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Hydromechanical Coupling Behavior Effects on The Bisotun Epigraph Damaging Process

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Abstract: Bisotun epigraph is one of the most important traditional monuments of Hakhamaneshi Period with 2500 to 2600 years old which is located 30 km far from Kermanshah. This epigraph has been subjected to various damaging factors, such as surface erosion due to water flow, ground water dissolution, weathering and rock block instability. Regarding to important role of water flow on damages, hydromechanical effects on the bisotun epigraph have been studied in this paper. Rock mass hydromechanical coupling behavior depends on various parameters such as stress conditions, rock modulus of elasticity, joint shear and normal stiffnesses and joint dilation which have been in center of this study. According to the results of this study, heterogeneity is one of the most significant factors on hydraulic and mechanical properties of the rock mass, also, fracture density, mechanical properties and stress conditions are another significant factors.

Key words: Hydrofracturing, hydromechanic, behavior, elasticity, flow, stiffness, coupling, rock mass

INTRODUCTION

Regarding to the importance of coupling behavior, specially in civil engineering, there has been a special attention to this subject in recent years, which proves that future studies will be on the way of coupling problems solution. Many experimental and in situ investigations in this field are good evidences for this statement (Anderson and Hudson, 2003).

Hydromechanical behavior has been studied in this study with Regard to the bisotun epigraph case study (Fig. 1).

Of course, exactly understanding, characterization and modeling of the rock mass properties, are unattainable. But coverage all geometrical details and mechanical effects is not needed in practice. How comprehensively the coupled mechanisms have to be modeled should be related to the objectives of the modeling. For many applications, existing understanding and computer codes are sufficient; whereas for some other applications, development of more sophisticated tools is required (Desai and Christian, 1997; Ewalds and Wanhill, 1984).

Fig. 1: View of bisotun epigraph

Regarding to complication of the hydromechanical coupling behavior and better understanding of main factors, softwares of UDEC and 3DEC and Ansys have been used. Usually, there are some limitations in most of softwares to model hydromechanical behavior exactly, therefore some codes have been written to remove limitations (ITASCA, 1999).

Analyses are based on following formulations:

The vertices of the triangular elements are gridpoints and the equations of motion for each gridpoint are formulated as follows:

$$\ddot{U} = (\int_s \sigma_{ij} n_j d_s + F_i^z + F_i^c + F_i^l)/m + g_i$$

where, s is the surface enclosing the mass m lumped at the gridpoint, $F_i^z = \int_c \sigma_{ij} n_j d_s$ and F_i^c is the contact force along boundary.

The following effects are modeled in UDEC:

$F_i \quad = \quad P n_i l,$
$q \quad = \quad -k_j a^3 \Delta p / l$

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Δp = kw $(\Sigma Q \Delta t - \Delta V)/V$
ΣQ = Flow into node
ΔV = Mechanical volume change
a = Joint aperture
l = Joint length
q = Domain flow rate
F = Joint force
p = Joint pressure
k_w = Bulk modulus of the fluid
k_j = Joint permeability factor

Flow is governed by the pressure differential between adjacent domains. The flow rate per unit width can be expressed as q, which is based on the obtained mean velocity from the analytic solution for laminar viscous flow.

Darcy's law for an anisotropic porous medium is:

$$V_i = k_{ij}\,\partial p/\partial x_j$$

where, V_i is the specific discharge vector, p is the pressure and $_{kij}$ is the permeability tensor.

The specific discharge vector can be derived by gauss' theorem:

$$\partial p/\partial x_i = \int_s p n_i d_s / A$$

Joint dilation is effective when the joint is at slip. The normal displacement increment, ΔU_n^d due to dilation is calculated as:

$$\Delta U_n^d = \text{tng}(\text{dil})\Delta U_s \text{sign}(U_s)$$

where, ΔU_S is shear displacement increment and dil is joint dilation angle.

Numerical analysis must be based on the proper comprehension of major factors, therefore we need to an appropriate understanding of their coupling to get the best results (Kanninen and Popelar, 1985).

GENERAL DESCRIPTION

This 18×3.2 m epigraph is located on a limestone rock mass which consist of some discontinuities. These fractures are effective on the value of elasticity modulus, rock mass strength, permeability, water flow direction and sedimentation on epigraph surface. Therefore study on the fracture network and joint development is essential. Epigraph has been subjected to Hydro-Thermo-Mechanical-Chemical processes which have made karstic holes and surface erosion (Karimnia and Shahkarami, 2006).

