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Numerical Modeling of Hydraulic Stimulation in HDR Reservoirs by 2D Distinct Element Method

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ABSTRACT

Hot Dry Rock geothermal reservoirs are considerably different from conventional geothermal reservoirs which exist only in the geologically privileged regions. In fact, HDR reservoirs are artificially created reservoirs which can be considered at any accessible depth of the Earth's crust with a suitable volume of hot dry rock. One of the main characteristics of HDR reservoirs is enough permeable paths to allow water flow in the region between injection and production boreholes. Hydraulic stimulation is a technique employed to create these permeable paths in such regions.

It is important to know the shape, size and permeability of the fractured zone created by stimulation in order to assess the feasibility of the project and to determine the optimum relative locations of the injection and production boreholes. Improving permeability allows the system to reduce its hydraulic resistance. This operational hydraulic parameter called impedance is related the pressure required to force water through the reservoir. Another parameter called the water loss rate is the difference between the rates of water injected and produced.

Since stimulation experiments conducted at great depths are very expensive, numerical modeling can play a significant role. In this paper, the hydraulic and mechanical response of jointed rock mass in an HDR reservoir is considered under the high pressure hydraulic injections using a distinct element code. The code is capable of considering the Hydro-Mechanical coupling. A parametric study on different joint specifications is carried out to illustrate the variation of impedance and water loss rate.

1. INTRODUCTION

The first Hot Dry Rock concept was based on the assumption that deep crystalline basement rock formations are nearly dry and impermeable. It was therefore suggested to create artificial fractures in the rock mass and to use these fractures as an underground heat exchanger. The concept is very simple; a pair of wells is drilled into the rock, which is several hundred meters apart. Water is injected into a borehole and circulated through a heat exchanger of hot cracked rock several kilometers below the surface. The water is heated through contact with the rock and is then returned to the surface through another borehole where it is used to generate electricity or heat for direct application.

This concept was then modified by scientists at Los Alamos and the Camborne School of Mines HDR site at Rosemanowes, Cornwall. They emphasized the natural joints or pre-existing fractures in rock. The scientists found that these natural fractures could be interconnected and their permeability improved by hydraulic stimulation.

In fact, injecting fluid into the rock mass raises the reservoir pressure sufficiently to increase the transmissibility of fractures in three ways: by restoring the permeability to its original state in joints that may have been sealed with water-rock geochemical interaction products, by simple reduction of confining stress or by shear slippage in unsealed fractures, or even possibly creating new fractures in the reservoir rock (Murphy et al., 1999).

A complete modeling of HDR systems includes coupling of thermal (T), hydrological (H), mechanical (M) and chemical (C) processes. The term "coupled processes" means that due to effects of one process to another, the rock mass response to the injection of high-pressure fluid cannot be predicted by considering each process separately. To date, many simulation codes have been reported in the published works, and each has its own advantage. Generally, the codes can be categorized according to their capability into four groups: exploration, stimulation, circulation, and heat extraction. The difference between models of stimulation and circulation is a natural one. Since the stimulation occurs only during some hours to days, evolving rapid fluid-rock hydro mechanical coupling, it differs significantly from circulation, which runs in years and involves thermal-mechanical-chemical coupling. Since the aim is to study HDR reservoir behavior during *stimulation*, the effects of high temperature and chemical changes are ignored.

2. HYDRAULIC PERFORMANCE

The purpose of stimulation or reservoir creation is to begin the process of opening or improving the interconnectivity of flow paths between the injector and producer. This enhancement of the connectivity must meet operational hydraulic parameters.

One operational hydraulic parameter of great interest is the flow impedance, Z, which is defined as pressure drop between the injector and producer divided by the flow rate at producer.

The impedance includes components of both wellbores in addition to that of the reservoir. The wellbore impedance is usually small and is comprised of two parts. The first is frictional resistance to flow, which can be calculated with the usual pipe friction equations and friction factor-Reynolds number correlations, and is usually very small. The second part varies with time and originates from the density difference in the injection and production wells. When injection proceeds, the temperature of entire length of injection well is the same as injected surface water temperature, typically 20-40°C, while the production well approaches the reservoir temperature. Therefore a thermo-siphon is constituted, resulting from both a deep column

cold, dense water and column of hot, lighter water. It is caused a pressure gain of less than 1 MPa, whereas the pressure loss in the reservoir is usually several times greater. Hence, the reservoir impedance is the main term of overall fluid impedance (Murphy et al., 1999).

For practical purposes, the impedance should be less than 1 MPa-s/l, and it is estimated that flow impedance should be in the range of 0.1 MPa-s/l to meet economic goals. Most engineered reservoirs operated to date have met the upper requirements, and some are approaching the lower. Larger impedance values require a much higher pumping capacity for fluid circulation. Obviously, circulation at high pressure is associated with enormous fluid losses. Such losses may occur by fluid penetration into the rock matrix.

Therefore, fluid loss is another important practical parameter which must be considered. This has been defined as the difference between injection and production flow rates. The water loss is related to the size of reservoir, the operating pressure, and permeability of the surrounding rock, as well as the possibility of connection to a nearby fault system. Flow impedance and water losses are highly dependent on pressure, but impedance is inversely proportional to pressure. Thus, high pressure increases water loss but decreases the impedance.

