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Numerical modeling of the effects of joint hydraulic aperture, orientation and spacing on rock grouting using UDEC: A case study of Bakhtiary Dam of Iran

O. Saeidi*, A. Ramezanzadeh, F. Sereshki, M. E. Jalali

Department of Mining Engineering, Petroleum and Geophysics, Shahrood University of Technology, Shahrood, Iran

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* *Corresponding author: osaeidi914@gmail.com (O. Saeidi).*

Abstract
This study aims at presenting a numerical model for predicting grout flow and penetration length into the jointed rock mass using Universal Distinct Element Code (UDEC). The numerical model is validated using practical data and analytical method for grouting process. Input data for the modeling, including geomechanical parameters along with grout properties, were obtained from a case study. The effect of rock mass properties such as joint hydraulic aperture, spacing, trace length, orientation and grout properties as yield stress and water to cement, w/c ratio was considered on grout flow rate and penetration length. To illustrate the effect of aforementioned properties, models were constructed with dimensions of 40×20m. A vertical borehole with diameter of 60mm and 10m depth was drilled in a jointed rock media. The results were in a good agreement with analytical method. It was observed that by increasing joint hydraulic aperture, grouting flow increases using a power law function. The optimum grout penetration observed with joint sets intersection of 40°-60° as experienced in practice. With an increase in joint spacing grout penetration increases around borehole when spacing exceeds two meters it decreases, gradually.

Keywords: *Jointed rock mass, numerical model, grout flow, grout penetration length, UDEC, Bingham plastic model.*

1. Introduction

Establishing a need for grouting is a main issue in dam foundation improvement. Better grouting assessment can be attained, by making a reliable zoning of dam foundation based on geological field investigations. The aim of the grouting is not only to reduce the hydraulic conductivity but also to improve the strength of the ground under the dam foundation. This type of grouting is permeation grouting which means that the grout has to penetrate into the joints and thus spread into the rock mass.

In discussion of the effects of rock mass properties on the grouting process, many researchers have described the rock's behavior with emphasis on its groutability, using various parameters both practically and theoretically [1-11]. Rock type itself does not usually affect grouting, but many rock types have special characteristics, including jointing system, porosity, and weathering as well as physical and hydraulic properties in which they affect the grouting process, directly. Houlsby outlined the most effective rock mass properties, which influence its groutability as joint spacing, dipping, persistency, filling, aperture and rock soundness, strength and ground stress. It was pointed out that in widely spaced joints the grouting is usually easier than closely spaced joints where it causes many problems as frequent surface leaks and collapsing boreholes [2]. According to Houlsby, the simplest rock joints to grout are those, which have aperture in the range of 0.5-6 mm; dipping 40°-60° in which vertical grout boreholes may give optimum interception; also, joints with high persistency. Wherever in the case of non-persistence joints more grout boreholes is needed.

Besides rock properties, the rheological properties of the grout have important role on the groutability of a rock mass. Amadei and Savage presented a complete analytical solution of the grout flow acting as non-Newtonian/Bingham plastic fluids in rock joints [12].Gustafson and Stille developed a numerical method to estimate grout spread area in the rock joints based on the geomechanical properties of rock and grout specification. They determined that because of stochastic distribution of joint apertures and channeling the results of grouting are beyond a unique amount of aperture and by increasing standard deviation of the joint aperture grout spread area and flow will increase considerably [7].

In this paper an attempt has been made to consider the effects of rock joint parameters on grouting process numerically by using UDEC software [13]. First of all, the constructed model was validated using practical data from Bakhtiary dam foundation. In a vertical section a grout borehole has been drilled with 10 m length and diameter of 60 mm into ajoint network based on site mapping data during grouting. Grout, a mixture of cement or other materials, is injected into the rock mass to seal its joints. Since the volume of rock mass into which the grout penetrated has its properties modified, it is necessary to calculate the penetration length of grout into the rock mass. This grout penetration length depends on various features, specifically the properties of the grout and the grouting pressure, as well as the joint size (aperture and length) and configuration in the rock mass. Through a parametric study, this research determines the effects of various features on the grout penetration length.

2. Governing equations for fluid flow in rock joints

The groutability was presented as the ability of rock to accept grout [14]. Therefore, groutability of rocks depends on the properties of the joint and the injected grout material. For a joint to be groutable, the grout must satisfy the conditions of penetrability and flowability. Penetrability means the ability of the grout to enter an opening is most important for cement based grouts, where the grout particles might be too large to enter the joint; and flowability means the ability of the grout to flow inside the joint.Some researchers use a limit aperture below which the grout cannot penetrate into the joint [12, 15, 16].

One of the simplest solutions on the flowability of the grout is presented by Gustafson and Stille where the authors use a simple force balance for Bingham fluid flow to get the grout penetration [7]. At refusal the injection pressure is balanced by the shear stress towards the joint walls.

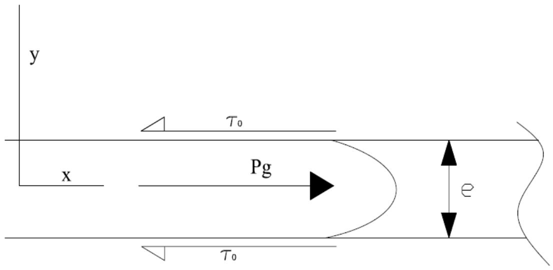


Figure 1. Grout flow through a rock joint.

Assuming a single joint in one dimension has parallel walls (Figure 1), with an aperture e the grout penetration, I_{max} was defined as in Equation1:

$$I_{max} = \frac{(P_g - P_w)}{2\tau_0} e \tag{1}$$

where I_{max} is the maximum penetration length, P_g applied pressure behind grout material, P_w is the water pressure inside the joint and τ_0 is the yield stress of grout. The model was developed to one and two-dimensional rock joint with mean and standard deviation of apertures in a network of joints. Subsequently, the above relation does not provide realistic penetration length of the grout in a joint then they considered time requirement for pumping grout as a key parameter for injection of grout material which was expressed as follows:

$$t_0 = \frac{6\Delta P.\mu_g}{\tau_0^2} \tag{2}$$

where μ_g is the grout viscosity and τ_0 is the yield stress of the grout.

