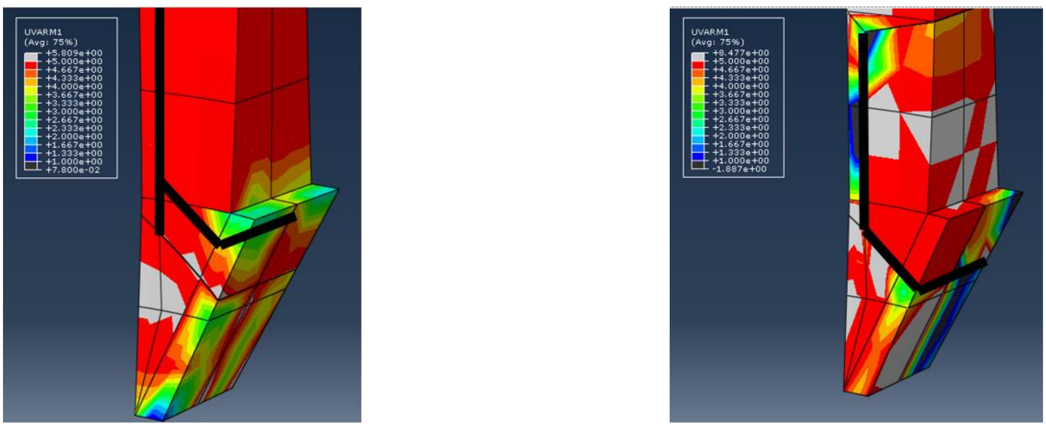
5.2 Safety factors related to the contraction joints

Contraction joints, which show compressional-shear behavior, must satisfy required safety factors against the compressional and shear stresses. These safety factors in joint surfaces are obtained using the Mohr-Coulomb criteria shown below

$$(\sigma_t = \sqrt{\sigma_1^2 + \sigma_2^2} \rightarrow (S.F.)_s = \frac{\sigma_n \tan\phi}{\sigma_t}) \tag{1}$$

$$\left((S.F.)_c = \frac{f_c}{\sigma_n}\right) \tag{2}$$

In these relations, σ_t is equivalent shear stress in the crack plane, σ_n signifies the compressional stress applied to the crack plane, f_c is compressional strength of concrete, and ϕ denotes the friction angle of the crack plane used for calculation of safety factors.



(a) (b)

Fig. 10 Safety factor changes for the cracked cantilever with a 35-meter crack and full penetration depth in the crust thickness with water pressure on the crack surface: (a) end of construction phase (weight load); (b) after application of the loads of weight, water pressure, and water penetration into the crack

For different models evaluated in the previous sections, the safety factor values for all of the contraction joints were similar with little difference and had suitable safety level. It was observed that the contraction joints had high safety factors under pressure even with non-usual water pressure loading inside the crack. In the lowest states, compressional safety factor of 5.836 is present in the contraction joint between the third and fourth cantilevers from both sides of the central cantilever (see Fig. 7). The same results are observed for shear safety factor of joint surfaces in different states.

It can be seen that shear safety factors of joint surfaces were in good standing; in the worst state, it was 2.5 for normal and non-usual loading of dam, which seems to be an appropriate value. The region that shows the safety factor of 2.5 is not a big area and the remaining safety factors are located in the bigger areas (Fig. 11).

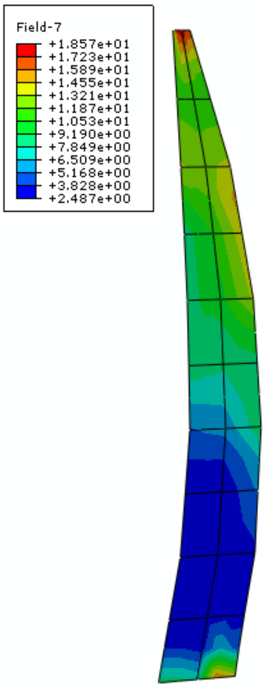


Fig. 11 Distribution of shear safety factor on the joint plane of the central cantilever and adjacent cantilevers under the loading of weight, water pressure, and water penetration inside the crack