If water loss is the major concern, the operator can attempt to establish the best balance between low impedance, obtained by increasing pressure, and low water loss, achieved by reducing pressure.

Many experiences to date suggest that a stepped flow rate stimulation with a maximum flow rate of around 100 l/s and a total volume of around 25000-30000 m^3 is sufficient to enhance the permeability to the required level (Baumgärtner et al., 1998).

Many computer codes have been developed to assist in the understanding of the processes during stimulation. Modeling stimulation and obtaining the pressure and flow rates values at injector and producer, makes it possible to estimate above hydraulic parameters and interpret them to choose the best option.

3. INTRODUCTION TO THE DISTINCT ELEMENT CODE

Generally, two methods are used for modeling a fractured rock medium. The first models the rock mass as an equivalent porous continuous material, so the solution technique can be based on continuum representations using mainly FEM and FVM methods.

In the second approach, a completely different method is used. The method models the rock mass as an assemblage of distinct blocks separated by discontinuities and the solution technique can be based on discrete element method. In this study, a distinct element code (DEM) is used.

The used two-dimensional code is capable of modeling coupled thermo-mechanical analysis for discrete block systems and coupled hydro-mechanical analysis through discontinuities. In rock with a low intrinsic permeability of the matrix, joints form the only detectable flow paths. In a rock with a low natural permeability of the matrix, joints are the major detectable flow paths. Therefore, fluid flows only across discontinuities, and poroelasticity is not considered for the solid matrix.

3.1 Hydromechanical Coupling

The coupled hydromechanical modeling consists of considering hydraulic and mechanical behavior and their effects on each other. As mentioned, the rock mass is assumed to be an assemblage of discrete blocks (rigid or deformable) interfaced by discontinuities. These blocks can interact with each other through joints. In deformable blocks, to achieve solid block deformation, an internal discretization with trianglular zones is used. The numerical approach uses a staged analysis for each element and its nearest neighbors. The numerical stability of the algorithm is provided by limitation of each time step.

The used distinct element code can perform fully coupled hydromechanical analysis for jointed rock masses in which the deformation of the solid rocks is affected by the water pressures in discontinuities according to Terzaghi's law:

$$\sigma'_{ij} = \sigma_{ij} + p\delta_{ij} \tag{1}$$

where p, δ_{ij}, $\sigma'_{ij,}$ σ_{ij} are fluid pressure, Kronecker delta, effective and total stresses (negative in compression), respectively. The apertures of the discontinuities and water pressures are updated at each time step. Conversely, the conductivity of discontinuities depends on the mechanical deformation of the solid rocks.

The blocks are considered as impermeable with fluid flows only through the joints. Flow analysis is carried out through hydraulic domains, which are defined as fluid volumes between the contacts. Domain volumes depend on normal displacement at two ends of the domain. Normal displacement, u_n, results in change in hydraulic aperture according to the following relation:

$$a = e^0 + u_n \tag{2}$$

where e^0, is the aperture at zero normal stress. A positive value of u_n is considered joint opening. A minimum (residual) aperture, e_{res}, is assumed for discontinuities to consider contact permeability even under high mechanical closure.

The cubic law for flow in planar fractures is adopted for conduction of fluid through discontinuities. The flow rate q, is then given by:

$$q = \frac{e^3 (\Delta p / L)}{12\mu} \tag{3}$$

where μ, L and Δp are dynamic viscosity of the fluid, length assigned to the contact, and pressure difference across a contact between adjacent domains, respectively. The fluid pressure in the domain is given by

$$p = p^0 + K_f \, Q(\frac{\Delta t}{V}) - K_f (\frac{\Delta V}{V_m}) \tag{4}$$

where p^0, Q, K_f, Δt, V^0, and V are domain pressure at the previous time step, sum of flow rates into the domain from all surrounding contacts, fluid bulk modulus, time step, domain volumes at previous, and current time steps, respectively. The volume change of a domain is given by $\Delta V = V - V^0$ and $V_m = (V + V^0)/2$.

The domain pressures are resolved into forces exerted by fluids at contacts and are added to the mechanical contact forces and external loads for kinematic calculation of blocks at the next time step. Therefore, total stresses are the results inside impermeable blocks and effective stresses are obtained for contacts between blocks (Chan et al., 1995).

4. NUMERICAL MODELING

In order to study the behavior of jointed rock mass under increasing water pressure, a two-dimensional problem of rock mass containing two sets of orthogonal, regularly spaced joints and subjected to a biaxial in-situ stress state is considered.

4.1 Model Statement

The numerical model used for the stimulation covers a surface area of 50×20 m^2 in a depth range of 3000m and with joint spacing of 2.5m. Three wells of 0.4m in diameter, one as injection well, located in the center and the others as production wells with a distance of 10m from center are defined. Figure 1 illustrates the pattern of joints, represented in this model. The discretization of the blocks and the domains are shown in Figure 2. A finer mesh is used in the vicinity of the wells.

The mechanical material properties used in this model are shown in Table 1. The blocks are assumed to behave elastically. This means that inelastic behavior is allowed to occur only along the joints. The other models such as Mohr-Coulomb model is used in cases which stress levels are such that failure of intact material is expected. But the elastic block model is generally applicable for this case in which jacking along discontinuities is predominant mechanism.