For a preferred penetration length, I at duration t, the relative penetration length and grouting time are defined as $I_D = I / I_{max}$ and $t_D = t / t_0$, respectively.

They calculated relative penetration length in terms of relative grouting time through series expansion for two-dimensional problems as follows:

$$I_D = \sqrt{(\frac{t_D}{2(3+t_D)})^2 + 4(\frac{t_D}{2(3+t_D)})} - (\frac{t_D}{2(3+t_D)}) \tag{3}$$

Flow rate into the rock joints was obtained using penetration length and assuming radial flow around joint. In 1-D flow (flow in channels) itwas expressed using Equation 4 as:

$$V_{\max} = \pi I_{\max}^2 e$$

$$Q = \frac{dI_D}{dt_D}\frac{V_{\max}}{t_0} \quad (4)$$

where Q is the flow rate and dI_D / dt_D obtained from the slope of penetration – time curve.

Most of the previous studies indicate that the grout flow is governed by Bingham fluid equations [17-19]. Bingham fluids can be simulated using a dynamic viscosity and cohesion approximation.

In this study, UDEC is employed to simulate grout flow through joints based on a fully coupled hydro-mechanical analysis. UDEC is a two-dimensional numerical program based on the distinct element method for discontinuum modeling. For coupled hydro-mechanical flow analysis, UDEC code is suitable when flow is mainly governed through a network of joints. Therefore, in this study it is assumed that grout flow takes place from a vertical borehole through interconnected joint networks and spreads in jointed media. The depth of boreholes is set to 10m below ground surface, which was suggested as effective grout interval depth [2]. To confine the grout interval, one meter of the upper part of the borehole is considered as impermeable material to simulate the pneumatic or mechanical packers. The lower, right, and left boundaries were regarded as fixed displacement boundaries. The zone size in the blocks is set to 2 mm and gravity load of 9.8 m/s^2. Ruining of the program in several steps is executed before grouting to stabilize the mechanical model.According to the rock density (2.8-2.9 gr/cm^3) and grouting depth (10-90m) calculated vertical stresses were in the range of 0.28-2.51MPa.

Several researchers, including [20-22] have used UDEC code to investigate fluid flow through jointed rock media. Rock blocks surrounded by discontinuities may be modeled as rigid or deformable material. Fluid flow analysis is performed in which the joint conductivity is directly related to the mechanical deformation associated with the joint (domain) water pressures. Each domain (filled with water) is separated by contact points at which mechanical interaction between blocks is established.

In UDEC fluid flow governing equations for steady laminar flow of a Bingham plastic fluid is calculated based on Buckingham's equation [23] for a rectangular channel as:

$$Q = \frac{1}{\mu}[-\frac{2\Delta P}{3L}e^3 + \frac{\tau_0^3}{3(\Delta P/L)^2} - \tau_0 e^2] \quad (5)$$

where Q is the flow rate per unit width of the joint, μ is the viscosity of Bingham plastic fluid and $\Delta P/L$ is the pressure gradient. The hydraulic aperture is given, in this analysis, by:

$$e = e_0 \pm u_n \quad (6)$$

where e_0 is the joint aperture at zero normal stress and u_n is the joint normal displacement. The variation of aperture with normal stress on the joint is depicted in Figure 2.

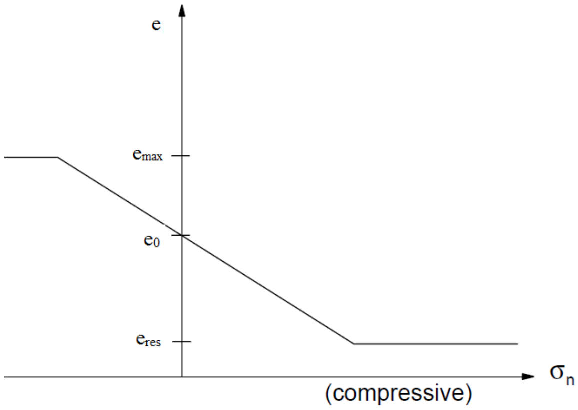


Figure 2. Relation between hydraulic aperture, e and joint normal stress, σ_n in UDEC [UDEC manual, 13].

In Equation 6 arithmetic positive and minus signs illustrate opening and closure of joint aperture. Therefore, by increasing normal compressive stress the hydraulic aperture of the joint decreases. As it can be seen all aforementioned solutions (analytical and numerical) consider grout properties along with joint aperture. However, other joint properties as orientation, roughness, spacing, trace length and persistency have important roles on rock groutability and spread area of the grout. Yang et al. have carried out a numerical simulation using a stochastic joint network and indicated the effects of the joint properties on grout penetration depth. Their model has related grout properties, mean and standard deviation amounts of joint orientation, aperture, length and joint density to the penetration depth [24]. However, they did not consider the influence of joint roughness and persistency on the grout extension area. The grout material and grouting pressure can be controlled in the operation, and therefore, their effects on the grout depth can be easily taken into account in the design. However, the joint characteristics are not easy to define. In addition, it has been recognized that natural joints in rock mass are randomly distributed [25]. In this study, a FISH program is adopted using Bingham plastic model for the grout to predict the rock mass groutability.

3. Case study features

The Bakhtiary dam and hydroelectric power plant project includes the design and construction of a 315m high, double curvature, concrete dam and an underground powerhouse, with nominal capacity of 1500MW, in the Zagros mountains in southwest Iran [26].Limestone layers of Sarvak formation, which are Mid-Cretaceous marine sediments, form the foundation of the dam, powerhouse and other appurtenant structures. These layers are generally tightly folded. An anticline (Siah Kuh anticline) with a sharp axial plane exists at the location of the planned dam axis [27]. The Sarvak formation is divided into seven geological units, namely Sv1–Sv7, with Sv1 being the oldest with no outcrop at the dam axis, and Sv7 the youngest.

