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Hydraulically fractured hard rock aquifer for seasonal storage of solar thermal energy

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Abstract

The intermittent nature of solar thermal energy derives from its oversupply during the low season and undersupply during the peak season. The solution is to accumulate and store the surplus energy that can be used in times of high demand and low supply. The HYDROCK concept is a method developed for seasonal heat storage in artificially fractured bedrock. This study aims to investigate the rock fracturing process in the construction of hydraulically fractured hard rock aquifer for seasonal storage of thermal energy. The primary objective of this study is to perform a sensitivity analysis of numerical simulations of rock fracturing processes that are taking place during the development of artificially fractured heat storage in hard rocks. Coupled hydro-mechanical numerical models are generated using rock fracture mechanics code FRACOD2D. The sensitivity of critical parameters is presented, and all relevant influencing factors are investigated. Suggestions for practical applications of HYDROCK are given.

Keywords: hydraulic fracturing, underground thermal energy storage, HYDROCK, numerical modelling, fracture mechanics

1. Introduction

The key of seasonal storage of solar thermal energy is to accumulate the surplus energy available in the low season to be used when the demand is high, and supply is low. The HYDROCK concept is a method for seasonal storage of thermal energy in artificially fractured hard rock aquifer, where the heat transfer takes place between the fluid and sub-horizontal fracture planes as depicted in Figure 1 (Larson, 1984; Hellström and Larson, 2001). The fracture planes are created by the use of hydraulic fracturing technique in boreholes, which is used commonly to increase the production rates in unconventional oil and gas reservoirs in tight shales and coal seams (Liu *et al.*, 2015). It has also been used successfully to increase the yield of water from boreholes in hard rock aquifer (Joshi, 1996) Additionally, the method is used commonly to measure the *in situ* stresses in rocks (Amadei and Stephansson, 1997).

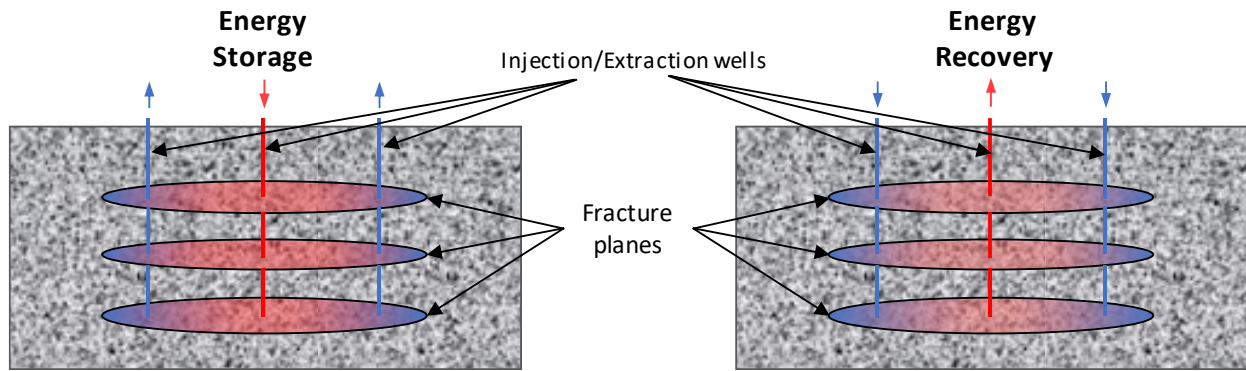


Figure 1. Schematic diagram of the HYDROCK method. During the energy storage phase (left), the heat carrier liquid is pumped into the central hole, flows through sub-horizontal fracture planes towards the peripheral wells and heats up the surrounding rock. During the energy recovery phase (right), the cycle is reversed and the cold fluid is pumped into the peripheral wells, flows through fractures and removes the heat from rock, and is extracted from the central well.