A linear-stiffness Coulomb joint model is used in this analysis.

Table 1: Mechanical properties used in hydro-mechanical analysis

	property	units
Intact rock		
	Density	2500 Kg/m^3
	Young's modulus	60 Gpa
	Poisson's ratio	0.20
Joints		
	Normal stiffness	200 Gpa/m
	Shear stiffness	200 Gpa/m
	Friction angle	35°
	Residual hydraulic aperture	2×10^{-5}m
	Permeability factor	83.33 $Pa^{-1}.s^{-1}$

The in-situ stress field is: σ_{xx}= -74.2MPa, σ_{yy}=-38.2MPa and p= 0 (as it assumed that the reservoir is dry), in which σ_{xx} and σ_{yy} are total stresses in the x- and y-directions and p is the fluid pressure in the joints.

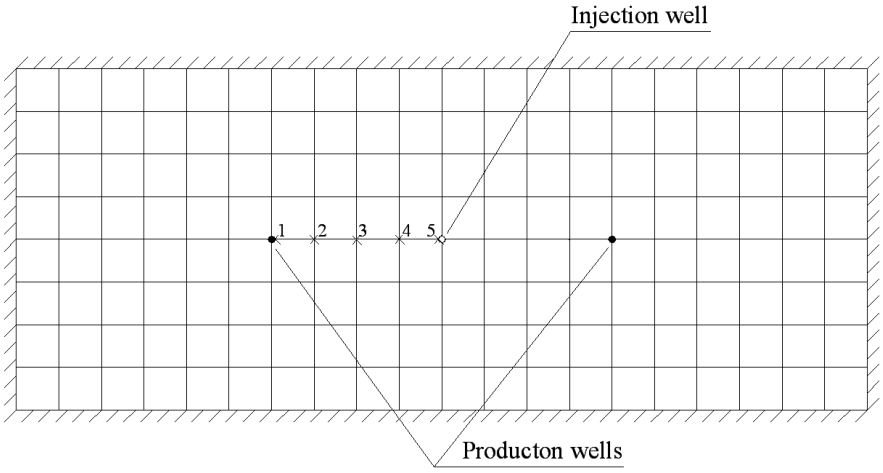

Figure 1: Model geometry, boundary condition, injection and production well locations.

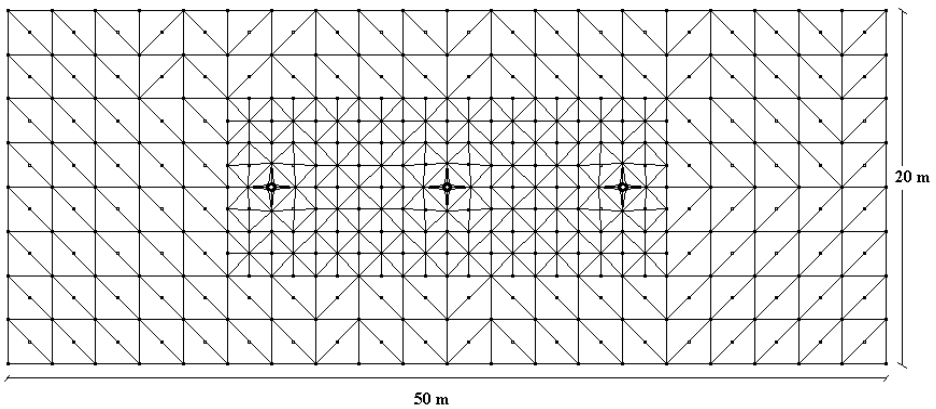

Figure 2: Mesh condition

The kinematic boundary conditions used in the model are shown in Figure 1, and are such that the two horizontal boundaries are restricted from moving in vertical direction and side boundaries are fixed in x-direction. For far field hydraulic boundary, a zero pore overpressure boundary (the so-called Dirichlet boundary condition) is specified, and the boundary condition of solid model is at equilibrium with initial conditions.

5. IMPLEMENTATION OF STIMULATION INTO CODE

The problem is solved with transient (incompressible) flow mode. Water is injected with stepped flow rate until the pressure for each injection step becomes steady. The total injection period covers 3800 s which started at 200s by a slow injection rate of 10 l/s. The injection proceeds during time periods of 1200s, 1200s and 1200s with the flow rates of 30, 50, 70 l/s, respectively.

The parametric study on initial joint aperture is carried out through the model.

At first, the primary aperture for all joints is defined as 0.21 mm. In a set of analyses, the joint primary aperture along injection and production wells is changed to 0.31, 0.41, 0.51, 0.61, 0.71 and 0.81 mm, while the other joint apertures remain the same. As mentioned, the injection in each step continues until the pressure becomes steady.

The fluid pressure histories at five points in the model (see Figure 1), obtained from one of the analysis are plotted in Figure 3. As shown in this Figure, the steps of injecting water with varied flow rate result in corresponding steps in pressure. Hence, the fluid pressure history is accompanied with four steps. It is in agreement with cubic law.

5.1 Flow Pattern

The flow patterns after 3800s, with final flow rate of 70 l/s obtained from three analyses are shown in Figure 4.

