Grouting of cracks in concrete dams: numerical modelling and structural behaviour

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Summary

Grouting is often considered to reinstate water tightness and displacement continuity in cracked concrete dams. Grouting alters the state of stress, deformation, and the strength of a dam in many ways. The state of stress prior to grouting is altered by the injection pressure that often increases the crack opening. This new state of stress will be 'locked-in' as the grout sets. Excessive injection pressure may also induce hydro-fracturing. Obviously, composite action of structurally repaired cracks will be fully effective only for incremental load applications occurring after the completion of the grouting programme.

The state-of-practice concerning structural response of cracked dams during and after grout injection is reviewed in this paper. The existing methods for structural analysis of dam rehabilitation by crack grouting, and the required modifications for modelling the hardened grout in the repaired dam are discussed. State-of-the-art techniques using contact elements are defined (i) to model the hardened grout in cracks of repaired dam; and (ii) to investigate the structural response of the rehabilitated dam to subsequent loading conditions. A 90 m high-gravity dam is considered in comparative analyses for numerical simulations of the incidence of grouting on the structural responses of cracked dams.

Key words: concrete dams; dam repair; crack grouting; numerical modelling; distinct element method

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Introduction

Due to the low tensile strength of concrete, massive unreinforced concrete dams are likely to experience cracking. Grouting is the most common repair/strengthening action undertaken to improve the performance of concrete dams with cracks and/or leaking joints. The objective might be just to seal a crack that is acting as a naturally formed joint, or to seal and provide a structural repair that will reinstate strength and displacement continuity in the dam body. Grouting is thus used to stop or slow down the deterioration process and to increase, if possible, the safety of the dam. Table 1 presents a list of some cracked dams that have been repaired by grouting[1]. Since grouting does not remove by itself the cause of cracking, it may be used in combination with other repair/strengthening strategies to remove or accommodate the cause of cracking and to provide an effective long-term crack repair.

The development of a grouting program to repair a cracked concrete dam obviously requires the consideration of several aspects related to the incidence of grouting on the dam structural behaviour. Some basic questions to be examined (Fig. 1) are: (i) at which crack opening, and related reservoir elevation /seasonal temperature condition, should grouting be performed? (ii) what is the allowable injection pressure to avoid hydro-jacking and/or hydro-fracturing ? (iii) what is the magnitude and spatial distribution of the internal stress field after setting of the grout ? (iv) what is the incidence of subsequent variations in reservoir elevation on the internal stress field of the grouted dam ? (v) what would be the response of the grouted dam to floods and earthquakes ? Structural analyses of the dam–foundation–reservoir (DFR) system should be performed to investigate the effect of grouting during the different phases of the grouting process. Therefore, the structural response of cracked dam

Table 1 Repaired dams by grouting

Dam Type Location	Height (m)	Cause of cracks	Injection type	Injection pressure (Mpa)	Remarks	Reference
Zeuzier arch Switzerland	156	Subsidence of foundation	Epoxy resin	1–4	Injection successful	[22,23]
Flumendosa arch Italy	115	Thermal stress	Epoxy resin	1–6	Restoration of continuity of cracked dam	[9,10]
Zillergründl arch Austria	186	Uplift pressure due to infiltration of water in joints	Epoxy resin	5–18	Secondary cracks due to high injection pressure	[24]
Daniel-Johnson multiple arch Canada	215	Geometry of structure and thermal stress	Microfine cement with superplasticizer	1.15–2	No water seepage through cracks after grouting	[8]
Kölnbrein arch Austria	200	Geometry of structure	Epoxy resin	3	Utilization of GIN method	[25]
Isle-Maligne gravity Canada	43	Deterioration of the construction joints	Cement grout with microfine cement	0–5	Crack hydro-jacking during injection	[7]
Sefid-Rud buttress Iran	106	Earthquake	Epoxy resin	6–10	Perfect bonding of fissure by resin grouting	[26]
Big Eddy buttress Canada	44	Deterioration and leaching of horizontal construction joints	Cement grout	Effective pressure+ 0.7 kPa	Successful grouting with some minor seepage	[5]

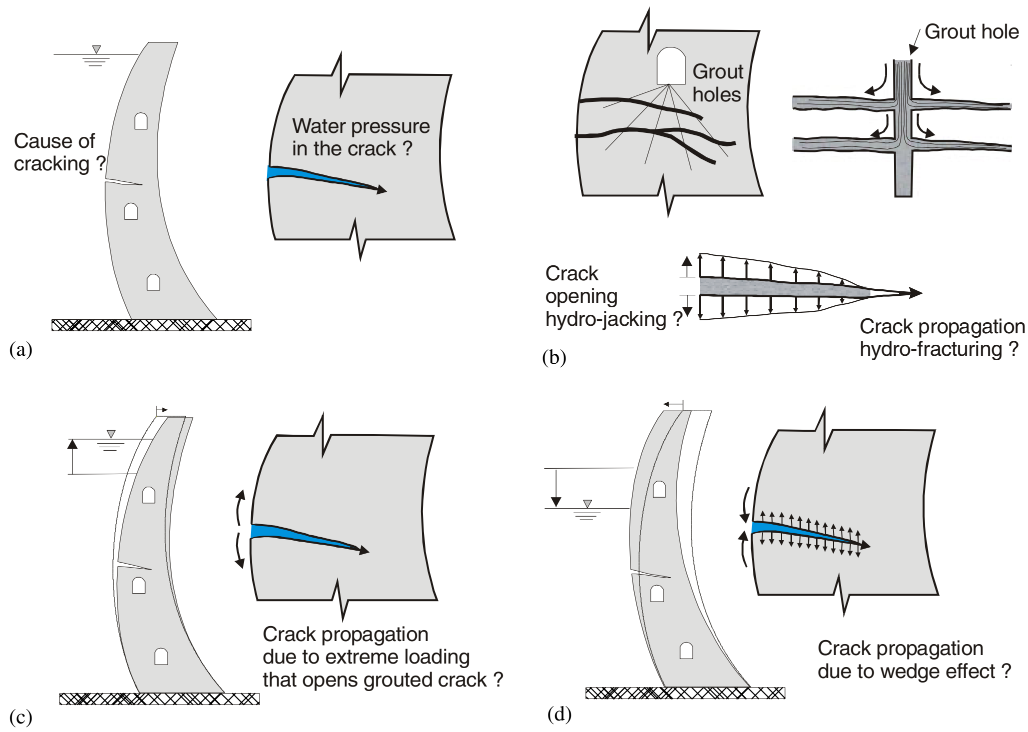

Fig. 1 Structural response of dam during and after the grouting process: (a) cracked dam; (b) injecting grout in cracks; (c) crack propagation; (d) wedge effect

before grouting (existing condition), during grout injection, during grout hardening, and the structural response of rehabilitated dam (after grout hardening) due to any possible loading changes, should be determined (Fig. 2).