3. 1. Rock mass properties

Based on geophysical surveys of the dam site using the petite seismic method, the rock mass is categorized into three general classes. Slightly deformed limestones of Sv2 unit form the most competent class with E=14GPa and intensely folded rocks of Sv3 form the weakest rock with E=2.7GPa. The middle class are slightly deformed thin layers of Sv3with estimated E=7.3GPa [27]. Laboratory tests on cored samples showed no distinct difference between the mechanical characteristics of the intact rocks taken from different geological units. Uniaxial compressive tests on 162 samples of intact rock gave an average unconfined compressive strength of 125±40MPa for dry samples and 110±30 MPa for saturated samples, excluding the tests on samples with pre-existing weakness planes.

3. 2. Discontinuities

Systematic discontinuities at the dam site consist of two joint sets that intersect at almost right angles and form a conjugate perpendicular system. A further joint set is observed at a few locations but its occurrence is not common throughout the site. Joints surfaces are characterized as planar and persistent with average spacing of 60–600 mm. The main joint set running through the dam site is J_1 (310°/15-90°). Joints in this set have a persistency of several to tens of meters. A second joint set J_2 (125°/35-75°) exists with persistency from a few centimeters to a few meters. The Geomechanical and grout properties are summarized in Table 1.

Table 1. Geomechanical and grout properties applied in the numerical modeling

Parameter	Range
Young modulus, E (GPa)	3
Shear Modulus, G (GPa)	9
Density (Kg/m^3)	3000
JKn & JKs (GPa/m)	10
Hydraulic aperture (mm)	0.01-5
Joint friction (deg.)	30-45
Jset # 1	310° /15-90°
Jset # 2	125° /35-75°
Grout mix ratio (w/c)	1-0.4
Grout specific gravity (Kg/m^3)	1450-1870
Grout viscosity (Pa.s)	0.007-0.044
Grout yield stress (Pa)	3-27
Grouting time (s)	600-1800

3. 3. Grout material properties

The most common grout mixture to seal the rock and soil is cement-based material. Portland cement is the most popular cement used in cementitious grouts. This hydraulic cement is composed of hydraulic calcium silicate and hardens by the chemical process of hydration. Portland cement normally has a specific gravity of 3.15 gr/cm^3 [3].In rock grouting the most important factors of grout penetrability includes water to cement ratio w/c, yield stress, grain size of cement paste, viscosity and setting time [28]. Low w/c ratio was suggested for micro-cement because of its increasing resistance after hardening and decreasing leaching of cement paste [29-30].In this case study, field trial grouting had been conducted by Portland cement with different w/c ratios from 1:1 to 0.4:1. Table 2 presents grout properties used at this site.

4. Grouting process at dam site

Trial grouting processat Bakhtiary dam site has been conducted to seal joints and fissures by decreasing rock mass permeability and improvement of foundation rock strength. Trial consolidation grouting was performed at the left abutment of dam in a cavern in King Band weak zone (Figure 3b). The zone contains frequent cracks, joints, anticline-decline and beddings because of high compression tectonic forces as shown in Figure 3a and 3c.

Grouting pattern is performed in an equilateral triangle. Grout boreholes are drilled with two meters distance from each other to 90m depth. To assess the grouted area water pressure test are conducted in the center of triangle. In fact the results of water pressure test and grouting flow rate of filed test have been used in this study.

Table 1. Grout properties used at dam site

w/c	SG (Kg/m^3)	Viscosity(Pa.s)	Yield stress (Pa)
1	1450	0.007	3
0.7	1590	0.012	7
0.6	1650	0.02	12
0.5	1770	0.025	21
0.45	1800	0.033	25
0.4	1870	0.044	27