The following factors are the most significant factors on making damages:

- Surface and groundwater flow on epigraph surface
- Weathering (consist of physico-chemical processes)
- Fatique due to temperature changing
- Rock geometry alteration

The rock mass contains many fractures. Regarding to the important effects of discontinuities on the rock mass behavior, we study on the properties of discontinuities in this part. This study shows that there are two major fracture sets, Two minor fracture sets and a bedding surface set.

Bisotun rock mass is formed by Bisotun limestone and located on a tectonic zone with many faults and fractures. Faults show the historical stress conditions in this area.

Water originates from a near minor fault which is located on intersection between two faults. Thus it can be concluded that this site has been subjected to tectonic stresses.

Because of steep slope and high mountains, it can be concluded that the rock mass strength is high.

The epigraph is divided to upper and lower parts by a bedding surface which it's slopecause water flow toward epigraph. Surface erosion of the upper part is more than the lower part.

GEOTECHNICAL INVESTIGATIONS AND MICROSCOPIC TEST RESULTS

To study the rock specifications, some tests have been done on some samples.

Results of this study show that regarding the voids which are full of calcite, increasing of the void ratio is unavoidable, because of calcite erosion.

Rock mass is under climatic condition and water influences through it and dissolves CO_2 of the soil, air and plants thus change to acid water and can dissolve calcium carbonate. Therefore lime dissolution due to this water is unavoidable. In addition, fracture development in this limestone and in the upstream of the epigraph make a karstic zone in Bisotun limestone (Mehdi Abadi, 2000).

Tectonic study shows that according to seismic zoning of iran, Bisotun mountain is located on the high risk zone. During the last 100 years, most of earthquakes have happened around 3 points which are around Bisotun mountain, kashmar and Bandar abbas.

More than 6 earthquakes have happened during 4.5 years in Bisotun. Bisotun bedding layer system and fracture network are unique in geological science. Sedimentary layers are nearly horizontal, fractures and faults networks are parallel to each other and vertical to bedding planes. Therefore damages happen due to landslide and slide happens along the surface.

The following items are major properties of Bisotun epigraph rock mass discontinuities:

Fracture orientation

The first major fracture set: This set is very important. That is parallel to the epigraph surface and is developed into the limestone deeply. Therefore it has a main role in water flow specially around epigraph.

The second major fracture set: This set is nearly vertical to the first one and intersects epigraph surface. This set is important to rock mass hydraulic conductivity .Where this set intersects epigraph, water flow and karstic holes are visible. Number of fractures in this set are less than the first one. Intersection of this set with bedding surface has made a flow channel to water conduction toward epigraph surface.

Minor fracture set: This fracture set is not developed very much into the rock mass, therefore it does not have an important role in ground water conduction, however, that is important to dissolution and development of karstic holes into the limestone.

Bedding planes: That is known as a main factor in water conduction toward epigraph surface.

Fracture spacing: Fracture spacing is 1-2 m in the first major fracture set and 3-5 m in the second major fracture set. Although bedding plane spacing is 1m, only two layers with 40 m distance are visible, thus bedding plane spacing is considered 40 m. Random fracture set spacing is variable.

Fracture length: Major and minor fracture sets consist of very long fractures and some of them are longer than 40 m. Bedding planes are developed very much but random fracture sets consist of short fractures (at most 5 m). Therefore major and minor fracture sets and bedding plane are important in water conduction.

Surface roughness: The most important fracture sets are rough, thus jrc 100 and jr are considered 9 and 3, respectively. This parameter value is considered 2.3 for bedding plane. Fracture surfaces are weathered and without filling material so ja is considered 1.5. Thus we can obtain the value of internal friction angle which is determined equal to 45. These fractures are developed into the rock mass deeply.

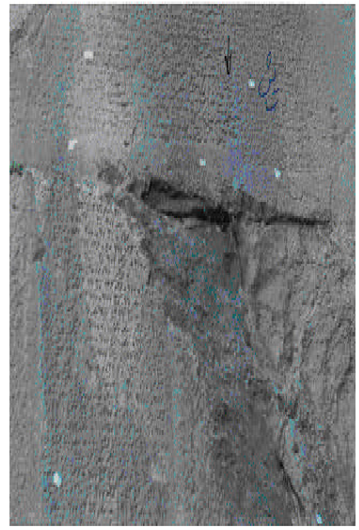

Fig. 2: Water flow into rock mass

Fracture's wall strength: According to the results of in situ tests, fracture's wall strength is obtained about 24 mpa.