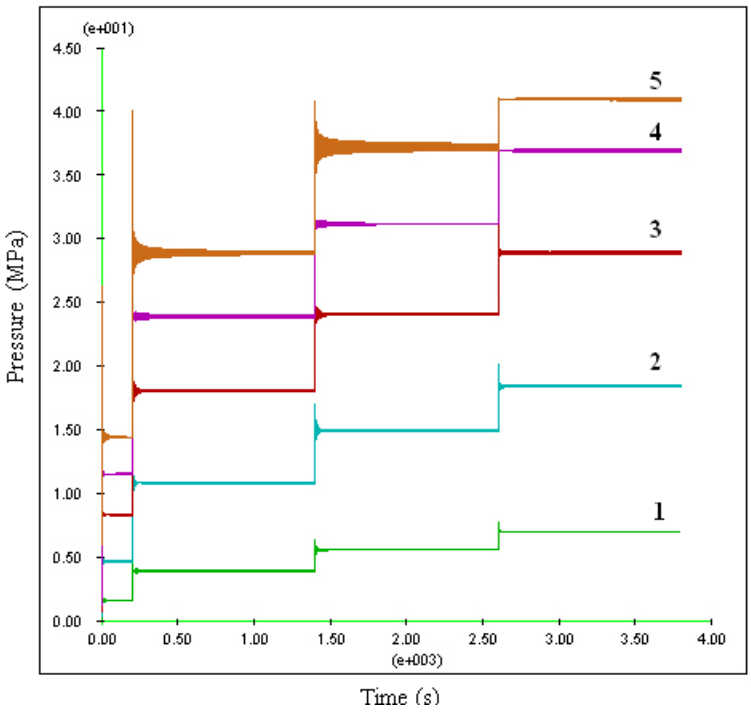

Figure 3: Fluid pressure histories at points 1, 2, 3, 4 and 5, (a_0 is equal to 0.31mm along inj. and prod. wells as it equals to 0.21mm for the others).

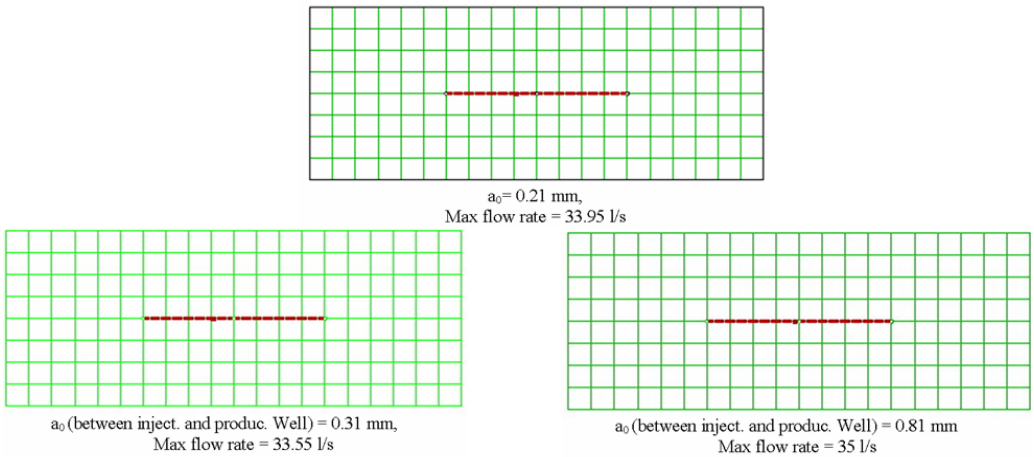

Figure 4: Flow in joints at 3800 sec after fluid flow initiates from the injection well.

Fluid injection preferentially opens the joints oriented approximately normal to the minimum principal stress and widens joints to balance the head loss. As shown in Figure 4, due to the difference in in-situ stresses, the dominant flow is in the horizontal joint set.

5.2 Pore Pressure Pattern

The flow paths illustrated in Figure 4 just show the predominant flow path in the system. The pore pressure distributions in the model obtained from three analyses are shown in Figure 5.

Since the primary pore pressure in joints was assumed to be zero, the pore pressure distributions shown in Figure 5 illustrate the complete pattern of penetrated fluid in system.

In systems with lower initial aperture, the pore pressure distributions cover larger areas in comparison with higher initial aperture. According to cubic law, for a constant flow rate, the lower initial apertures result in higher pressure. So the pressure difference in systems arises and leads to force fluid in more joints.

5.3 Hydraulic Aperture Profiles

The hydraulic aperture profiles along the joint between injection and production wells are shown in Figures 6 and 7. The profiles illustrate changes in hydraulic aperture after 200s, 1400s, 2600s and 3800s.

As expected, the hydraulic apertures increased over time, while the maximum apertures were observed in the vicinity of the injection well.