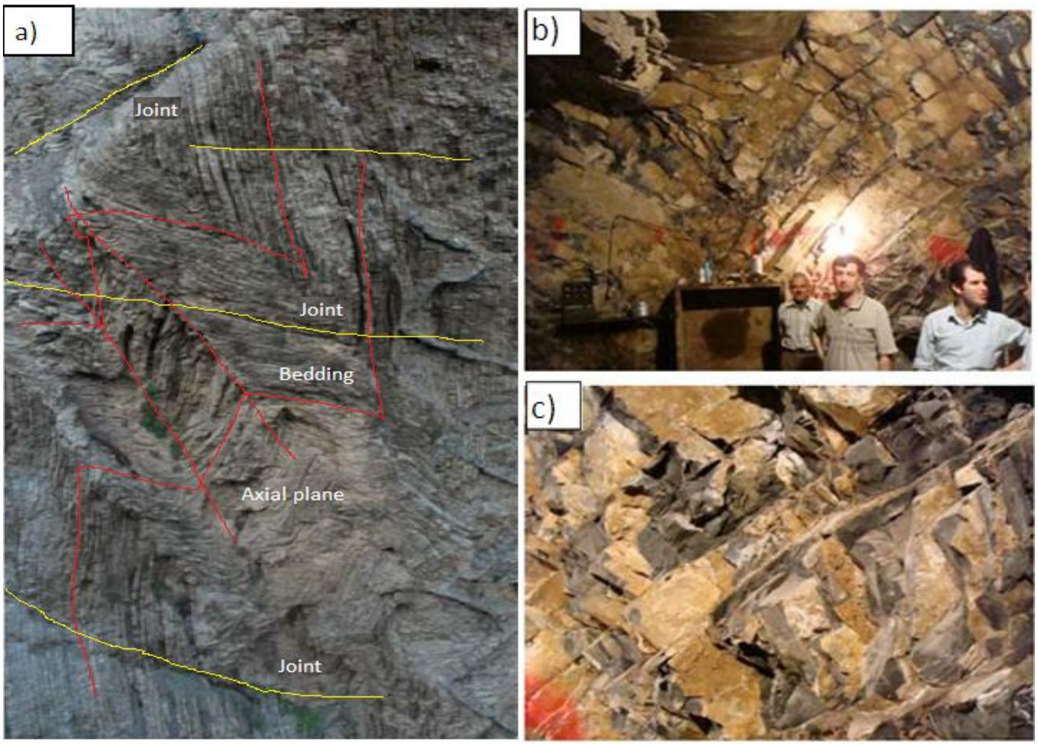


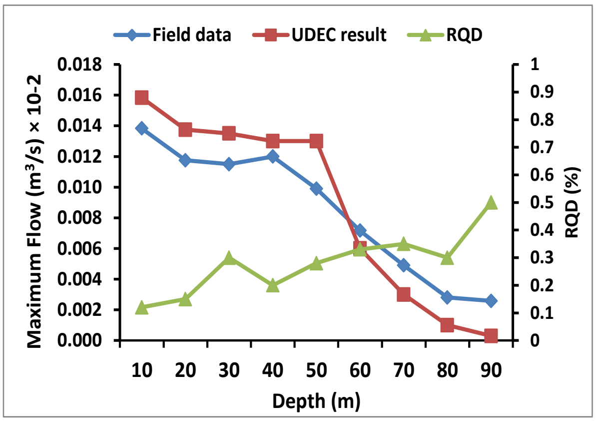
Figure 3. a) View of King Band zone (Sv2-Sv3), b) Cavern of grouting gallery (GL1), c) Close view of bedding, joints, clayey and calcite fillings.

5. Results

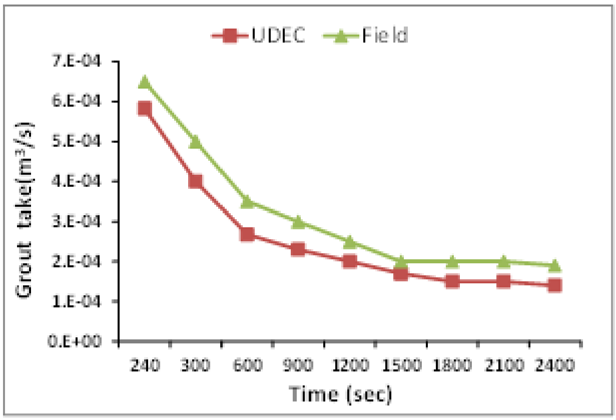
To obtain penetration radius of grout material around a vertical borehole, numerical models have been built in UDEC with 40×20 m (length×height) boundary with two regular joint sets according to case study in first scenario. The depth of grout boreholes is set to 10m below ground surface, which was suggested as an effective grout interval depth [2]. To confine the grout interval one meter of the upper part of borehole considered as impermeable material instead of pneumatic or mechanical packers. Having validated the model with practical data and analytical solution, a parametric study was done to observe the effect of joint properties on grout penetration radius. Figure 4 (a-b) compares the results of the flow rate and grout take obtained from lugeon tests in a borehole at the dam site with maximum flow rate from UDEC.

Before conducting lugeon test, core recovery was carried out and RQD was obtained for each section. As it can be observed, RQD will improve by increasing depth. On the other hand, the flow rate decreases. The results were roughly consistence consistent with [31], where he obtained a good correlation between joint

frequency with water loss at a dam project. As stated in Equation 6 and showed in Figure 2 by increasing the depth of grouting and vertical stress, the hydraulic aperture will decrease that leads to decreasing of flow rate. As shown in Figure 4 (a) numerical results using UDEC are in a same trend with practical data.
Moreover, in the grouting process, the grout take starting the filling of the borehole and jointed medium then it tends to reduce, gradually with time (Figure 4b). The input data for analyses to compare numerical model with analytical method included *P=2.4MPa*, *w/c=1*, *cohesion= 1.4Pa*, *viscosity=0.02Pa.s*, *grouting time=40min* and rock mass data obtained from Table 1. In addition, underground water flow and pore water pressure were neglected during modeling because of the dry area of grouting in dam site.



(a)