Nonlinear finite element analysis is a common method to simulate dam cracking response which is considered an existing condition for the grouting process. The simulation of grout injection in cracks requires a coupled hydro-fracture analysis, but due to

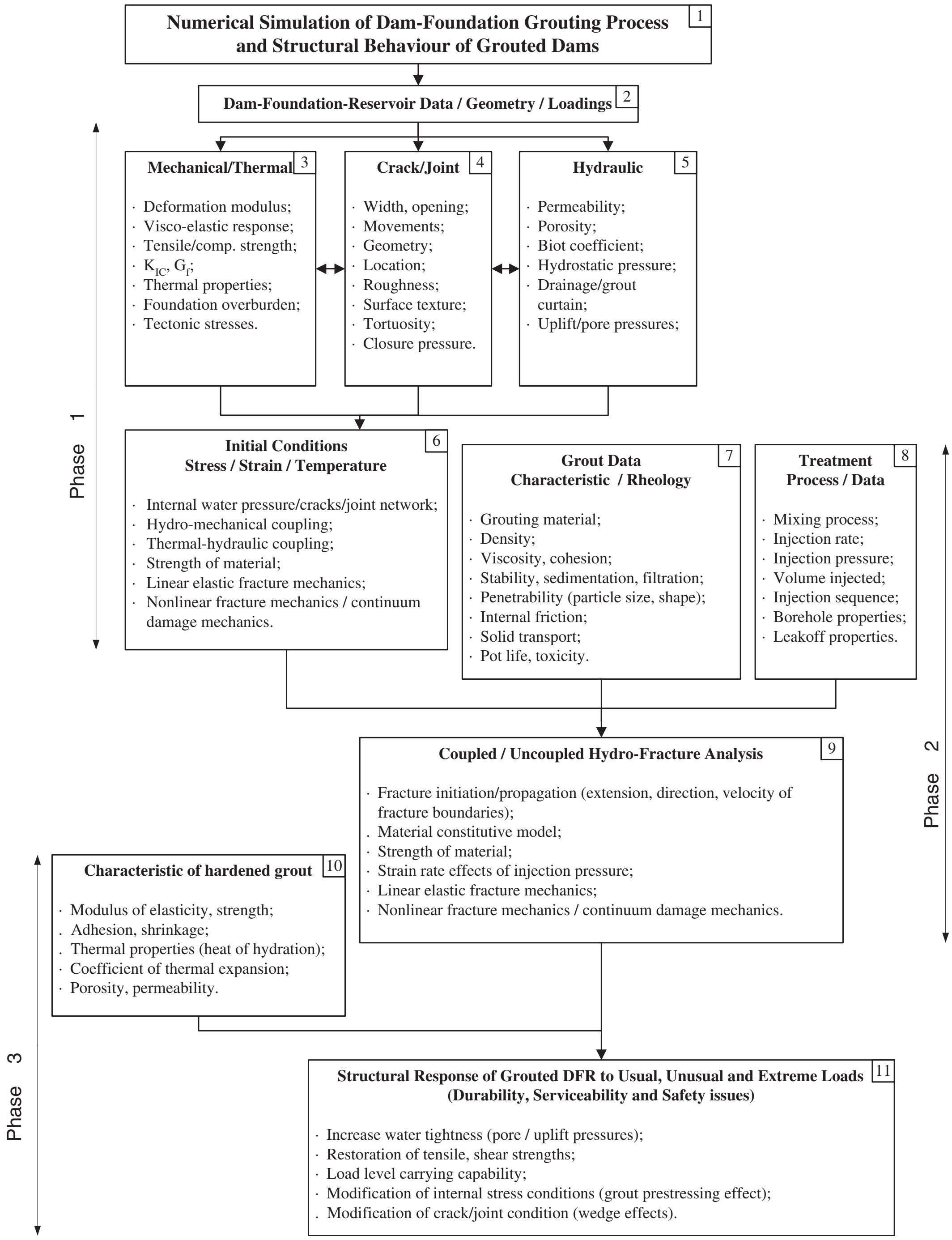

Fig. 2 Numerical simulation of grouting process and structural behaviour of grouted dams

the complexity of the problem a combination of field tests with numerical computations is often used. Field or laboratory tests are used to determine allowable injection parameters. In the state-of-practice, nonlinear finite element analysis (without hydro-fracture coupling effect) is used to determine some allowable response criteria that should be checked during the course of injection to prevent crack propagation. Finally the structural response of the dam after grout setting is determined assuming monolithic behaviour of the repaired dam. The need for numerical methods to simulate more accurately cracked dam structural response during the different phases of the grouting process is obvious. Solid contact (gap-friction) elements with predefined crack wall contact pressure have been proposed for that purpose. These analyses can provide a better understanding of the structural behaviour and failure mechanisms of dams repaired by grouting.

This paper focuses on structural aspects of crack grouting in concrete dams. A review of cracked concrete dams that have been repaired by grout injection is first presented. The lack of knowledge and uncertainties to predict the structural response of a dam during grout setting and after grout setting subjected to subsequent loading is discussed. The theoretical concepts to model the hardened grout in concrete cracks are explained. A simple contact element is implemented in UDEC[2], a commercial distinct element method software with the ability to do grouting analysis representing a state-of-the-art coupled hydro-mechanical approach to this class of problem. The grouting response of a single crack induced in a 90 m high-gravity dam is then considered in comparative analyses using different simulation methods.