Joint aperture: The maximum value of joint aperture, 1-2 mm, is related to two bedding surfaces, 40 m distant from each other. This joint aperture is only visible on the surface and there is no information about it's development into rock mass. This aperture is made due to water dissolution. Two major fracture sets aperture values are not greater than .1 mm and minor fracture sets aperture are nearly closed. Therefore we conclude that the major fracture sets conduct raining water toward the bedding surfaces and then conduct it toward rock mass surface.

Filling materials: Only random fracture sets and small fractures are filled with calcite but another fracture sets does not have any filling materials. It is considerable that water flow into the rock mass, has made rock mass fractures (Fig. 2).

EFFECTIVE FACTORS IN NUMERICAL ANALYSIS

Stability of Bisotun epigraph is changing in some aspects (Fig. 3):

- Tectonic loading which can be explained by weight and changing boundary conditions
- Thermal loading
- Loading and erosion due to water suspended solids

Fig. 3: Main fractures in bisotun epigraph

- Dissolution due to ground water
- Micro-structural changes, weathering and degradation

This research intend to explain a methodology using fracture and fatique. To study on stability analysis, critical points of the Bisotun epigraph and the physical comprehension about the reason of inclined crack in the right side of the epigraph, numerical modeling is used by ansys software, which is a powerful software.

Regarding the geotechnical investigations and analysis of the test results, rock mass mechanical properties are mentioned below:

MODELING AND NUMERICAL ANALYSIS OF HYDROMECHANICAL COUPLING

To study on the rock mass hydromechanical behavior, Ansys, 3Dec and Udec softwares have been used. These softwares are among the most powerful softwares for:

- Intact rock rock mass
- Compressive strength 30 4
- Tensile strength 4.5 .53
- Elasticity modulus 5.7 2
- Poisson ratio .31 .3
- Cohesion 8.5 1.5 Internal friction angle 30 25

M 4.86 0.22 S 1 0.012 geotechnical modeling but have some limitations to hydromechanical modeling. Therefore these limitations have been removed with programming (Sato and Hiragawa, 2003).

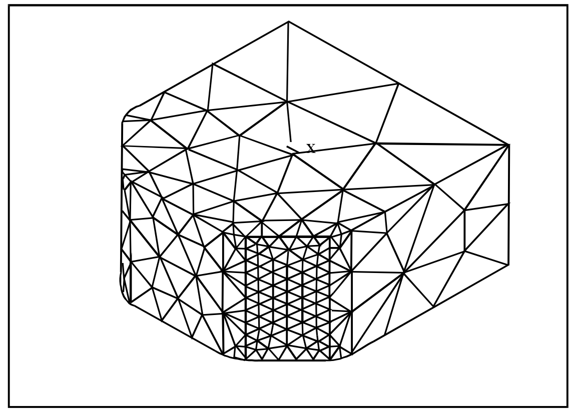

Fig. 4: Modeling of bisotun epigraph domain

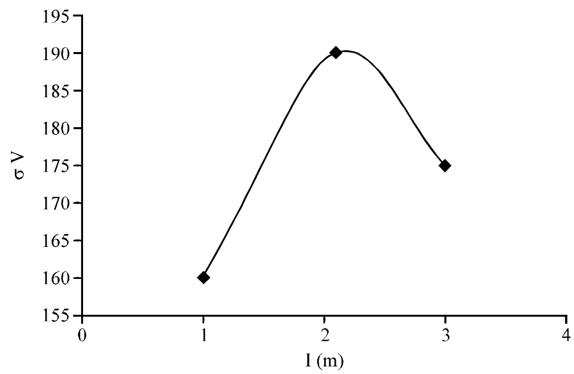

Fig. 5: Vertical stress state around epigraph

Rock mass initial conditions have been studied and blocks stability analysis have been done in this paper. In this modeling, joint geometrical and mechanical properties, rock mass mechanical properties, boundary conditions and loading have been considered exactly (Fig. 4), then hydraulic properties sensitivity to mechanical properties, stress variation, mechanical boundary conditions, initial mechanical aperture and geometrical fracture net have been studied.