5.3 Safety factors of the crack plane

There are two compressional and shear safety factors for the crack plane similar to joint planes obtained by equations provided in the previous section. These safety factors are calculated for different states of presence and non-presence of water inside the crack. However, to be brief, results for more critical states of water presence in the crack are shown graphically. They can be generally explained as follows. For models in which the crack is penetrated to the half of thickness, comparison of the compressional stresses of the crack surface showed that the pressure inside the crack surface remains almost stable. Therefore, compressional safety factor for this group of cracks stands in safer zone of the compressional stress of concrete. For 44-meter crack, the minimum compressional safety factor in maximum pressure of 3.441 MPa was obtained around 8.35, which shows that such cracks present higher safety factor against pressure (Fig. 12). For shear safety factors, the following comparison can be discussed. In friction angle of 50 degrees, range of safety factors with values less than 5 represents a very small area, which means this angle is in good standing from the safety aspect. Friction angles of 15 and 25 degrees showed similar situations, and an area in vertical section of crack showed a safety factor of 3. Accordingly, it can be concluded that with decrement of friction angle in this group of cracks, their working conditions deteriorate. These cracks are safe against shear stress considering the above points. For friction angle of zero, there is no safety factor for slip and shear stress (Fig. 13).

In case of 35-meter crack, values for maximum pressure on the crack surface and minimum compressional safety factors are equal to 2.443 MPa and 11.7, respectively, which shows safety of this group of the cracks against the pressure loadings. In friction angle of 50 degrees, due to produced shear stresses under the friction effect in the crack surface, the denominator of safety factor increased, while the safety factor decreased. The contoured region showed an area with safety factor of less than 5. The minimum safety factor for this state was 0.4, which showed weakness of the crack surface against shear stress. For friction angles of 15 and 25 degrees with decrement of shear stresses of the crack surface, the denominator of safety factors decreased, whereas the safety factors increased. It is true that minimum safety factors in these two cases are close to 0.4; though,

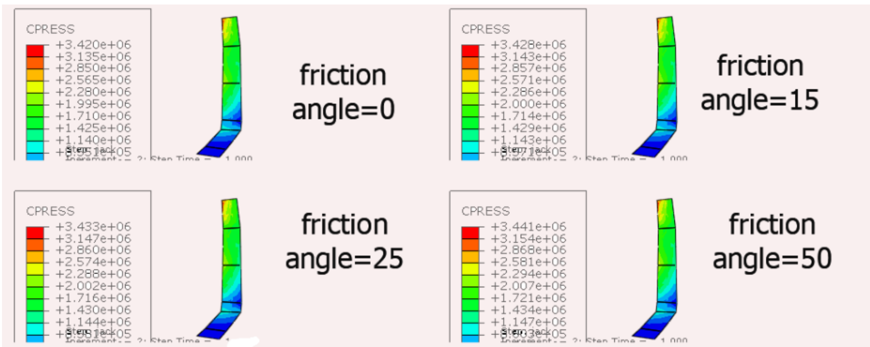


Fig. 12 Distribution of the crack plane pressure for depth of penetration equal to the half of crust thickness and elevation of 44 meters with different friction angles

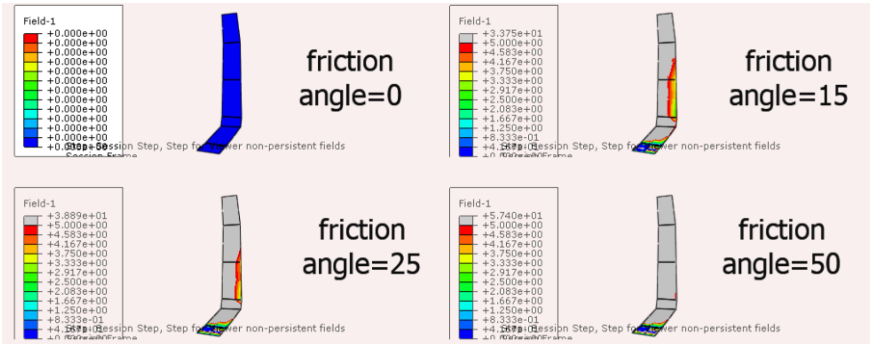


Fig. 13 Shear safety factor of 44-meter crack plane for the depth of penetration equal to the half of crust thickness and with different friction angles