Application of grouting to repair cracks in concrete dams

Grouting is the process of injecting fluid grout materials that eventually harden into voids, fissures, or cavities in rock, concrete or soils. The inventor of grouting technique was a French engineer, Charles Bérigny, who used a suspension of water and puzulana cement to fill up caves in the foundation of a sluice damaged by settlement[3]. Grouting was applied to seal the joints in the foundation of dams around 1900[4]. Now different types of grouting materials, ranging from cement grout to various types of chemicals, are used to fill foundation cavities and joints to reduce permeability and improve mechanical properties of foundation, to fill construction joints as well as to repair cracked concrete dams.

Modern grouting techniques were mainly developed from practice, and they are based on experience of the grouting personnel and empirical relationships[3]. Grouting of dam foundations, with less information about the nature of its porosity and discontinuities, requires special grouting procedures that have been developed over the years. The maximum grouting pressure is often defined based on the existing overburden pressure at the grouted section to prevent hydro-jacking (opening of existing joints in the rock mass) and hydro-fracturing (forming of new cracks). This concept for determining maximum pressure was used in grouting of the Big Eddy concrete buttress gravity dam (44 m) in Ontario[5]. Leaking lift joints were a major problem in this case. In addition to post-tension anchors to improve the stability, cement grouting of the dam body was used to restore water tightness and structural integrity. The effective pressure to inject the grout was calculated according to the depth, leading to grout pressure of 0.23 kPa per metre of concrete above the injected section. Overall, the grouting programme has been successful to control the seepage.

The grout intensity number technique (GIN) was developed by Lombardi & Deere[6] to control the grouting procedure in rock foundations. The GIN technique recognizes that the possible damage to a structure during injection is related to the product of the applied pressure and the surface on which the pressure acts, and not the pressure alone. A GIN value defined as the product of the injection pressure (bar) by the volume injected (litre) is defined to prevent crack opening and propagation. This method was adopted in grouting of the Isle-Maligne concrete gravity dam constructed in 1927[7]. Investigations revealed that concrete deterioration was mainly concentrated along seeping horizontal lift joints. The deterioration within the mass has been caused by leaching action while the concrete surface had deteriorated due to the repeated action of freeze–thaw cycles. It was decided to rehabilitate the mass concrete with an extensive grouting programme designed to seal wide and small discontinuities. Larger discontinuities were grouted with type 30 cement, while fine discontinuities required micro-fine cement. For each grout stage along the height of the dam, the weight of concrete and the post-tension anchors working load resisting the grout pressure has been computed to establish the maximum grouting pressure allowable at the point of injection and the maximum volume of grout that can be injected under the given pressure. For a constant GIN value of approximately 850, the effective grouting pressure varied between 0.4 and 5.3 MPa for grouting stage below a depth of 20 m. No investigation to study the effect of grout pressure and subsequent hardened grout on the evolution of the internal stress field was reported.

A more realistic grouting process, concerning structural response of the dam, was developed for grouting of the Daniel Johnson dam[8] and the Flumendosa dam[9,10]. In grouting of the Daniel Johnson dam[8], a finite element model was used to determine the maximum injection pressure and the maximum injected area at a given time to prevent crack propagation. The horizontal displacement at the base of the arch and the maximum allowable crack openings were also determined and monitored as additional safety checks.

During the final construction stage of the Flumendosa dam, a 115-m-high double-curvature arch dam in Sardinia, a large number of horizontal cracks appeared on the upper part of the upstream face. The cause of cracking consisted mainly of an unacceptable state of stress caused by the temperature field in the structure during and after construction[9,10]. Because the causes of cracks were not acting any longer, only epoxy grouting of the cracks was considered to restore a monolithic structure. The maximum allowable injection pressure was determined after performing a series of preliminary grouting tests. The designed pressure varies from 8.0 to 0.8 Mpa, based on the elevation of grouted cracks. Moreover, a video camera introduced into the drilled holes and an image processing system were used to determine the geometric features of each crack. The grouting was separately done for each specific crack, starting from the deepest holes in crack toward the upstream face and adjacent lateral joints. The maximum crack opening was determined as a structural response criterion that was measured at the crack being grouted and the one above. The superposition method was used to compute the structural response of the repaired dam after grout setting. Structural analyses of the rehabilitated dam were carried out by freezing the stress distribution existing before grouting and superposing it on the stress generated by the force variations (e.g. water level) acting later on an assumed monolithic structure. This results in a nonlinear stress distribution across the dam sections.

A rigorous structural safety assessment of a grouted dam requires that the structural response be evaluated during and after grout injection into the cracks. Considering the cracked state as the initial existing condition before grout injection, the following structural analysis should be performed:

1. Analysis of cracked dam (with possible water pressure in cracks) to find the cause of cracking and establish initial conditions;
2. Analysis of grout injection in the crack with possible hydro-fracturing;
3. Analysis of state change of grout material from fluid to solid;
4. Analysis of repaired dam considering the effect of hardened grout in the cracks.

Existing computational methods, that can be used for analysis of concrete dams considering these stages, are discussed below.

Analysis of dam initial cracked state

Cracking of concrete could be described or predicted by various constitutive models based on the strength of materials, fracture mechanics, damage mechanics, etc. Two approaches have generally been used for finite element modelling of cracks in concrete structures: the discrete model, and the smeared crack model. Both models have been used over the decades because of the advantages and the inconveniences that they bring to the numerical implementation of the constitutive models in finite element crack propagation analysis of concrete structures.

The discrete crack model, in a finite element analysis, introduces displacement discontinuity along the crack by altering the mesh to accommodate propagating cracks. The discrete crack model is a realistic representation of a physical discontinuity and water penetration and uplift pressure can be easily modeled as external loads along the crack walls in a finite element mesh. Bruhwiler & Saouma[11] developed an experimental equation for water pressure in terms of the crack opening displacement. The transient water flow and pressure in a propagating crack has also been studied[12,13] to simulate concrete dam cracking during earthquakes.

Using predefined contact elements is a common method to model cracking of lift and construction joints, as well as dam–foundation joint, in a finite element analysis of dams[14,15]. In the analysis of a cracked dam, it is possible to define contact elements at the location of existing cracks. By defining the proper material strength and stiffness for contact elements, the cracking response of the dam can be modelled. The distinct element method (DEM), is a more generalized computational method with a similar approach. In the DEM, the structure is modelled as an assembly of 'distinct' bodies (or blocks) interacting through predefined contacts or interfaces. The blocks could be rigid or deformable, following linear elastic or nonlinear stress–strain constitutive models. The interfaces are represented by nonlinear 'gap-friction' type of contact elements with various options to model their shear and normal displacement responses.