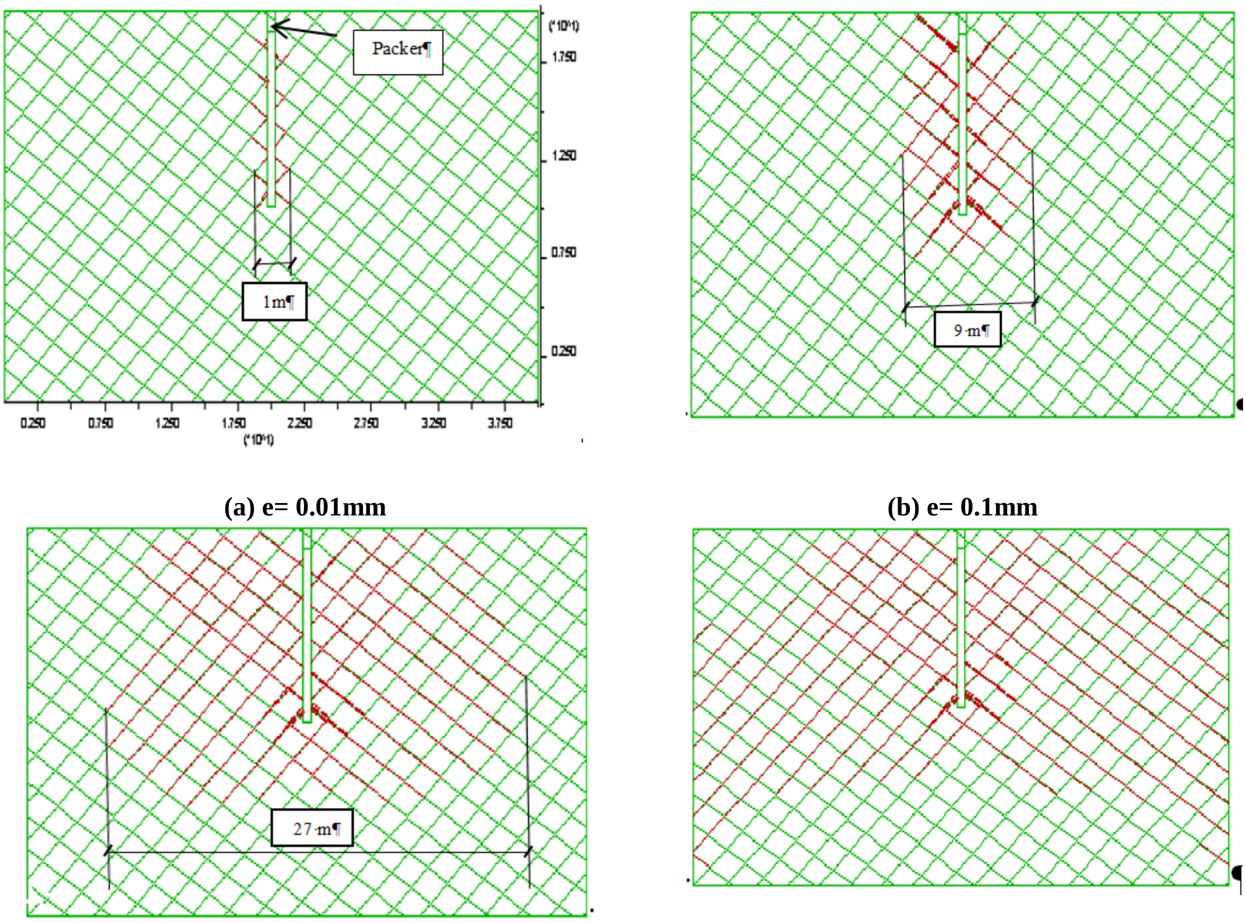
(b)

Figure 4. (a)Variation of RQD and maximum flow rate from lugeon test (field data) and UDEC with depth; (b) Variation of grout intake with time

Joint aperture is the key parameter for determining the flow characteristics of jointed rock media. However, measuring the joint aperture distribution is an extremely difficult task. For simplicity, joints have often been simulated as smooth and parallel joint walls to develop mathematical models [32-33]. Figure 5 shows grout spread simulation around a grout borehole under different apertures of rock joints using UDEC. Red lines show grout penetration into the jointed rock media.
The joints properties accounted for modeling were taken from Discontinuities Section. Because of the geometry of joints which can spread grout in horizontal direction rather than vertical direction the length of models is assumed to be two times its height. It can be understood that by increasing hydraulic aperture of rock joints from 0.01 to 2 mm the grout spread around the borehole will increase, significantly (Figures on the plots show radii of grouted area around the borehole). It is because of the important role of joint apertures where its effect on flow rate returns to well-known cubic law formulationas expressed in Equation 5. The above simulation has been carried out for more different joint apertures which were surveyed at the dam site. Figure 6 compares obtained grout flow rate from numerical solution by UDEC and analytical solution of Equation 4.
It can be seen that by increasing hydraulic aperture, analytical and numerical results of flow rate increase, similarly. For the small apertures, the numerical curve matched the analytical one. However, when joint aperture exceeds 1mm, the numerical calculation gave much flow rate than analytical method. The reason is that numerical calculation is based on cubic law however in analytical solution the exponent of aperture is of second order.

5. 2. Joint orientation

As grout will be flowing along the joints, the direction of the joints is also an important parameter. Since the most frequent discontinuity running through the dam site is J_1, then J_2 direction is taking constant and varying the value of J_1 direction from 10° to 90°, a series of analyses were carried out to determine the length of grout penetration. The results are shown in Figure 7(a-d). Figure 7e shows the grout flow rate as a function of angle between mean orientations



(a) e= 0.01mm

(b) e= 0.1mm

(c) e=0.3mm

(d) e= 2mm

Figure 5. Grout penetration around borehole under different apertures of rock joints; for all cases P=1MPa, C=7 Pa, w/c=1, t=15 min; Figures on the plots show radii of grouted area around borehole; red lines show grout penetration into the jointed rock media.

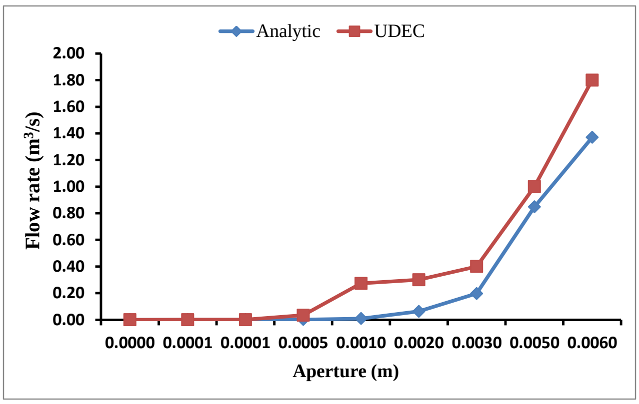
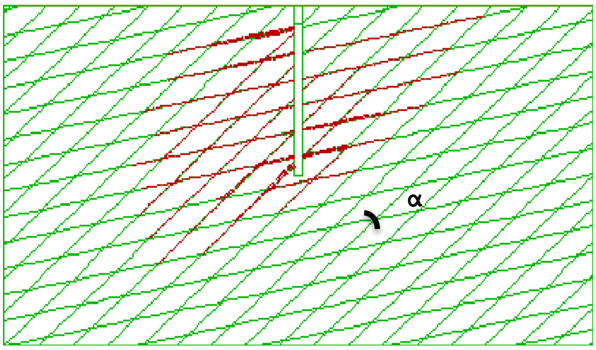
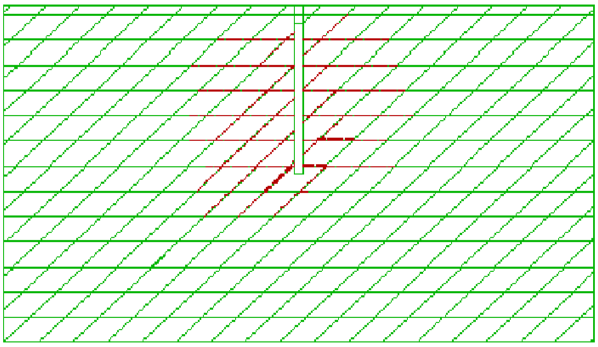