Study has been done on the behavior of rock mass and stress-strain state around epigraph. Rock mass consists of various joint sets and bedding surfaces which are introduced with more details in this part (Wilson, 1997; Zienkiewicz and Taylor, 1989).

According to the analysis results, stress and strain distribution have been evaluated. Maximum vertical stress and maximum shear stress are equal to 1.9*10e2 (KP) and 0.9*10e2 (KP), respectively. Stress and strain distribution show that, rock mass around epigraph has been subjected to significant stresses (Fig. 5, 6).

Induced stresses on epigraph rock mass due to water pressure, has been considered. This pressure value is 18

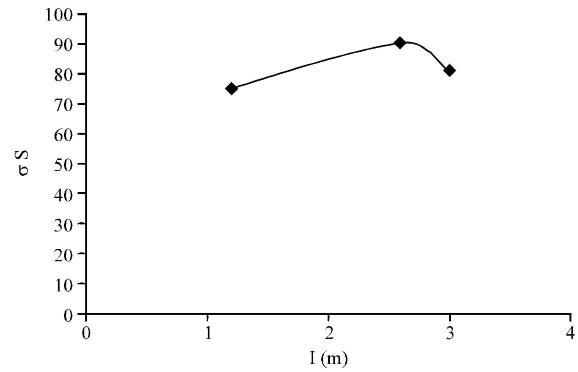

Fig. 6: Shear stress state around epigraph

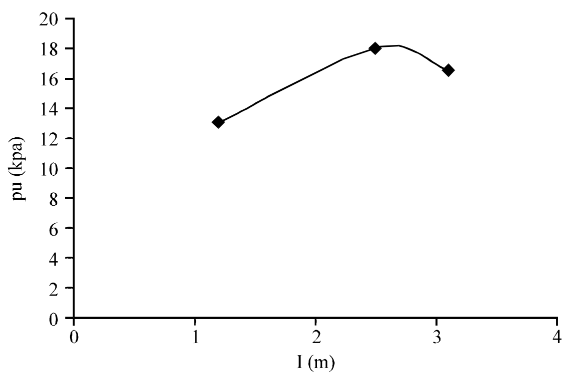

Fig. 7: Hydraulic pressure around epigraph

(KP) which is a significant value. Obtained results show that, hydraulic pressure has had a significant role on epigraph behavior (Fig. 7).

Analyses which have been done to assign blocks stability safety factor around the epigraph, show that the most critical value of the safety factor is limited to 2 which can be considered as an appropriate safety (Fig. 8).

To study on the joints density effects on the seepage condition, various analyses have been done. Firstly, j1 and j2 joint sets with 1(M) and 2(M) spacing then j3 random joint set have been considered (Fig. 9).

Obtained results show that, increasing fracture density cause increasing the seepage value. Also seepage in random fractures is more than organized fractures in order that there are more connected fractures in this case.

Regarding to the importance of stresses on seepage value, some models have been analysed to study on this subject. According to the results, increasing of the lateral stresses from 20 to 80 KP cause about 40% decrease in seepage value (Fig. 10).

Regarding to significant effects of stress state on seepage value, proportion of the joint shear stress to joint