UDEC[2] is commercially available software for two-dimensional distinct element analysis. Water flow and pressure along cracks and joints can be modelled in UDEC. Water is a Newtonian fluid with no cohesion. To formulate water flow through concrete cracks it is common to assume that cracks are composed of two parallel smooth plates with aperture e. Assuming steady and laminar incompressible flow, water flow per unit width of crack q can be defined by the following equation which is known as the cubic law:

$$q = \frac{g}{12\nu} J e^3 \tag{1}$$

where ν is the kinematic viscosity of the fluid, J is the dimensionless hydraulic gradient, and g is the gravitational acceleration. A coupled hydromechanical analysis is possible using this software.

In smeared crack models, the mechanical properties of finite elements are modified along the path of the crack according to the selected constitutive relationships, to represent the loss of strength and stiffness. In smeared crack models it is difficult to introduce uplift pressures in cracked elements. Bhattacharjee & Léger[16] considered uplift pressure inside smeared crack bands using the effective porosity concepts for two-dimensional cracking analysis of dams. Water pressure in a porous concrete dam, and its cracks and joints, are also considered in SCADA[17], a finite element program for smeared crack analysis of arch dams.

Grout injection analysis

For hydromechanical coupled analysis of grout injection, liquid grout flow in concrete cracks is most effectively modelled in discrete crack or distinct element based computer programs. A stable grout is considered as a Bingham fluid, exhibiting both cohesion and viscosity. The flow gradient relation of a Bingham fluid is similar to that of a Newtonian fluid, except that no flow occurs until the threshold gradient J_0 is exceeded, where J_0 is computed as:

$$J_0 = \frac{2C}{\gamma e} \tag{2}$$

where C is the cohesion of the fluid, and γ is the specific weight of the grout. Assuming laminar and steady flow Wallner[18] shows that the flow gradient can be written as:

$$q = \frac{g}{12\nu} Je^3 \left[1 - \frac{3t}{2e} + 2\left(\frac{t}{e}\right)^3\right] \tag{3}$$

where $t(t = 2C/\gamma J)$ is the stiff kernel thickness (Fig. 3) and other parameters are similar to eq. (1). Depending on the magnitude of the existing pressure gradient, the grout flow may develop along the whole crack length, as with water, or the flow may stop at a certain distance from the grouting point (the crack mouth in Fig. 3). In this case, only the cohesion force is present and the viscosity-resisting force is zero. Using the equilibrium of forces along the crack, the grout penetration distance $L_{\max}$ can be computed as:

$$L_{\max} = \frac{Pe}{2C} \tag{4}$$

where P is the grouting pressure.

Fig. 3 shows the differences between Bingham and Newtonian fluid along a smooth crack. A constant Newtonian flow with linearly varying pressure will developed along an open crack if a pressure gradient is applied along the crack. Depending on the magnitude of the pressure gradient developed, water flow may develop along the crack or just a fraction of its length may be filled with liquid grout. In the case of a crack with a closed end, if the crack length is longer than $L_{\max}$ a partially filled crack will exist, otherwise the grout will fill the crack and the pressure will vary linearly (Fig. 3). For the case of an applied injection pressure along the crack, the pressure variations for Newtonian and Bingham fluids are also shown in Fig. 3. Hassler *et al.*[19] assumed that the joint/crack plane can be described as a mesh of one-dimensional channels. They used the Bingham formula to evaluate the grout flow along the cracks. The cases of grout with internal friction of the cement material as well as unstable grouts are discussed elsewhere[20]. Amadei & Savage[21] have presented an analytical solution for the transient Bingham flow through cracks.

A Bingham fluid with cohesive properties typical of cement grout is available in UDEC[2], to simulate the coupled hydromechanical response during grout injection.

Grout setting analysis

During grout setting, the state of the grout material changes from fluid to solid. If we assume that state of

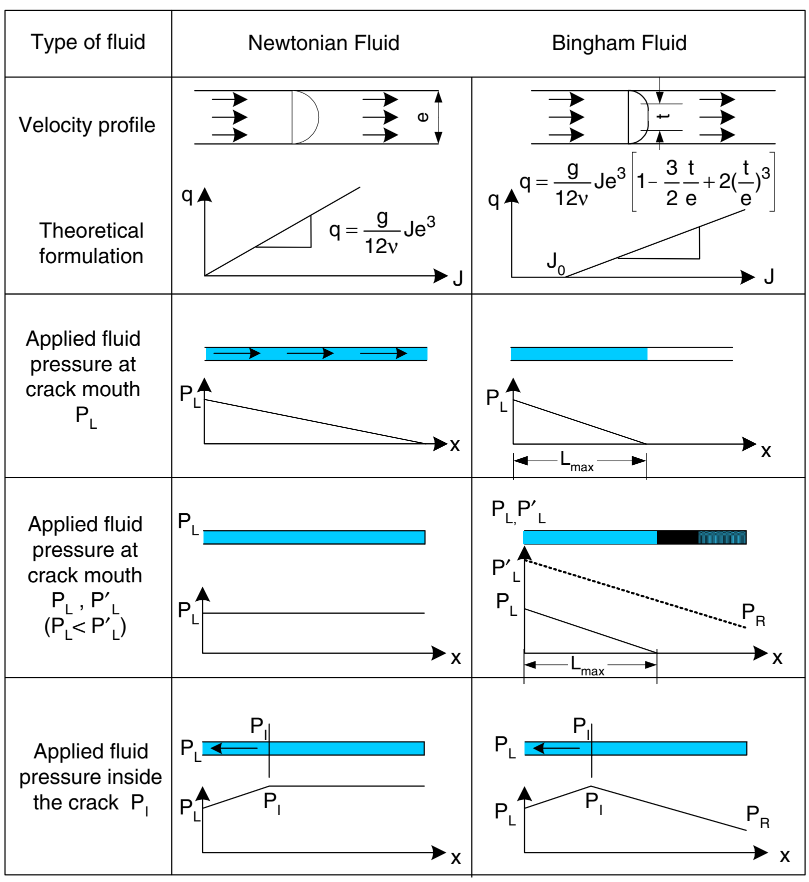

Fig. 3 Newtonian and Bingham fluid flow relations

stress in the crack walls does not change during setting, then the existing pressure in the fluid grout before setting should appear as compressive stresses in the hardened grout. The real condition could be different due to shrinkage or expansion of grout that may change the state of contact stresses to reach a new equilibrium condition. The precise determination of the dam response at the end of grout setting would thus theoretically require an elaborate setting–mechanical coupled analysis that to the best knowledge of the authors has never been done so far. Moreover, bleeding of grout and sequential injection of a crack from different holes makes it difficult to estimate the final stress in the grout. The state of stress in hardened grout may also be affected by the grouting of other cracks in the dam body.