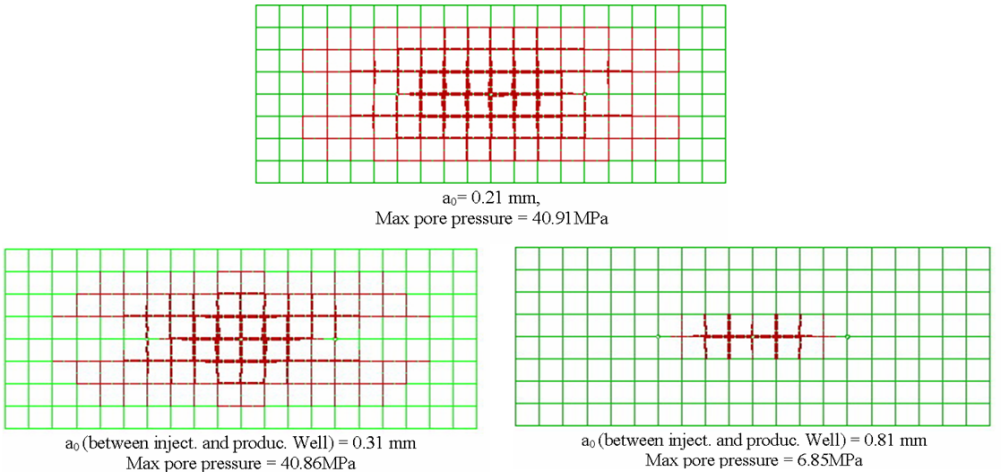

Figure 5: Pore pressure distribution in joints at 3800 sec after fluid flow initiates from the injection well.

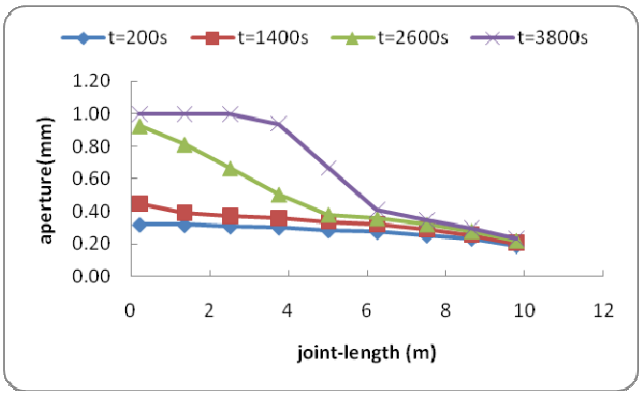

Figure 6: Hydraulic aperture profile along the fracture between injection and production wells, (a_0=0.21mm).

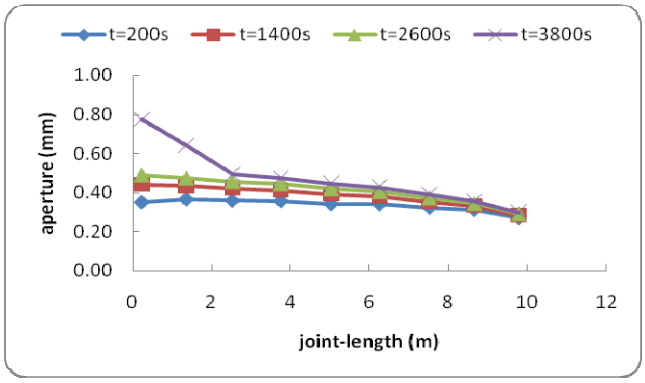

Figure 7: Hydraulic aperture profile along the fracture between injection and production wells, (a_0=0.31mm)

5.4 Flow Rate and Pore Pressure Changes

The flow rate and pore pressure profiles along the joint between injection and production wells for various hydraulic apertures are shown in Figures 8 and 9.

Since it is assumed that the aperture changes occur only along the joint between injection and production wells, the increase in aperture result in increasing production flow rate.

As it illustrated in Figure 9, the pressure changes along injector and producer are accessed. Specially, pressure values at injector can help to choose the injecting pump with proper pressure level.

The pressure levels decreases gradually along the joint between injector and producer and, as shown, an increase of initial aperture leads to increased pressure levels in the joint. Obviously, according to cubic law and reversed relation between pressure and aperture, the profiles are fully justified.

5.5 Fluid Impedance and Water Loss

Hydraulic performance parameters of the system as a function of injection pressure are illustrated in Figure 10.

As mentioned before, water losses and impedance are very pressure-dependent. The trade-off is clearly shown for this system.

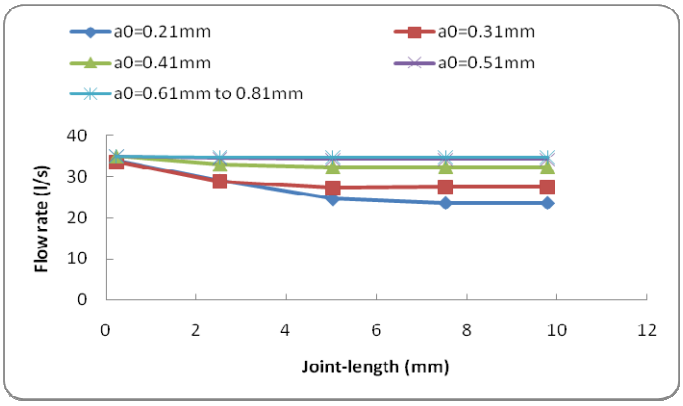

Figure 8: Flow rate changes for various hydraulic apertures along the joint between injection and production wells.