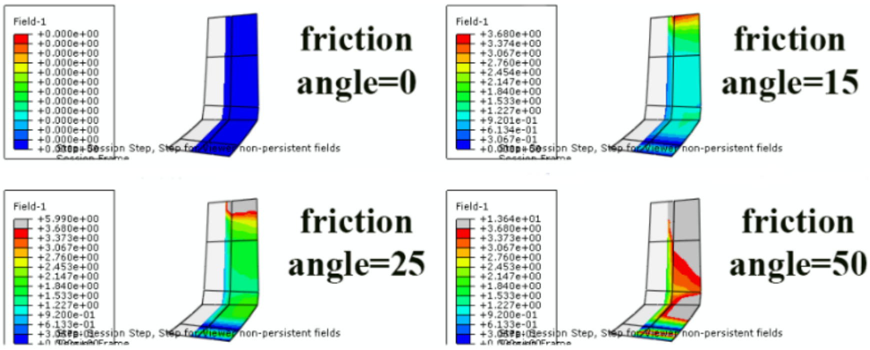


Fig. 14 Shear safety factor for the upper section of the 35-meter crack with full penetration depth in the crust thickness and in different friction angles

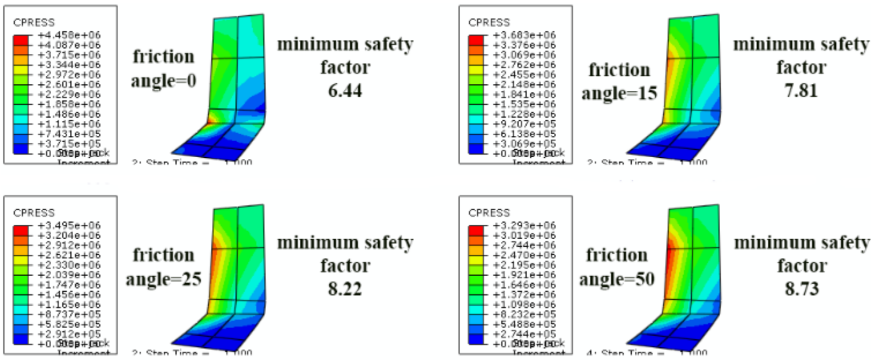


Fig. 15 Pressure distribution and location of the minimum compressional safety factor for the 35-meter crack with full penetration depth inside the body of the dam

area that the crack surfaces have a safety factor of less than 3 is a big area compared to friction angle of 50 degrees. It provides suitable conditions for these two friction angles. Zero friction angle that does not have numerator and denominator of safety factor (both zero), cannot show strength and safety against the shear stress, which results in lower safety levels. But for the cracks that are penetrated into the whole dam thickness, the following results can be discussed.

For this group of 35-meter cracks with the decrement of friction angle of the crack, safety factor against the pressure will decrease in the crack surface (Fig. 15); however, even with this decrement, safety level will stay high for the crack surface against the pressure. For the upper section of the crack, with decrement of the friction angle, safety factors will decrease, too. There is a suitable safety level against the shear stress for friction angle of 50 degrees (Fig. 15). However, for friction angle of 25 degrees, safety factors will see considerable decrement in such a way that their general distribution is around 2, which is considered a boundary for non-usual loading. Friction angle of zero will not have any strength against slip, as it can be expected. For the lower section of the dam, for friction angle of 50 degrees, the above safety factors can be observed. With decrement of the friction angle, safety factors will decrease, and for 15 and 25 degrees, safety factors will stand in the

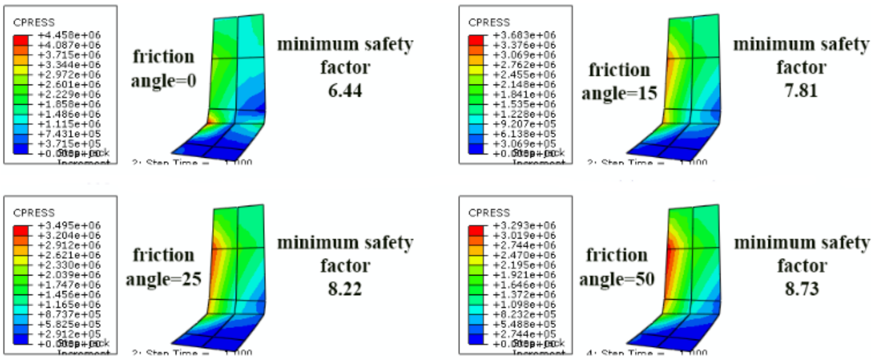


Fig. 15 Pressure distribution and location of the minimum compressional safety factor for the 35-meter crack with full penetration depth inside the body of the dam