Figure 6. Variation of flow rate with joint hydraulic aperture by numerical and analytical solution

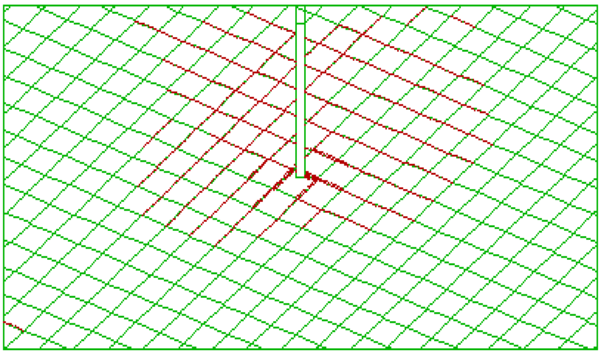
of the two joint stets. Maximum flow rate of grout occurs when the angle between the two joint sets is around 40°, whereas [21] shows that permeability is maximum if the angle between the joint sets is around 30°. However, the maximum flow- rate occur at the angle of 40° between two joint sets, the maximum penetration of grout is not related to this angle (Figure 7 c-d). It can be seen that the flow rate of grout will significantly decrease when joint angle exceeds 60°. This result is in agreement with experiences of Houlsby where he suggested joint dip 40-60° as the simplest joints for cement-based grouting point of view [2].



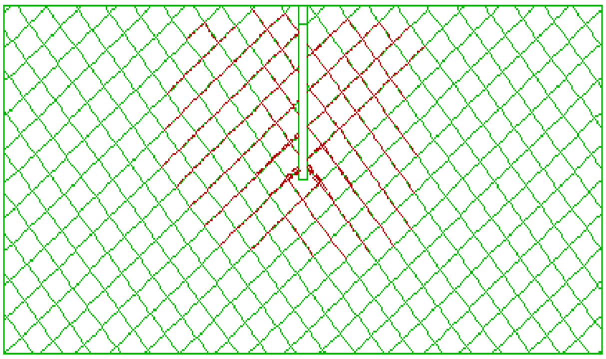
(a) α=30°



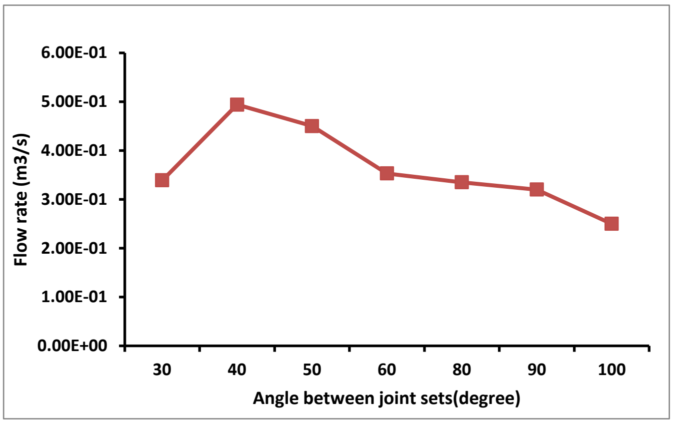
(b) a=40°



(c) a=60°



(d) a=90°



(e) Angle between joint sets

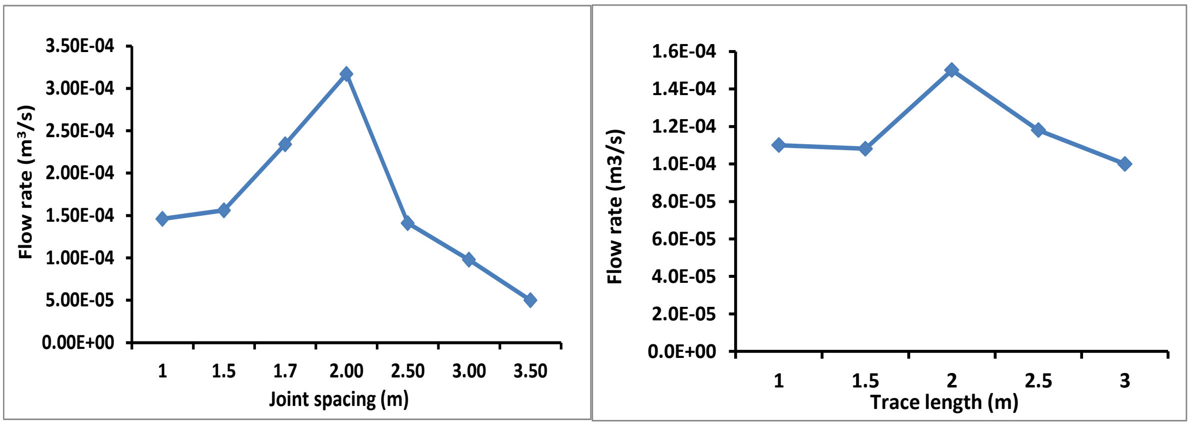
Figure 7. The effect of joint orientation on grout flow; (a-d) grout penetration (red lines) around a borehole with different orientation; (e) variation of grout flow with joint orientation.