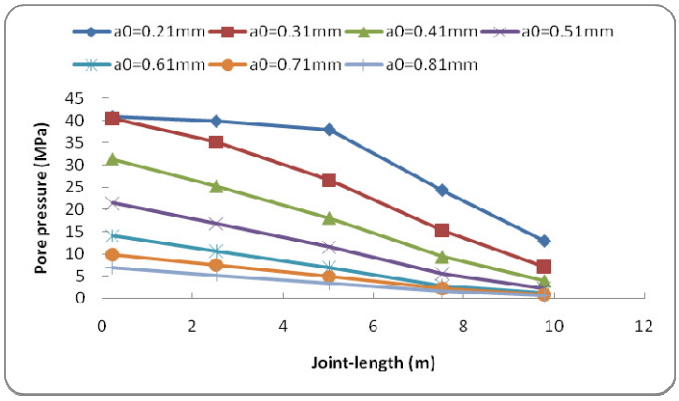

Figure 9: Pore pressure changes for various hydraulic apertures along the joint between injection and production wells.

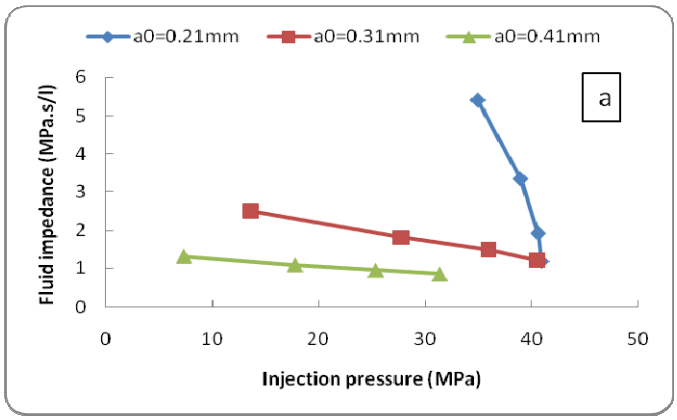

Figure 10 (a): Hydraulic performance parameters in the system versus injection pressure impedance

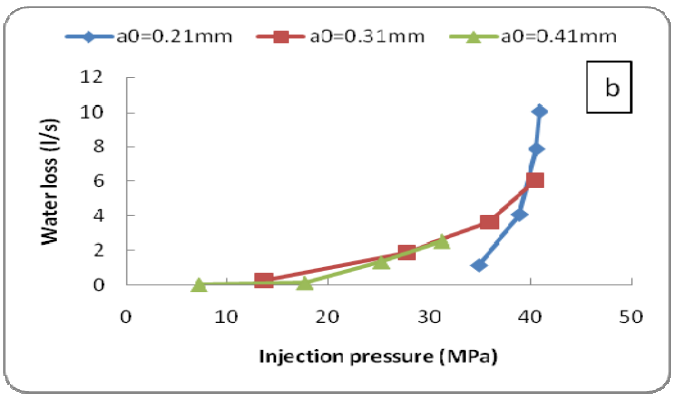

Figure 10 (b) (continued): Hydraulic performance parameters in the system versus injection pressure water loss.

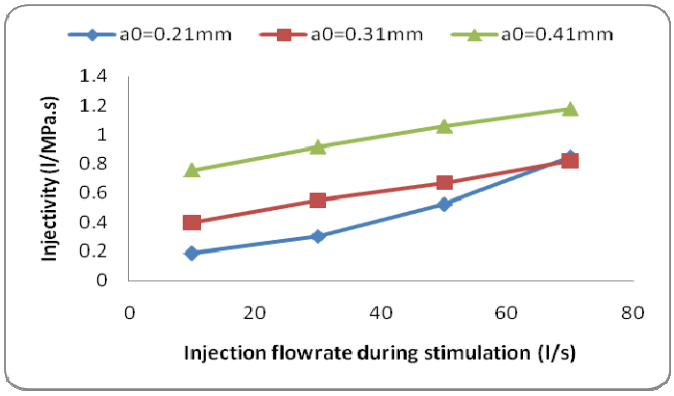

Figure 11: Injectivity as a function of the flow rate applied during stimulation.

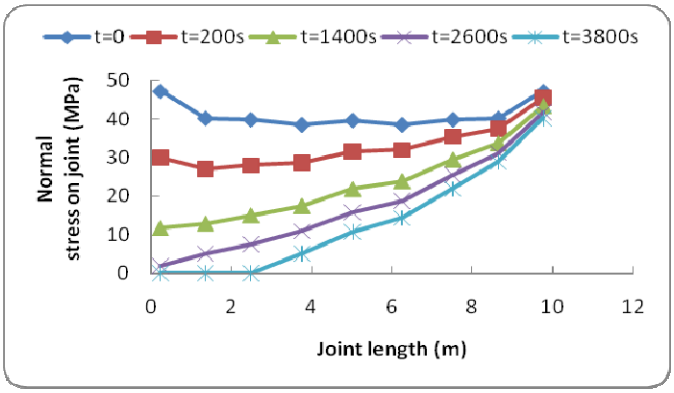

Figure 12: Normal stress changes on a joint between injection and production wells.

In the case of 0.21mm for initial aperture, at an injection pressure of 35MPa the loss rate is only 1.1 l/s, but at 40MPa, the loss is 10 l/s. But at 40MPa the impedance is 1.18MPa.s/l, whereas at 35MPa the impedance is 5.4MPa.s/l.