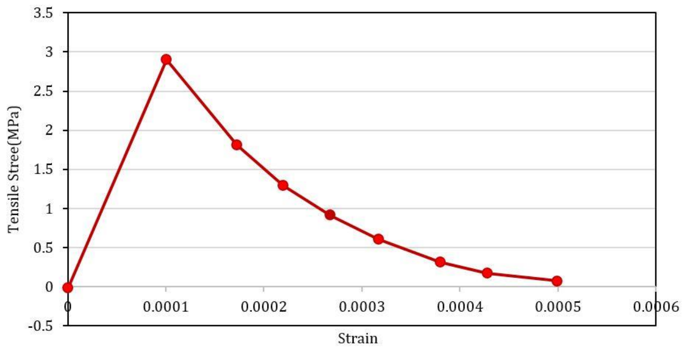


Fig. 16 Non-linear stress-strain graph of concrete used in the non-linear analysis

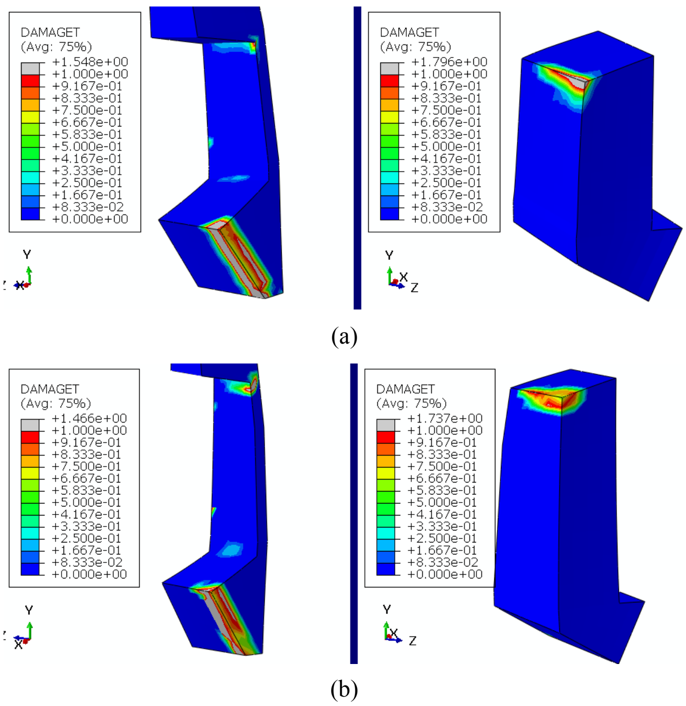


Fig. 17 Tensile damage contour of the 35-meter and 44-meter crack (lower part) with full penetration depth in the crust thickness in crack plane state, which has no friction

range of 1.5 to 2.5. For 44-meter crack in the compressional state, safety factors stay high, which shows this crack has a suitable safety level against pressure. For the upper section of this crack, except in friction angle of 50 degrees, which shows suitable safety factor, with decrement of the friction angle from 25 degrees to 0, safety factors will decrease. It happens in such a way that even for friction angle of 25 degrees, there is no suitable safety factor for providing safe dam status. Conditions in the lower section of dam is similar to the upper section of the crack and for friction angles of lower than 50 degrees, a safe status for the crack surface against the shear stress and slip cannot be seen.

6. Evaluation of crack growth in the dam and stresses of abutment

Considering that analyses only discussed the reduction of safety factor and crack growth danger, which provides an important engineering judgement for future of the dam, the goal was not set to analysis of procedure and amount of crack growth; only the danger threshold was evaluated. Since this crack with its development will decrease the safety factors, non-linear analysis of concrete materials (Alembagheri and Ghaemian 2016) (Fig. 16), was applied for the crack in full thickness cracking of the dam. This was done so that the possibility of development and growth of this crack can be evaluated. Gray sections in the contours of concrete damage are due to extrapolation error from software, which has been reduced to number one for display purpose.

Damage in the crack tip can be seen in analyses related to zero friction angles, which shows possibility of crack growth and development in these conditions (Fig. 17). The first point is related to the reduction of the foundation shear safety due to increase of Von-Mises stresses in the connection location of the dam and foundation in the cracked section. The second point is related to the increment of displacements in this section, which is undoubtedly important in the dam behaviour.

7. Conclusions

This study examines the specific conditions of a cracked dam against water pressure. Studies have shown that the arch dam has been able to maintain its stability and survive in the event of a damage. In case of a crack which penetrates only the half- thickness of the dam, the dam continues to behave almost like an undamaged dam. In the face of another crack, which penetrates into the full thickness of the dam, except when the friction of the cracking planes is zero, the dam could be safe.