Hardened grout-repaired dam response to subsequent loading

The structural response of the rehabilitated dam is different from the response of the unrepaired cracked dam, or a similar monolithic dam, due to the existence of hardened grout in the cracks. Any crack opening or closing tendency due to changes in the loading conditions is resisted by the existing grout in the crack. The mechanical properties of the grout will affect the structural response of the repaired dam to subsequent loadings. For example, in the case of soft grout material, the expected crack closure due to compression, and therefore the dam displacement, will be larger compared with the displacement of a similar dam repaired with stiffer grout material. Therefore, modelling of hardened grout in the cracks of repaired concrete dams could be important in structural analysis of repaired dam. A simple way is to model the hardened grout with contact elements in discrete crack finite element method. Therefore new contact elements should be added or the properties of existing contact elements should be modified. A similar approach was used by Divoux *et al.*[14,15] to model the hardened grout in the contraction joints of arch dams. The normal and tangential stiffnesses of predefined gap-friction elements were modified to consider the effect of hardened grouted materials. The definition of contact element closure was also modified to accommodate the existence of hardened grout in joints. As an approximation to the effect of liquid grout injection pressure, a constant pressure was applied via pre-compressed gap-friction elements along the grouted part of the contraction joints

Structural analysis of grouting process

Development of numerical methods to simulate the structural response of dam from grout injection to subsequent loading of the grouted dam can be of great use for the design of suitable grouting process in particular cases. The state-of-the-art of dam crack grouting reveals that numerical analysis to automatically investigate the structural response of a dam with a coherent transition during the different phases of the grouting process has never been done. This is due to the complexity of a rigorous treatment of the problem that requires consideration of different types of analysis including; (i) nonlinear finite element (crack) analysis, (ii) hydromechanical coupling analysis with Newtonian or Bingham fluids, (iii) liquid–solid grout state change, and (iv) modelling hardened grout in cracks of the repaired dam. UDEC[2] can be used directly for the analysis of first two types of analysis. Moreover, the embedded programming language, called 'fish', can be used to model the hardened grout in the cracks of the repaired dam. Therefore the structural response of cracked dam repaired by grouting can be automatically evaluated using this software while considering a coherent transition between the different types of analysis.

MODELLING OF HARDENED GROUT IN CRACKS

To analyse the repaired dam after grout setting (Fig. 2, Phase 3), it is required to replace the liquid grout with hardened grout in the cracks. The existing grout pressure in cracks from hydromechanical analysis of grout injection could be replaced by a series of linear uniaxial springs. The stiffness of each spring is computed based on its length (crack opening) and its tributary area, as shown in Fig. 4. It is also required to consider an initial force in the springs to model the removed fluid flow pressure in the crack to maintain equilibrium conditions. In other words, it is assumed that the liquid grout pressure at the end of the grouting process appears as the initial stress in the hardened grout. An equivalent compressive force corresponding to the existing pressure at each contact element is computed and considered as initial conditions for subsequent structural analysis. This is a correct assumption if there is no volume change when the grout state changes from liquid to solid.

The possible normal stress distribution, after grout setting, along the assumed crack line is shown in Fig. 4. The normal stress on crack walls should be equal to the initial stress of the hardened grout. This is also true before grout setting where liquid grout is present in the crack. In dam engineering, the effective stresses (total mechanical stresses minus uplift pressures) are generally used to show the stress distributions along the crack, therefore the total and effective stress distributions appear different. For consistency between the stress distribution representations, the total stress definition will be used to show the stress distributions along the cracks (Fig. 4a).

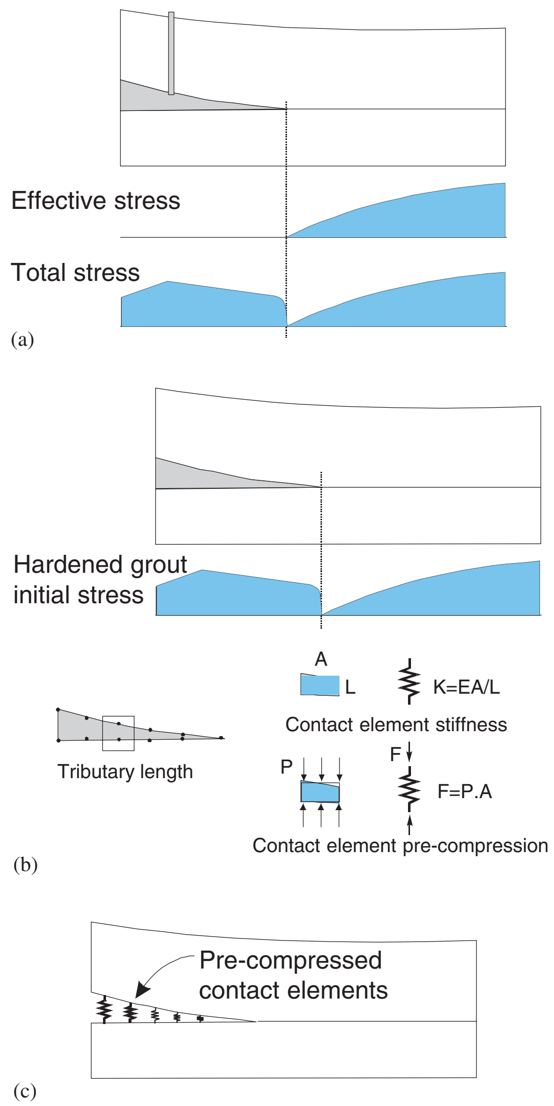

Fig. 4 Modelling of hardened grout in crack: (a) grout flow in open crack; (b) state change from liquid to solid; (c) equivalent mechanical model

It should also be noted that, in an opened crack, the relative tangential displacements of crack walls is possible before grouting, but after grout setting it is restricted by cohesion or even friction between the grouting material and crack walls. In the proposed method, only the normal stiffness of the hardened grout is considered in the contact element model, and the possible tangential stiffness of grouting materials is not considered herein.