In hydraulic fracturing, a liquid (most often water) is pumped into a sealed section of a borehole until the pressure reaches a level needed to initiate a hydraulic fracture. The orientation of hydraulic fracture is perpendicular to the least principal stress and parallel to maximum and medium principal stress. Hence, in reverse faulting stress regime which is typical for the Fennoscandian shield area, the hydraulic fracturing in vertical boreholes will result in sub-horizontal fracture planes. The first field experiment using HYDROCK method was conducted during 1982 in Bohus granite quarry in Rixö, Sweden (Larson et al. 1983, Eriksson et al. 1983, Larson 1984, Sundquist and Wallroth 1990). The test confirmed that hydraulic fracturing could produce sub-horizontal fractures in shield areas.

The HYDROCK is advantageous compared to other heat storage methods, e.g. borehole storage, as it requires fewer boreholes to be drilled and the investment cost is reduced. Latest HYDROCK field experiments have shown that reduction of 50% in the construction cost could be achieved if the energy extraction is larger than 105 MWh (Ramstad, 2004; Ramstad et al., 2007).

The HYDROCK method requires a sufficient fracture hydraulic conductivity and works best in homogenous rocks, but anisotropic and layered rock can also be utilised. Grouting may be needed if natural, vertical or steeply inclined fractures are present in the rock mass. Sufficient hydraulic conductivity in the fracture plane is required for fluid flow to connect the boreholes hydraulically. Hence, one of the most critical parameters for a successful operation of a fractured hard rock aquifer for seasonal thermal energy storage is the resulting aperture of the created fracture planes. Nordell *et al.* (1986) proposed that a fracture aperture of 1 mm is required for a proper water circulation. Results of HYDROCK *in situ* experiments indicated that proppants, such as quartz sand might be required to increase the hydraulic conductivity of fractures and to get a more controlled flow (Larson, 1984; Nordell *et al.*, 1986; Ramstad, 2004). Reaming of the borehole wall was also confirmed to reduce the impedance of the fracture (Larson, 1984).

The combined effects of explicit rock fracturing (mechanical), fluid flow (hydraulic), and temperature change (thermal) are essential to understand and forecast the rock behaviour in underground thermal energy storage in hard rocks. When constructing HYDROCK thermal storage, the hydro-mechanical coupling is most important. This study focuses on fluid flow in rock fractures because in low permeability rocks the fluid flows through fractures predominantly. The pressure of the fluid in fractures may cause movement and an increase of aperture and propagation of the fracture. The changes in fracture geometry will change the hydraulic conductivity of the fracture and create new flow paths, which will enhance the flow of fluid (Shen et al. 2014).

This study aims to investigate the rock fracturing process that is used in the construction of hydraulically fractured hard rock aquifer for seasonal storage of thermal energy. Coupled hydro-mechanical (HM) numerical model is prepared using the commercial FRACOD2D rock fracture mechanics code. The primary

objective of this study is to perform a sensitivity analysis of the output values on varying input parameters and to give practical suggestions regarding the implementation of HYDROCK method.

2. Methodology

In this study, coupled hydro-mechanical numerical models were generated using rock fracture mechanics code FRACOD2D. FRACOD is a Boundary Element Method (BEM) and uses an indirect boundary element technique - Displacement Discontinuity Method (DDM) with fracture mechanics theory integrated into it. The model consisted of one injection borehole, where the fluid was injected under high pressure to produce a single horizontal hydraulic fracture propagating from the borehole (see Figure 2). The rock was assumed to be perfectly isotropic and homogeneous with no internal fractures present. The reverse faulting stress regime was assumed, with horizontal rock stresses being five times higher than vertical.

In the numerical model, a flow rate boundary condition was used to supply pressure into the injection borehole. The total flow rate in borehole was specified, and it remained constant throughout the whole process. The operational parameters of the hydraulic equipment applied in field experiments by Ramstad (2004) were employed.

First, a base case scenario of hydraulic stimulation was simulated using the base value input properties presented in Table 1. The properties were selected to represent a generic case of a hard crystalline rock, which is used in the HYDROCK method. Next, a sensitivity analysis of the output values on varying input parameters in hydraulic fracturing model in FRACOD2D was performed. The input parameters were varied by $\pm 50\%$ (see the list in Table 1). The maximum fracture aperture was measured as the primary output result. Additionally, the maximum flow rate and maximum vertical and horizontal induced stress were measured at a monitoring point positioned 0.1 m to the right of the injection borehole.