5. 3. Joint spacing and trace length

Figure 8 (a-b) shows the results of the analyses carried out by varying the spacing and trace length of the joints respectively. According to the analyses, it can be understood that by increasing joint spacing and trace length grout flow into the rock mass increases, however when they exceed 2 m the grout flow will decrease, significantly. It seems that the joint spacing and length of 2 m is a cut-off for increasing flow rate of grout into the rock because the joint spacing and length more than 2m tend to formation of large block size then less joints will intersect the grout borehole, consequently grout flow decreases.

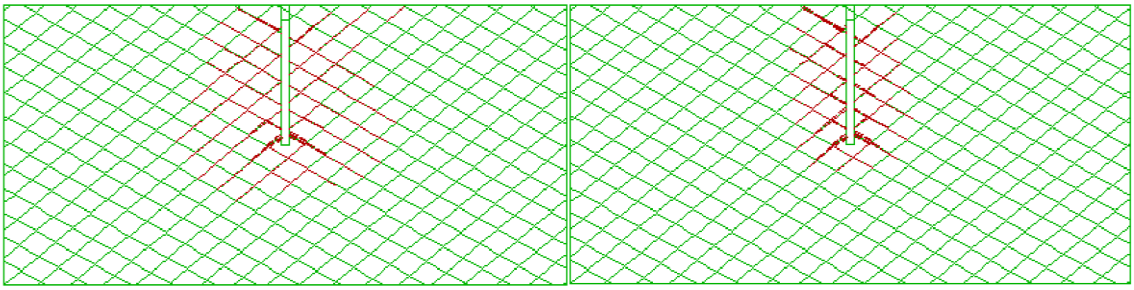
5. 4. Properties of grout

As stated in Table 2, grout properties are undoubtedly related to its w/c ratios. In this case study at the first run of grouting process the ratio was set to w/c=1 which decreased to w/c=0.45 with time. Since grout properties including specific gravity, cohesion (yield stress) and viscosity depend on the w/c ratio, then in this analysis the effect of grout cohesion (maximum shear stress that can be applied to grout in the static condition) is studied on flow rate into the rock using numerical model by UDEC and is compared to analytical solution by [8]. Figure 9 (a-d) shows the grout penetration into the joints around the borehole. Input parameters were P=1MPa, hyd. aperture =0.1mm, total grout time=25min.

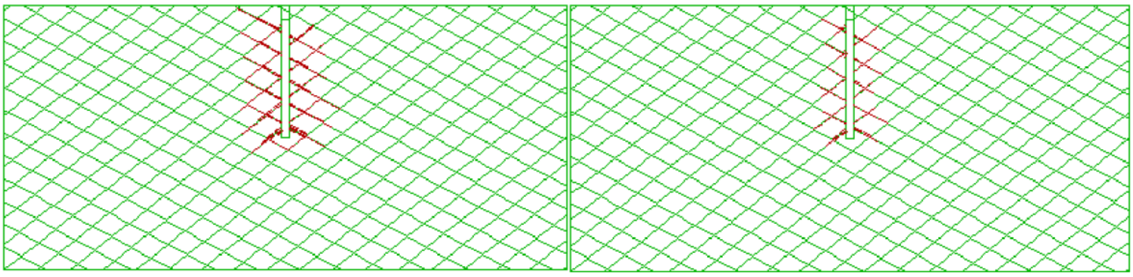


(a) Joint spacing **(b) Joint length**

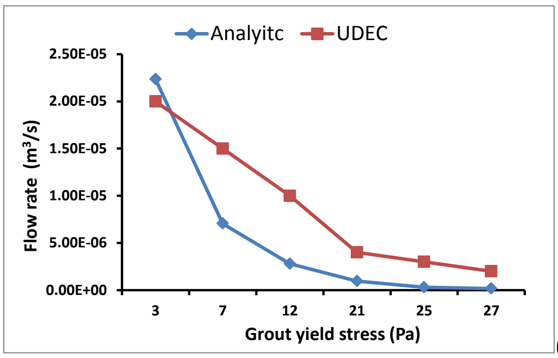
Figure 8. Variation of grout flow with joint spacing and length.



(a) C= 3Pa, t=5min **(b) C=12Pa, t=10min**



(c) C= 21Pa, t=15min **(d) C=27 Pa, t=25min**



(e)

Figure 9. (a-d) the effect of grout yield stress on grout penetration around the borehole; (e) variation of grout flow into the jointed rock with cohesion (yield stress).

As shown in Figure 9 (e) flow rate will decrease when cohesion of the grout increases. It can be understood that increasing the penetration length of grout with thick density, more pressure and time is needed to achieve the desired penetration length as cited by [7-8].

6. Discussions

One of the most significant parameters in measuring the usefulness of grouting is the penetration length of grout during the grouting process. However, the pre/post packer tests are not capable of precise estimations of this vital parameter [7]. Numerical simulations can predict the grout penetration in different directions under different conditions of grouting [36].

In this study, as shown in Figures 5, 7 and 9, the penetration length of grout and rock joints with different properties, joint orientation, spacing, aperture and trace length, and also grout cohesion was simulated using UDEC. More than 200 plots were obtained for different conditions and penetration length measured by averaging grout penetration in all directions using AutoCAD software.In some conditions such as different apertures and cohesions of grout, the results were compared with analytical method. The results can be seen in Figure 10.

It can be found that, penetration length of grout will increase when joint aperture increases (Figure 10a).

The results of numerical model are in good agreement with analytical method.

With an increase in angle between two joint sets the grout penetration length will increase, when it exceeds 60° the penetration length decreases (Figure 10b). Though flow rate maximized at 40°(Figure 7e) and afterward decreased, it can be stated that the most effective orientation of rock mass with two main joint sets for grouting process is where they meet at angle 40-60°.

By increasing joint spacing, the penetration length will increases (Figure 10c) because of creation of large block size and covering much area by joints.

Figure 10 (d) shows the decrease of penetration length when grout yield stress increases.