Example

The proposed application of UDEC[2] for the automatic analysis of grouting processes according to the three phases of Fig. 2 is demonstrated for a typical 90-m-high gravity dam. This dam was also analysed using the simplified state-of-practice superposition technique for comparison purpose. A lift joint is assumed at elevation 10 m from the dam base, it is also assumed that the dam will crack along this horizontal joint. The dam geometry and material properties of the dam and joint are shown in Fig. 5 where σ_t is the joint tensile strength, K_n and K_s are the normal and tangential joints stiffness, and a_0 is the joint aperture at the zero normal stress. Joint aperture for hydraulic computations in UDEC is defined as the summation of a_0 and the joint mechanical displacement to account for the joint aperture at zero stress due to crack wall roughness. The magnitude of $a_0 = 0.05$ mm is negligible compared with the mechanical crack opening displacements (around 1 mm in this case) and does not affect results. Structural analysis of the dam has been performed in five steps with five different loading conditions (Fig. 5). In the first step, only gravity load (self-weight) is applied, and in the second step the hydrostatic water pressure was added to the self-weight of the dam. In the third step, the water pressure in the cracked part of the joint is added to the existing loading from step 2. Grouting of the developed crack is simulated in step 4, and finally in step 5 the water level behind the dam is reduced to investigate the structural response of the repaired dam after grout setting.

Increasing water level behind the grouted dam may open the crack further and propagate it. The possible cohesion of grout material and concrete may increase its strength against crack opening and propagation. Reducing the water level has the tendency to close the crack filled with the hardened grout that has a general tendency to increase compressive stresses in the grout and may promote the development of tensile stress near the crack tip (wedge effect, Fig. 1d). The developed compressive stresses may change the structural response compared to the cracked dam.

STRUCTURAL RESPONSES OF THE DAM TO GROUTING

The results of analyses for each step including crack (joint) normal opening displacement (COD) and joint normal stresses are shown in Fig. 6. No crack can develop at the end of step 2 just by the application of hydrostatic load and the weight of the dam. Therefore there is no opening along the joint and it is completely in compression. Because the assumed joint does not crack due to the applied loading, no water pressure can be developed along the joint. However, in UDEC it is possible to define water pressure along an uncracked joint. By defining the full uplift pressure acting along 2 m of joint, cracking is initiated. Due to the crack opening, water could penetrate along the opened part of the crack causing the crack to propagate. The crack propagation phenomenon stops when its length becomes 26 m at the end of step 3. Crack mouth opening displacement (CMOD) is almost 1.4 mm and the crack opening displacement (COD) profile is shown in Fig. 6a. The corresponding

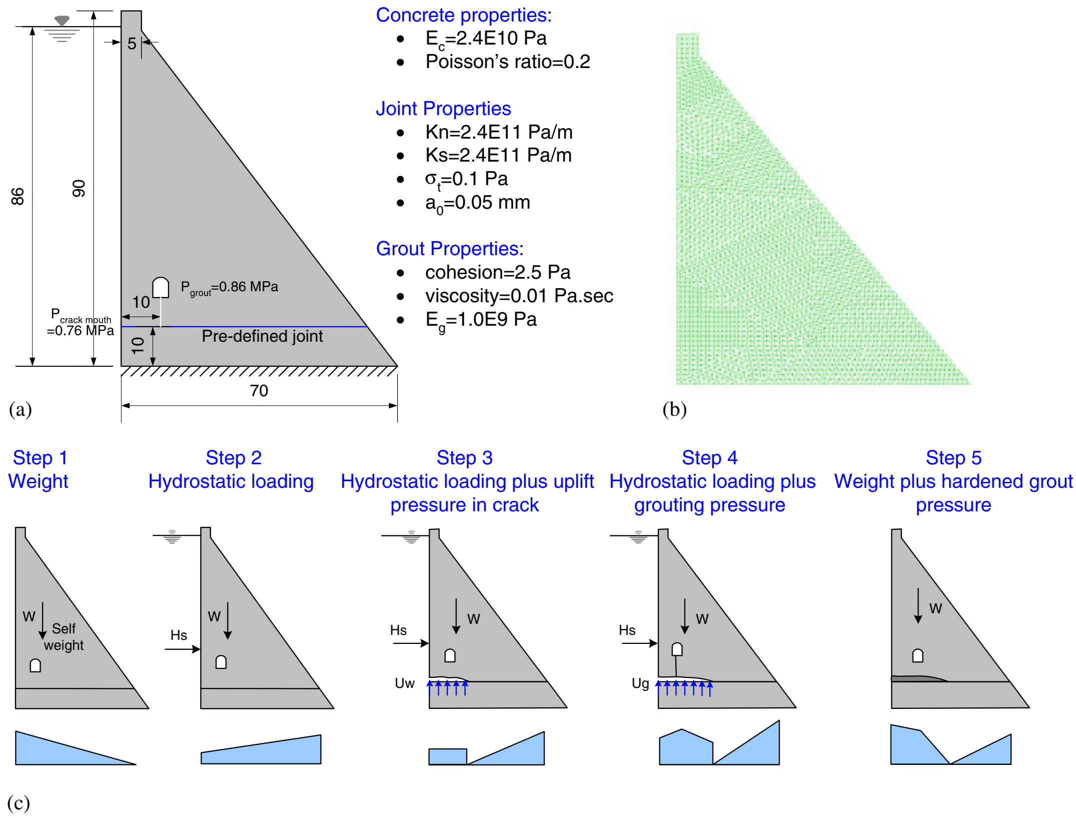

Fig. 5 Case study, 90-m high-gravity concrete dam and loading steps: (a)90-m-high dam; (b) UDEC mesh; (c) loading steps