Also, it is shown that by increasing joint aperture in the special joint, both impedance and water losses are decreased.

Figure 11 gives another result of stepped stimulation at the system for three hydraulic apertures. Following each injection, the reservoir inlet injectivity, the reciprocal of impedance, is computed. It is increased typically 2-5 times.

5.6 Normal Stress on Joint

The variation of normal stress acting on joint between injector and producer is illustrated in Figure 12. It is shown that due to increase of hydraulic pressure during stimulation, the normal stress on a joint is decreased.

The normal stress on a joint between injector and producer after 3800s and for various initial apertures is illustrated in Figure 13. It is shown that for joints with lower initial aperture, the final normal stress on joint is decreased. As mentioned previously, joints with lower initial aperture have higher pore pressure values which result in reduction of normal stress on joints.

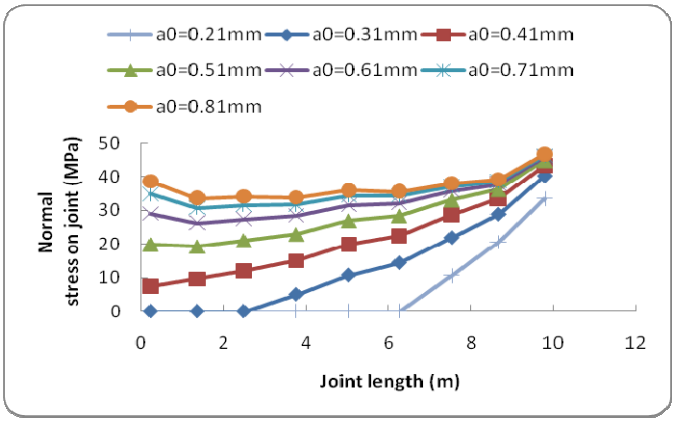

Figure 13: Normal stress changes on joint between injector and producer for various initial apertures.

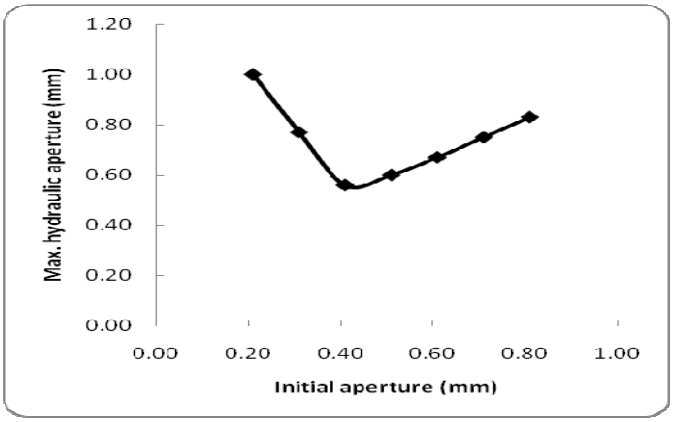

Figure 14: Maximum hydraulic aperture as a function of primary aperture.

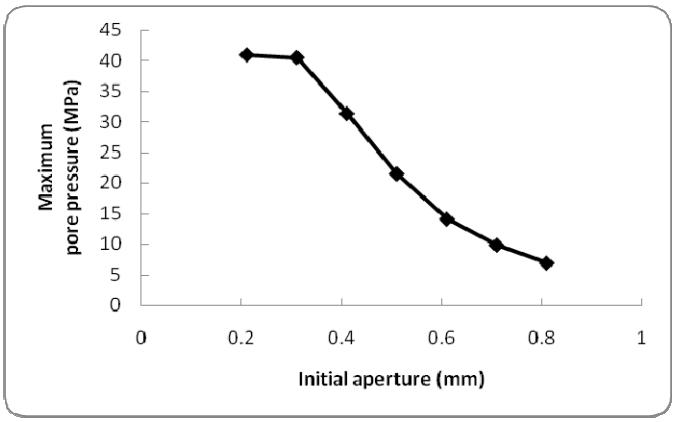

Figure 15: Maximum pore pressure as a function of initial aperture.

5.7 Sensitivity of Joint Aperture

In order to study the effect of joint aperture on hydraulic parameters, the sensitivity of the results with respect to different primary apertures is investigated. All material properties remain constant and only primary aperture is changed.

The maximum hydraulic aperture is derived from each analysis as illustrated in Figure 14.

As it is shown in Figure 14, up to a distinct value the maximum hydraulic aperture is decreased by increasing the primary aperture, while after that the maximum aperture increases. A possible explanation is that the hydro mechanical process is more sensitive to low aperture values. It means the lower primary aperture leads to the larger ratio of the final hydraulic aperture.

In other words, in joint with low primary aperture, the fluid exerts great pressure to the contact walls which result in reduction of effective stress and increase of hydraulic aperture in joints. Subsequently by increasing the primary aperture the fluid needs less pressure to flow and that gives lower final hydraulic aperture as depicted in Figure 14.

The variation of maximum pore pressure of the system in terms of different initial apertures is illustrated in Figure 15. The more the primary aperture, the less the maximum pore pressure created in the system. This is totally in agreement with cubic law.