Table 1. Sensitivity analysis of the input parameters for hydraulic fracturing models in FRACOD2D.

Parameter	Symbol	Low Value	Base Value	High Value	Unit
Poisson's ratio	ν	0.125	0.25	0.375	-
Young's modulus	E	18.75	37.5	56.25	GPa
Internal friction angle	ϕ	16.5	33	49.5	°
Cohesion	c	16.5	33	49.5	MPa
Tensile strength	σ_t	6.25	12.5	18.	MPa
Fracture normal stiffness	K_n	500	1000	1500	GPa/m
Mode II / Mode I toughness ratio	K_{IIc}/K_{Ic}	1	2	3	-
Flowrate at the boundary	$value_h$	0.004	0.008	0.012	m ³ /s
Initial borehole (pump) pressure	$value_pi$	12.5	25	37.5	MPa
Borehole volume	vol_hole	0.015	0.03	0.045	m ³
Initial fracture aperture	e_{ini}	0.05	0.1	0.15	mm
Residual fracture aperture	e_{res}	0.05	0.1	0.15	mm
Rock porosity	ϕ	0.05	0.1	0.15	%
Horizontal rock stress	S_{xx}	2.5	5	7.5	MPa
Vertical rock stress	S_{yy}	0.5	1	1.5	MPa

3. Results and discussion

The result of the base case simulation is presented in Figure 2. The maximum fracture aperture of 2.5 mm was reached after 50 cycles and then decreased to 1.2 mm with decreasing fluid pressure as the fracture propagated further. The resulting fracture aperture is higher than the minimum width of 1 mm required for proper circulation of water that was suggested by Nordell *et al.* 1986. Nevertheless, using propping agents such as quartz sand may be required to increase the flow capacity of created fractures as suggested by Larson (1984), Nordel *et al.* (1986) and Ramstad (2004).

The fracturing process stopped after the fracture plane reached 15.6 m radius. As expected, the orientation of hydraulic fracture was perpendicular to the least principal stress and parallel to maximum and medium principal rock stress and is perfectly horizontal due to the homogenous rock without any internal discontinuities. This outcome corresponds well to the results of the first HYDROCK field experiment, where the resulting hydraulic fractures had at least a 10 m radius and were parallel to each other (Larson, 1983). However, in some *in situ* conditions, the hydraulic fracture may alter its orientation away from the drill hole if the local stress orientation is disturbed by discontinuities or flaws.