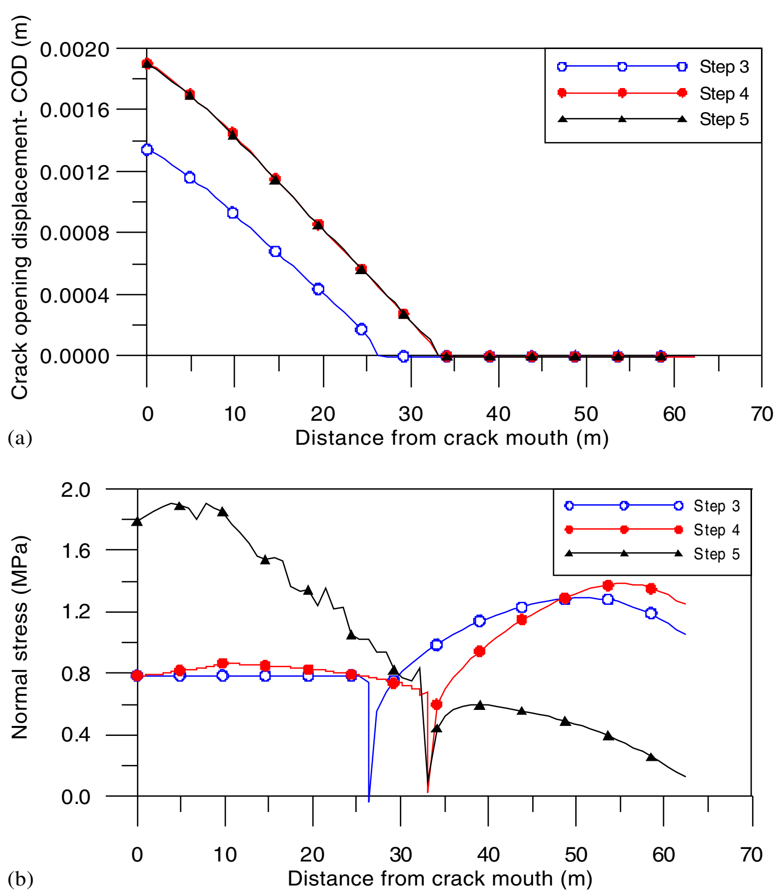

Fig. 6 Joint responses to grouting: (a) mechanical crack opening displacements (COD); (b) normal stress along the joint

developed total stresses along the crack are also shown in Fig. 6b.

It is assumed that grout injection into the crack is applied from only one grouting hole at a distance of 10 m from the crack mouth and the grouting pressure is assumed equal to 0.86 MPa while the crack mouth water pressure is 0.76 MPa. The tensile strength of the uncracked joint is assumed 0.1 MPa. The excess grouting pressure in this case propagates the crack, and the crack become longer, equal to 33 m at the end of the grout injection (step 4). Therefore, the hydro-fracture effect of grouting that opens and propagates crack due to excess grouting pressure is occurring in this case. The total stress distributions along the joint and normal opening of crack are shown in Fig. 6. It should be mentioned again that the assumed conditions are a simplification of a possibly more complicated grouting process. Using different grouting holes along the length of the crack makes the problem more complicated. The two-dimensional analysis of dam grouting, while the injection pressure is applied in a certain width of the dam is also an approximation. But it is appropriate to define the initial conditions to perform structural analysis of the repaired dam (after grout setting).

For step 5, it is assumed that the existing liquid grout in the crack was set and hardened without any change in the dam stress field. It is also assumed that subsequently, the reservoir becomes empty (water level reduces to 0 m). Crack opening displacement (COD) at the end of step 5 is almost equal to the COD from step 4 because the introduction of spring elements along the crack prevents crack closing as expected in a grouted crack (Fig. 6). The crack propagation due to the pressure of hardened grout while reducing the water level (wedge effect) is not occurring in this case.

The final response of the repaired dam is also computed by superposing the dam 'initial' stress distribution at the end of the grouting process and the stress variations generated by the loading variations (i.e. water level reduction in this application) applied on a monolithic dam without cracking (superposition method). The normal stress change along the joint when the reservoir level reduces from 86 m to 0 m can thus be computed by subtracting the stress distribution in step 1 from the stress distribution in step 2 (Fig. 5). By addition of this stress variation to the existing stress distribution at the end of the grout injection (step 4) the final stress distribution in the repaired dam is obtained. The results of this stress superposition method, along with the results of the contact element method are shown in Fig. 7. The stress distribution along the joint of an uncracked dam loaded by its own weight (step 1- in Fig. 5) is also presented in this figure for comparison. Note the other two curves also present the response of the repaired dam under its own weight by two different methods (contact element and superposition). Therefore the final applied loading is similar for the three cases considered in Fig 7, whereas the loading histories along the joint are different.

Comparing the three stress distributions shows that the normal stress distribution along the assumed joint according to the contact element method is different from the computed stress distributions from the superposition method. To generalize this conclusion to the dam body stress field, the stress distributions along other sections of the dam should also be verified. The normal stress distributions along some horizontal sections in different elevations are also computed by the superposition method and the proposed contact element method as shown in Fig. 8. It is clear from this figure that the computed normal stresses from these two methods are also slightly different in the regions of the dam around the grouted section. The stress distributions from the contact element method are more accurate than the stress distributions from the superposition method. This is because the contact element method follows more realistically the effect of the stiffness of the grouted joint to subsequent loading variations.