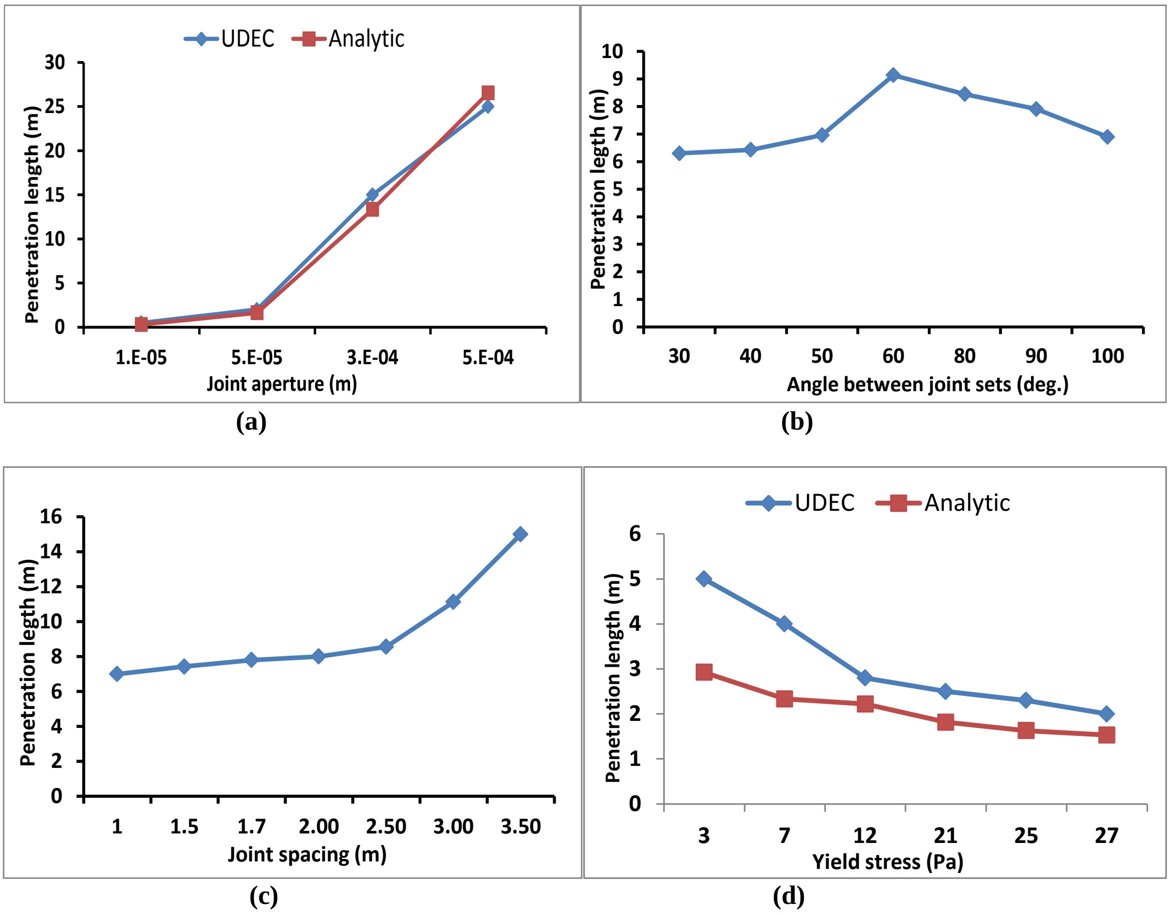


Figure 10. Variation of penetration length with (a) aperture, (b) orientation, (c) spacing, (d) grout yield stress

7. Conclusions

Predicting the grout penetration in jointed rocks is of interest because of its significance in engineering and scientific applications. Presuming that the grout functions as a Bingham fluid, a numerical model was developed to predict the flow of grout and its penetration length in jointed rock masses by means of Universal Distinct Element Code, UDEC.The findings were compared with analytical methods. In most cases results were in a good agreement with analytical method. The model was also validated with practical data from a case study. From the findings following consequences can be extracted:

- With an increase of the depth of grouting process, rock permeability and groutability will decreases because of the reducing hydraulic aperture under high insitu stresses.
- RQD, as rock jointing index, showed good correlation with permeability data in this case study. It was observed that, with improving RQD of rock mass the permeability will decreases.
- By increasing joint hydraulic aperture, the flow of grout increases significantly, using numerical and analytical method. Thus it can be concluded that the effect of hydraulic aperture on fluid flow is reasonably presented using cubic law.Analytical relation was presented to relate grout flow rate into the jointed rock mass with effective hydraulic aperture of rock joints. It was found that, the relation obey power law function with high correlation coefficient. The relation can be used to predict grout flow rate in this case study.
- Joint sets orientation have important role in grout flow and grout penetration length and it was observed that the most effective joint orientation for easy grouting is 40-60°.
- By increasing joint spacing and trace length the grout flow into the rock mass increases, however when they exceed 2 m the grout flow will decrease, significantly. the joint spacing and length of 2 m can be assumed as a cut-off for flow rate of grout into the rock because the joint spacing and length more than 2m tend to formation of large block size then less joints will intersect the grout borehole, consequently grout flow decreases.
- Grout flow rate will decrease when cohesion of the grout increases. It can be understood that to increase the penetration length of grout with thick density more pressure and time is needed to achieve interest penetration length.
- Grout penetration length will strongly depend on the rock joint hydraulic aperture, angle between joint sets, spacing, length of joints, cohesion or yield stress of the grout, grout pressure and duration time of grouting process. Some of these parameters are in direct relation with grout penetration length and others are in indirect relation.

Finally, the presented numerical model in this study can predict penetration length and flow of cement-based grout into jointed rock mass. Therefore, by determining the precise time of grouting and flow rate, pressure and distance of penetration, one can obtain a sealed and strengthened rock foundation and saves money in high costoperations.

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