The only cases where dangerous behavior is observed in the dam are related to the friction coefficients of zero. Studies with non-linear concrete materials and considering the damage index have also tested the possibility of crack growth. The desire to expand the crack at its tip is also a confirmation of the claim that in this case, the behavior of the dam will be dangerous and will require special arrangements for repair and care. Furthermore, the growth of stresses related to the abutment at the connection area of the crack indicates the unsafe behavior of the dam. Finally, the capability of this simulation can be used as a suitable method for analyzing the safety factor of different structures.

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Conflicts of interest

The authors declare no conflict of interest.

References

Abaqus, F.E.A. (2009), ABAQUS analysis user's manual, Dassault Syst Vélizy-Villacoublay, France.

Akbari, J., Ahmadi, M.T. and Moharrami, H. (2011), "Advances in concrete arch dams shape optimization", *Appl. Math. Model.*, **35**, 3316-3333. https://doi.org/10.1016/j.apm.2011.01.020

Akkose, M., Bayraktar, A. and Dumanoglu, A.A. (2008), "Reservoir water level effects on nonlinear dynamic response of arch dams", *J. Fluids Struct.*, **24**, 418-435. https://doi.org/10.1016/j.jfluidstructs.2007.08.007

Alembagheri, M. and Ghaemian, M. (2013), "Damage assessment of a concrete arch dam through nonlinear incremental dynamic analysis", *Soil Dyn Earthq Eng.*, **44**, 127-137. https://doi.org/10.1016/j.soildyn.2012.09.010

Alembagheri, M. and Ghaemian, M. (2016), "Seismic performance evaluation of a jointed arch dam", *Struct. Infrastruct. Eng.*, **12**, 256-274. https://doi.org/10.1080/15732479.2015.1009124

Altarejos-García, L., Escuder-Bueno, I., Serrano-Lombillo, A. and de Membrillera-Ortuño, M.G. (2012), "Methodology for estimating the probability of failure by sliding in concrete gravity dams in the context of risk analysis", *Struct Saf.*, **36**, 1-13. https://doi.org/10.1016/j.strusafe.2012.01.001

Amina, T.B., Mohamed, B., André, L. and Abdelmalek, B. (2015), "Fluid–structure interaction of Brezina arch dam: 3D modal analysis", *Eng. Struct.*, **84**, 19-28. https://doi.org/10.1016/j.engstruct.2014.11.011

Bruce, D.A. and De Porcellinis, P. (1991), "Sealing cracks in concrete dams to provide structural stability", *Hydro Rev.*, **10**, 116-124.

Chen, B., Gu, C., Bao, T., Wu, B. and Su, H. (2016), "Failure analysis method of concrete arch dam based on elastic strain energy criterion", *Eng. Fail. Anal.*, **60**, 363-373. https://doi.org/10.1016/j.engfailanal.2015.11.045

Chen, B., Hu, T., Huang, Z. and Fang, C. (2019), "A spatio-temporal clustering and diagnosis method for concrete arch dams using deformation monitoring data", *Struct Heal Monit.*, **18**, 1355-1371. https://doi.org/10.1177/1475921718797949

Chopra, A.K. (2012), "Earthquake analysis of arch dams: factors to be considered", *J. Struct. Eng.*, **138**, 205-214. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000431

Dias, I.F., Oliver, J., Lemos, J.V. and Lloberas-Valls, O. (2016), "Modeling tensile crack propagation in concrete gravity dams via crack-path-field and strain injection techniques", *Eng. Fract. Mech.*, **154**, 288-310. https://doi.org/10.1016/j.engfracmech.2015.12.028

Hariri-Ardebili, M.A. and Mirzabozorg, H. (2013), "A comparative study of seismic stability of coupled arch dam-foundation-reservoir systems using infinite elements and viscous boundary models", *Int. J. Struct. Stab. Dyn.*, **13**, 1350032. https://doi.org/10.1142/S0219455413500326

Hariri-Ardebili, M.A. and Saouma, V.E. (2016), "Probabilistic seismic demand model and optimal intensity measure for concrete dams", *Struct Saf.*, **59**, 67-85.