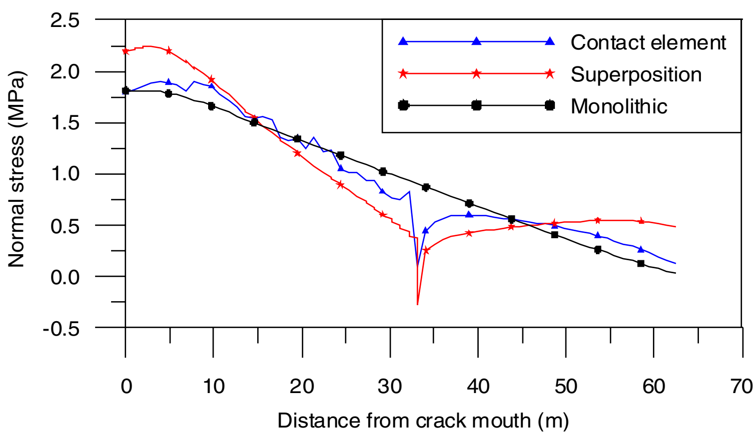

Fig. 7 Normal stresses along the joint from three different analyses

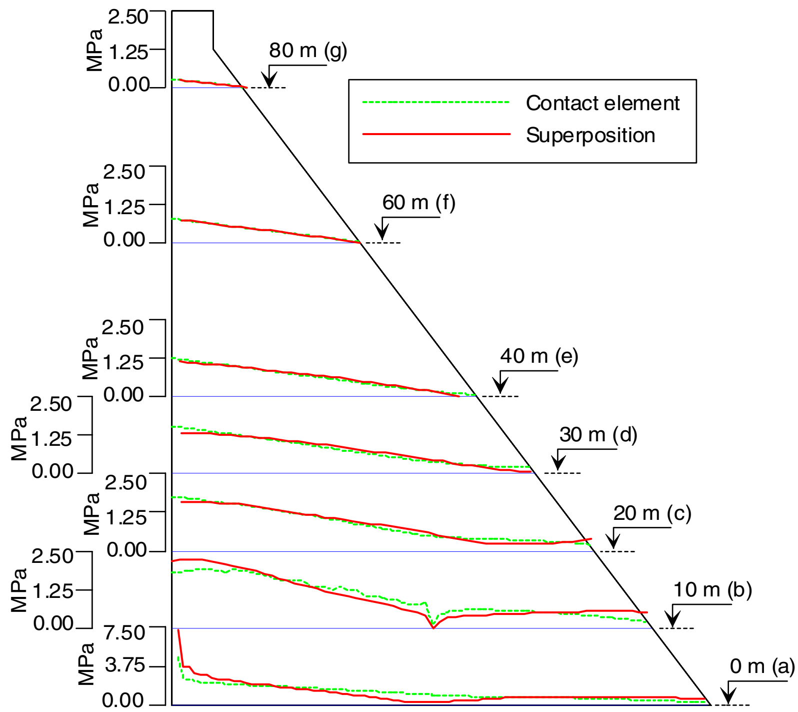

Fig. 8 Normal stress distributions in different elevations

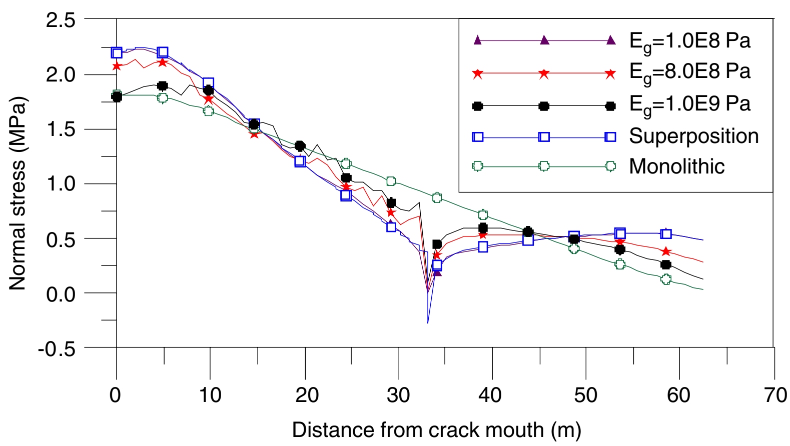

Fig. 9 Effect of grout stiffness on normal stresses along the joint

EFFECT OF GROUT ELASTIC MODULUS

To investigate the effect of grout stiffness on the repaired dam response, similar analyses are performed with the grout modulus of elasticity equal to $E_g = 1.0 \times 10^{8}$ Pa and $E_g = 8.0 \times 10^{8}$ Pa. The normal stress distributions are shown in Fig. 9 along with the stress distributions from previous analyses (contact element with $E_g = 1.0 \times 10^9$ Pa and superposition). Comparing the results of different analyses in Fig. 9 it can be concluded that the computed normal stress distribution by the contact element method lies between the results of the monolithic dam assumption and the superposition method. By decreasing the grout elastic modulus, the computed stress distribution approaches to corresponding distribution from the superposition method. By increasing the grout stiffness it becomes closer to the stress distribution from monolithic dam analysis. It should be mentioned that the stiffness of contact elements representing the hardened grout in the joint is a function of the grout elastic modulus and joint aperture at the element location (Fig. 4b). Therefore it is not possible to determine and generalize a specific range for the grout elastic modulus where the superposition or monolithic approach is acceptable. It can be concluded that for an accurate evaluation of the rehabilitated dam response, the hardened grout in the cracks should be added to the cracked dam model using the proposed contact element method. The superposition method or a monolithic dam analysis might not be accurate enough in all conditions.

Conclusions

Due to the low tensile strength of concrete, massive unreinforced concrete dams are likely to experience cracking. Grouting is the most common repair/strengthening actions undertaken to improve the performance of concrete dams with cracks and/or leaking joints. The development of a grouting programme to repair a cracked concrete dam obviously requires the consideration of several aspects related to the incidence of grouting on the dam structural behaviour.

In current state-of-practice of crack grouting a combination of in situ test with some simplified computations are used to overcome the difficulty of accurately modelling each stage of the grouting process. The realistic modelling of the grouting process require different types of analysis including; (i) nonlinear finite element of concrete cracking, (ii) hydromechanical coupled analysis, (iii) analysing of grout state change, as well as (iv) the effect of hardened grout in the repaired dam.

It was shown that UDEC[2] could be used to simulate the grouting process in cracked dams. A numerical method, using 'fish' programming, is developed to model the hardened grout with precompressed contact elements to analyse the repaired dam considering the hardened grout effect on the structural response of the repaired dam.

The structural response of a 90-m-high cracked concrete gravity dam during the grouting process shows the possibility of hydro-fracturing during grouting. The structural response of the repaired dam with hardened grout in the cracks is computed for the case of reservoir level decrease that cause additional compressive stresses in the grouting materials due crack closing. Parametric analyses show the normal stress variations along the assumed joint are affected by the magnitude of grouting material elastic modulus. The computed stress distribution approaches the corresponding distribution from the state-of-practice superposition method by decreasing the grout elastic modulus, while it becomes closer to stress distribution from monolithic dam analysis while increasing the grout elastic modulus. The so-called wedge effect, which is the crack propagation due to tendency of the repaired crack to close as the subsequent load removal was not observed in the cases considered here. It is concluded that the response of repaired dam should be computed considering the effect of hardened grout, as in the proposed method using precompressed contact elements, and the superposition method or just monolithic dam analysis results are not accurate in all circumstances.

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