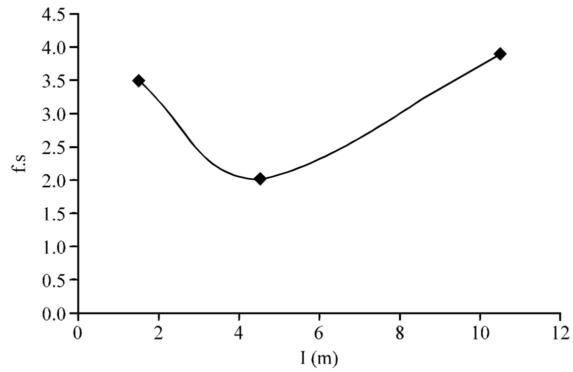

Fig. 8: Blocks stability safety factor around epigraph

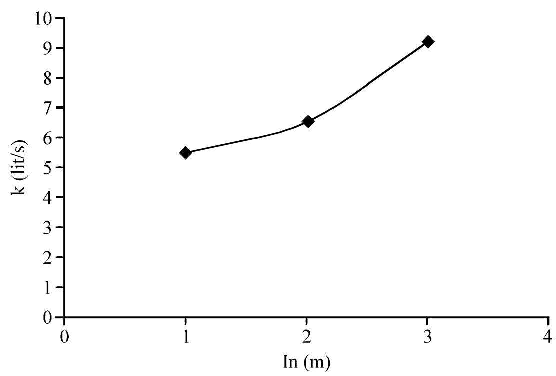

Fig. 9: Joint density effects on seepage

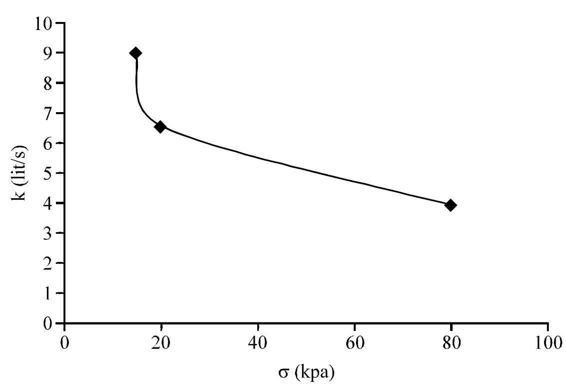

Fig. 10: Effect of stresses on seepage

normal stress has been considered as a main factor. If this factor remains constant and sliding does not happen in the fracture, normal stress increase makes seepage reduction.

If the mentioned factor changes but joint slip does not happen, increasing of this factor cause seepage value reduction (Fig. 11).

If increasing the mentioned factor causes joint slip, seepage value will increase (Fig. 12, 13).

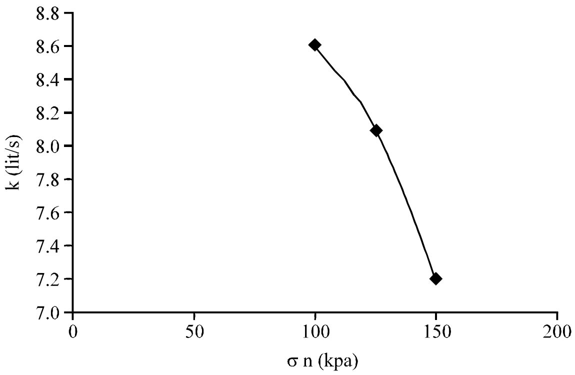

Fig. 11: Stress state effects on seepage

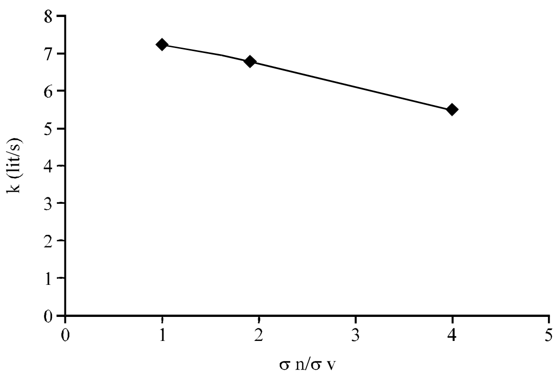

Fig. 12: Proportion of joint shear stress to joint normal stress effect on seepage

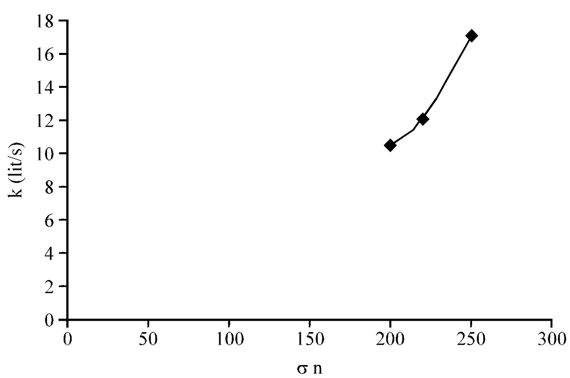

Fig. 13: Stress state effects on seepage

Joint length effects on seepage value has been studied. Obtained results show that, seepage value has been increased with joint length increase.

Two significant factors in rock mass seepage value are elasticity modulus of the rock mass and joint normal stiffness. Reduction of the rock mass elasticity modulus cause seepage increasing because of joint aperture increasing due to deformability increasing. Also joint normal stiffness decreasing cause seepage increasing (Fig. 14, 15).