https://doi.org/10.1016/j.strusafe.2015.12.001
Hariri-Ardebili, M.A. and Seyed-Kolbadi, S.M. (2015), "Seismic cracking and instability of concrete dams: Smeared crack approach", *Eng. Fail. Anal.*, **52**, 45-60. https://doi.org/10.1016/j.engfailanal.2015.02.020
Hariri-Ardebili, M.A., Saouma, V.E. and Porter, K.A. (2016), "Quantification of seismic potential failure modes in concrete dams", *Earthq. Eng. Struct. Dyn.*, **45**, 979-997. https://doi.org/10.1002/eqe.2697
Hibbitt, H., Karlsson, B. and Sorensen, P. (2011), Abaqus analysis user's manual version 6.10, Dassault Systèmes Simulia Corp Provid RI, USA.
Hu, J. and Wu, S. (2019), "Statistical modeling for deformation analysis of concrete arch dams with influential horizontal cracks", *Struct. Heal. Monit.*, **18**, 546-562. https://doi.org/10.1177/1475921718760309
Koopialipoor, M., Tootoonchi, H., Marto, A., Faizi, K. and Jahed Armaghani, D. (2018), "Various effective factors on peak uplift resistance of pipelines in sand: a comparative study", *Int. J. Geotech. Eng.*, 1-8. https://doi.org/10.1080/19386362.2018.1482987
Kupfer, H.B. and Gerstle, K.H. (1973), "Behavior of concrete under biaxial stresses", *J. Eng. Mech. Div.*, **99**, 853-866.
Lin, P., Guan, J., Peng, H. and Shi, J. (2019), "Horizontal cracking and crack repair analysis of a super high arch dam based on fracture toughness", *Eng. Fail. Anal.*, **97**, 72-90. https://doi.org/10.1016/j.engfailanal.2019.01.036
Mata, J., Leitão, N.S., De Castro, A.T. and Da Costa, J.S. (2014), "Construction of decision rules for early detection of a developing concrete arch dam failure scenario. A discriminant approach", *Comput. Struct.*, **142**, 45-53. https://doi.org/10.1016/j.compstruc.2014.07.002
Momenzadeh, M., Koopialipoor, M. and Mansoori, M. (2018), "Determination of the racking reduction factor in a horseshoe shaped tunnel section considering the soil-structure interaction", *Geotech. Geol. Eng.*, **36**(6), 3903-3910. https://doi.org/10.1007/s10706-018-0581-0
Omidi, O. and Lotfi, V. (2017), "A symmetric implementation of pressure-based fluid–structure interaction for nonlinear dynamic analysis of arch dams", *J. Fluids Struct.*, **69**, 34-55. https://doi.org/10.1016/j.jfluidstructs.2016.12.003
Perera, R., Barchín, M., Arteaga, A. and De Diego, A. (2010), "Prediction of the ultimate strength of reinforced concrete beams FRP-strengthened in shear using neural networks", *Compos. Part B Eng.*, **41**, 287-298. https://doi.org/10.1016/j.compositesb.2010.03.003
Pisaniello, J.D. andt Tingey-Holyoak, J.L. (2016), "Best practice land use planning and cost-effective tools to assure safety downstream of private dams", *Water Resour.*, **43**, 730-742. https://doi.org/10.1134/S0097807816040126
Salazar, F., Toledo, M.A., Oñate, E. and Morán, R. (2015), "An empirical comparison of machine learning techniques for dam behaviour modelling", *Struct. Saf.*, **56**, 9-17. https://doi.org/10.1016/j.strusafe.2015.05.001
Sevim, B., Altunisik, A.C. and Bayraktar, A. (2013), "Structural identification of concrete arch dams by ambient vibration tests", *Adv. Concrete Constr., Int. J.*, **1**(3), 227-237. https://doi.org/10.12989/acc2013.1.3.227
Valliappan, S. and Chee, C. (2009), "Ageing degradation of concrete dams based on damage mechanics concepts", In: *Computational Structural Engineering*, Springer, pp. 21-35. https://doi.org/10.1007/978-90-481-2822-8_3
Visser, J.H.M. (1999), *Extensile hydraulic fracturing of (saturated), porous materials*.
Wang, R. (2016), "Key technologies in the design and construction of 300 m ultra-high arch dams", *Engineering*, **2**, 350-359. https://doi.org/10.1016/J.ENG.2016.03.012
Wang, G., Wang, Y., Lu, W., Yu, M. and Wang, C. (2017), "Deterministic 3D seismic damage analysis of Guandi concrete gravity dam: A case study", *Eng. Struct.*, **148**, 263-276. https://doi.org/10.1016/j.engstruct.2017.06.060

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