The production flow rate as a function of primary aperture is shown in Figure 16. The increase in initial aperture of joint between injector and producer leads to increase of flow rate in production well. Fluid flows preferentially along wider joint so that it can circulate with less pressure through the system. In such case, which initial aperture is increased only along injector and producer, the larger apertures result in less water loss in the system (as it shown in Figure 17) and therefore the production flow rate will increase.

The effects of primary aperture and injection flow rate on fluid impedance are illustrated in Figure 18. By increasing the primary aperture, fluid impedance is decreased. Also as it shown, the larger value of injection flow rate results in reduction fluid impedance, but this difference is highlighted for less initial aperture. The explanation is that the increase of injection flow rate causes increase of production flow rate either, while the pressure drop, especially for joints with higher initial aperture, varies almost close to previous stage.

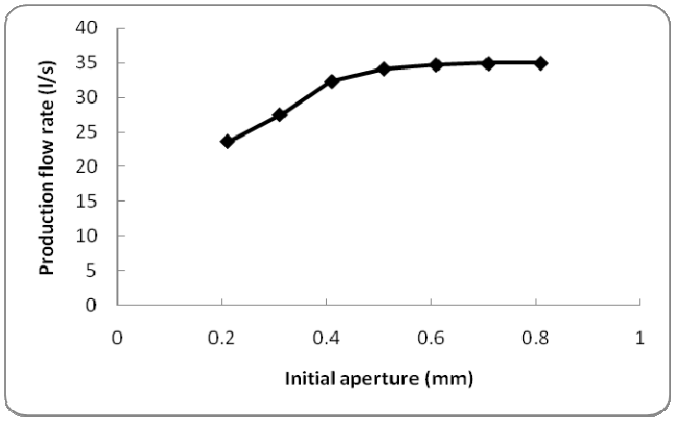

Figure 16: Production flow rate as a function of initial aperture.

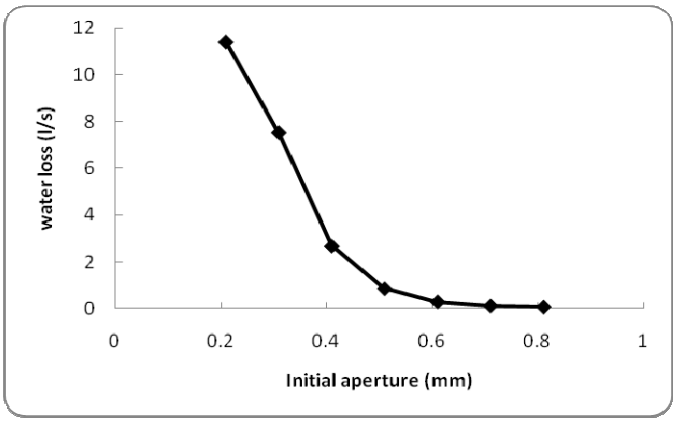

Figure 17: Water loss as a function of initial aperture.

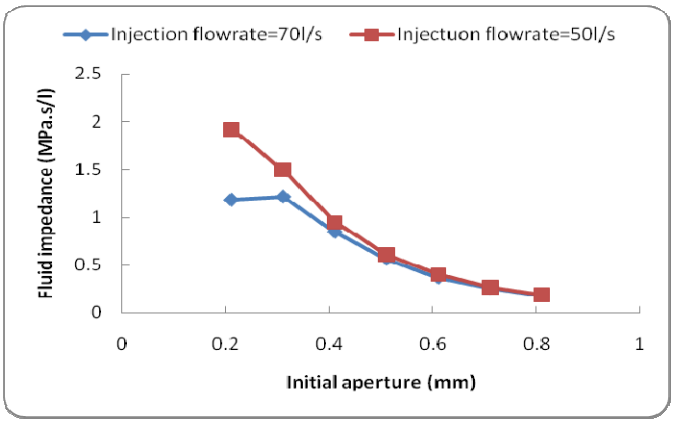

Figure 18: Fluid impedance as a function of initial aperture and injection flow rate.

6. CONCLUSION

This study demonstrates the hydro mechanical response of rock masses during HDR stimulation. The analysis of stimulation process was carried out through a two–dimensional model. In this study, the effect of different joint initial aperture between injector and producer wells was investigated.

Fluid injection opens the joints oriented approximately normal to the minimum principal stress and at the end of analysis the dominant flow paths are specified. By increasing the injection flow rate during stimulation, the hydraulic aperture and injectivity of joints arises. The results confirm the pressure-dependency of fluid impedance and water loss. By increasing of injection pressure, the fluid impedance decreases, while the water loss arises. Hence it is necessary to select best strategy to meet the requirement in every geological condition. For example in some impermeable rock formations, the water loss rate may be so small that tends to pressure rising which can reduce impedance and increase energy production. But sometimes the water loss is a concern and hence a balance between low impedance and low water loss is required by lowering pressure.

The results of parametric study on initial aperture show that the greater values of primary aperture give desired hydraulic performance of the system. By increase of initial aperture the fluid impedance and water loss decreases and injectivity arises.

The results obtained from a distinct element code, show qualitative agreements with experimental data, specially impedance and water losses fields.

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