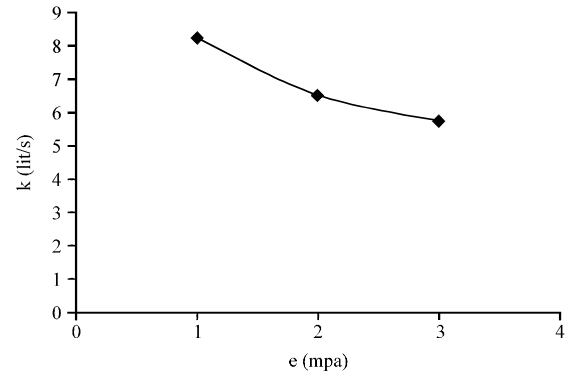

Fig. 14: Elasticity of rock mass effects on seepage

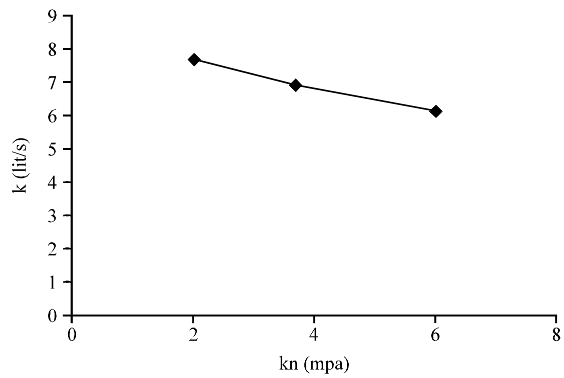

Fig. 15: Joint normal stiffness effects on seepage

How to solve fractures problem: The best solution to correct cracks and joints and fractures around the epigraph is the use of injections. Because of that, from the inside of boreholes with approximate diameter of 10 cm must inject into the rock mass around the epigraph. Considering the importance and sensitivity of the project and its historical value, Injection operation must be done carefully and with high quality. One of the most important parameters in this project is injection pressure, which should be fully controlled and its value must be assigned using numerical analysis.

Therefore the numerical analysis are performed on the result and specifications and limitations of injection pressure has been analysed.

Model and analysis scheme are shown in the model in Fig. 16. Analysis results show that in order to improve joint and cracks in rock mass should have a maximum injection pressure about five bar.

Results of the analysis are shown in Fig. 17-19. In fact, if the injection pressure to reach more than five bar, hydraulic fractures will actually begin, It means that five bar pressure is hydraulic fracture initiation value, Therefore injection pressure should never be more than five bar.

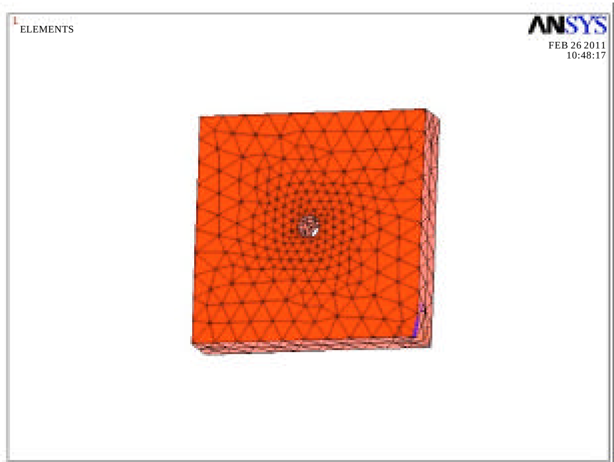

Fig. 16: Meshing of the injection model

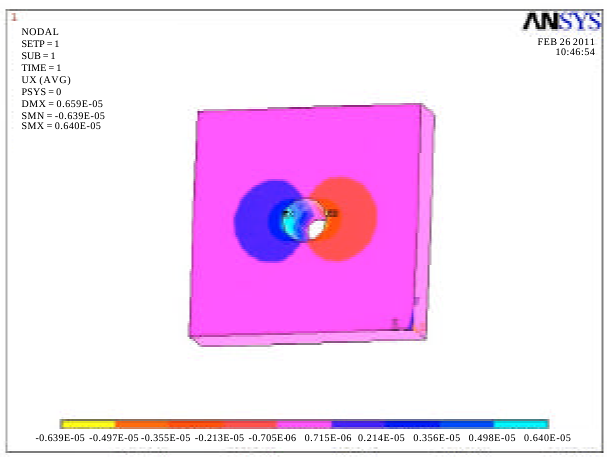

Fig. 17: Stress state around borehole in the model

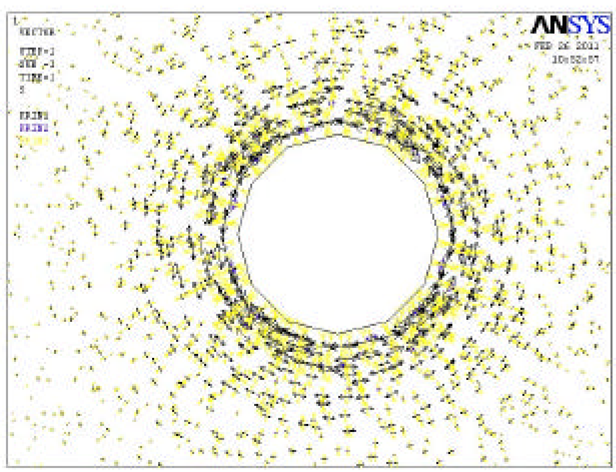

Fig. 18: Stress state vectors around the model

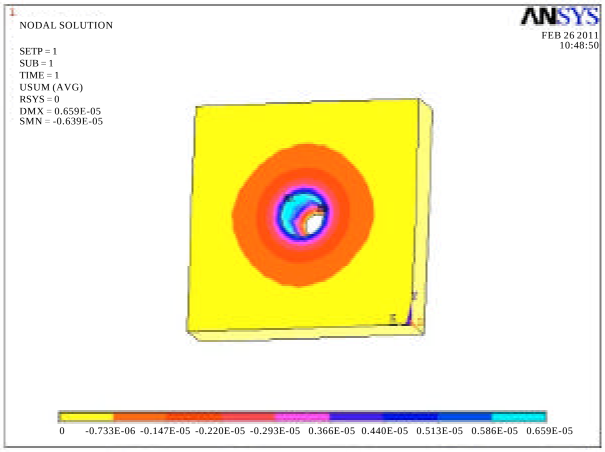

Fig. 19: Displacements around the model

DISCUSSION

The following items are the main results of this study:

- Obtained results show that the fracture density is a very effective factor in hydromechanical behavior of fractured rock mass, because of the significant effect of the fracture as a localized path to fluid flow
- Regarding to heterogeneity of rock mass, mechanical loading can cause opening and closure of joints. This can induce changes in rock structure and fluid properties
- If the stress state in the model changes and proportion of the joint shear and normal stresses remains constant, increasing the normal stress cause decreasing the joint permeability. The reason of this result can be explained by the joint closure due to normal stress increase which results permeability decrease
- If the stress state in the model changes in a manner that joint shear and normal stresses proportion increase but joint does not slip, then hydromechanical behavior will be same as previous item
- If stress state changing causes joint slip, then joint dilation will happen which cause normal displacement and joint permeability increase
- Joint dilation will not continue after critical shear stress, therefore in a certain proportion of shear stress to normal stress, the permeability value will be constant
- Joint aperture changes with joint length variation and block size change, but aperture sensitivity to these factors is much less than to mechanical properties and stress conditions
- Joint and rock mass mechanical properties are important factors on fluid flow through rock mass. It can be explained with this reality that joint and rock matrix stiffness are directly related to deformability of joints and rock matrix therefore they will be effective on joint aperture and fluid flow (Khak Payeh Consulting Engineers, 2002)
- Confining pressure increasing, cause permeability reduction which can be explained with joint closure due to confining pressure increase

CONCLUSION

Bisotun epigraph which is located on a limestone rock mass, has been subjected to different damaging factors which water flow has been the most important one among them. Therefore, rock mass hydromechanical coupling behavior has been studied in this paper to evaluate the effects of these factors on the rock mass hydraulic and mechanical behavior. Results show that the main geometrical effect on hydraulic behavior is fracture density. Also, sensitivity investigations show that hydromechanical coupling effects is significantly related to the rock mass and joints mechanical properties. Therefore understanding of the mechanical properties of joints and rock mass and fracture densities is a key factor to better understanding of the rock mass hydromechanical behavior. Joint and rock matrix stiffness and their properties are significant factors in rock mass permeability.

Furthermore, if induced stresses cause normal stress increase then joint closure happens and permeability reduces, but if they make joint slip then permeability increases.

Regarding to the rock mass strength gradually reduction during the long time due to the mentioned factors, possibility of current fracture development and new fracture initiation and propagation will increase. Therefore finding appropriate methods such as rock pressure reduction and water flow prevention is needed to prevent development of epigraph damages.

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