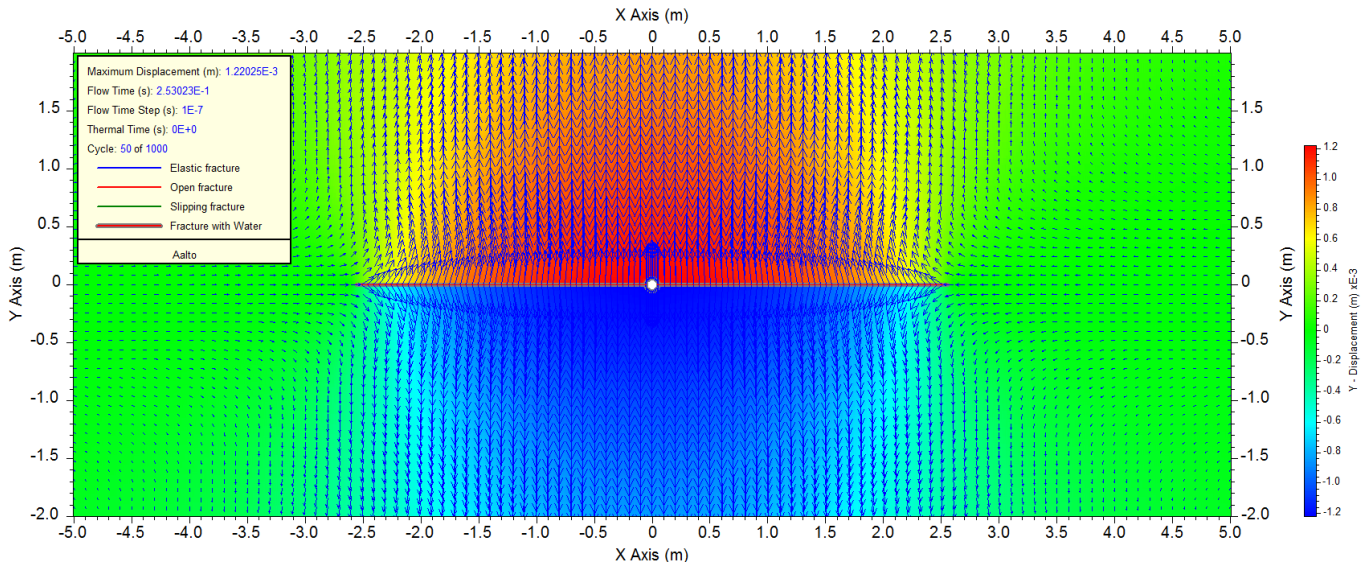


Figure 2. Vertical displacement of the rock mass during hydraulic fracturing in a borehole after 50 cycles of fracture propagation.

The results of the sensitivity analysis are plotted on tornado plots in Figure 3. The maximum aperture of the resulting hydraulic fracture (Figure 3a) was most sensitive to changes in the Young's modulus (+33.9% and -11.8% change in the aperture for -50% and +50% change in Young's Modulus, respectively). The bigger the Elastic modulus of the rock, the lower the resulting fracture aperture. Second input parameter with high influence on the fracture aperture was the borehole volume (-11% and -29.9% change in the aperture for -50% and +50% change in borehole volume, respectively). This is dictated by the length of the borehole sections at which it is pressurized. The longer the segment, the higher the borehole volume and the larger the resulting aperture of the hydraulic fracture. The maximum aperture of the fracture was also influenced by the maximum pressure of the pump used for hydraulic fracturing (-11.8% and 23.6% change in the aperture for -50% and +50% change in pump pressure, respectively). This is undoubtedly logical, as more pressure delivered by the pump results in higher pressures at the fracture tip available for fracture propagation. Other input parameters had a very low influence on the aperture (+1.6% change for -50% change in the vertical rock stress, and +1.6% change for -50% change in Poisson's ratio) or no influence at all. Surprisingly, the increase of flow rate had a relatively low influence on resulting fracture aperture (2.4% increase). Sundquist and Wallroth (1990) suggested that high flow rate (>10 l/s) should be used to increase the hydraulic conductivity of hydraulic fractures based on the field test results in granite. However, it should be noted that the hydrological behaviour of rock fracture is not only influenced by the mechanical aperture, but also other properties such as contact area, roughness, matedness, or presence of channels (Hakami, 1995).

The maximum flow rate at the monitoring point (Figure 3b) was most sensitive to the two operational parameters of the hydraulic fracturing used as a boundary condition in the model. By increasing the borehole volume and initial pump pressure by 50%, the flow rate was increased by 49.3% and by 24.8%, respectively. Interestingly, the decrease of Young's modulus resulted in higher flow rate in the fracture. However, the change was small (+12% change). Other parameters had low or no influence on the maximum flow rate at the monitoring point.

The max initial pump pressure and borehole volume were also influencing heavily the resulting induced rock stress at the monitoring point (Figure 3c,d) so that the 50% increase in their value resulted in 20% increase in both horizontal and vertical stress. The resulting rock stresses were also influenced by the elastic properties of the rock. However the increase was low (around 7% and 1% increase in stress with increased Young's modulus and Poisson's ratio, respectively).

The main limitation of the numerical modelling results presented in this study is that no natural fractures were included in the rock mass, which could influence the outcome and alter the path of the propagating fracture as observed by Ramstad (2004). In some cases, it can even lead to a situation where the hydraulic fracture is arrested on a natural fracture and stops propagating. However, the focus of this study was to investigate how the generic rock properties and the operational parameters of the hydraulic fracturing equipment affect the resulting fracture, without the influence of existing discontinuities that are very site dependent. This phenomenon will be investigated more closely in future studies, where a back-calculation of an HYDROCK field test will be performed taking into account the distribution of natural discontinuities in the rock mass.

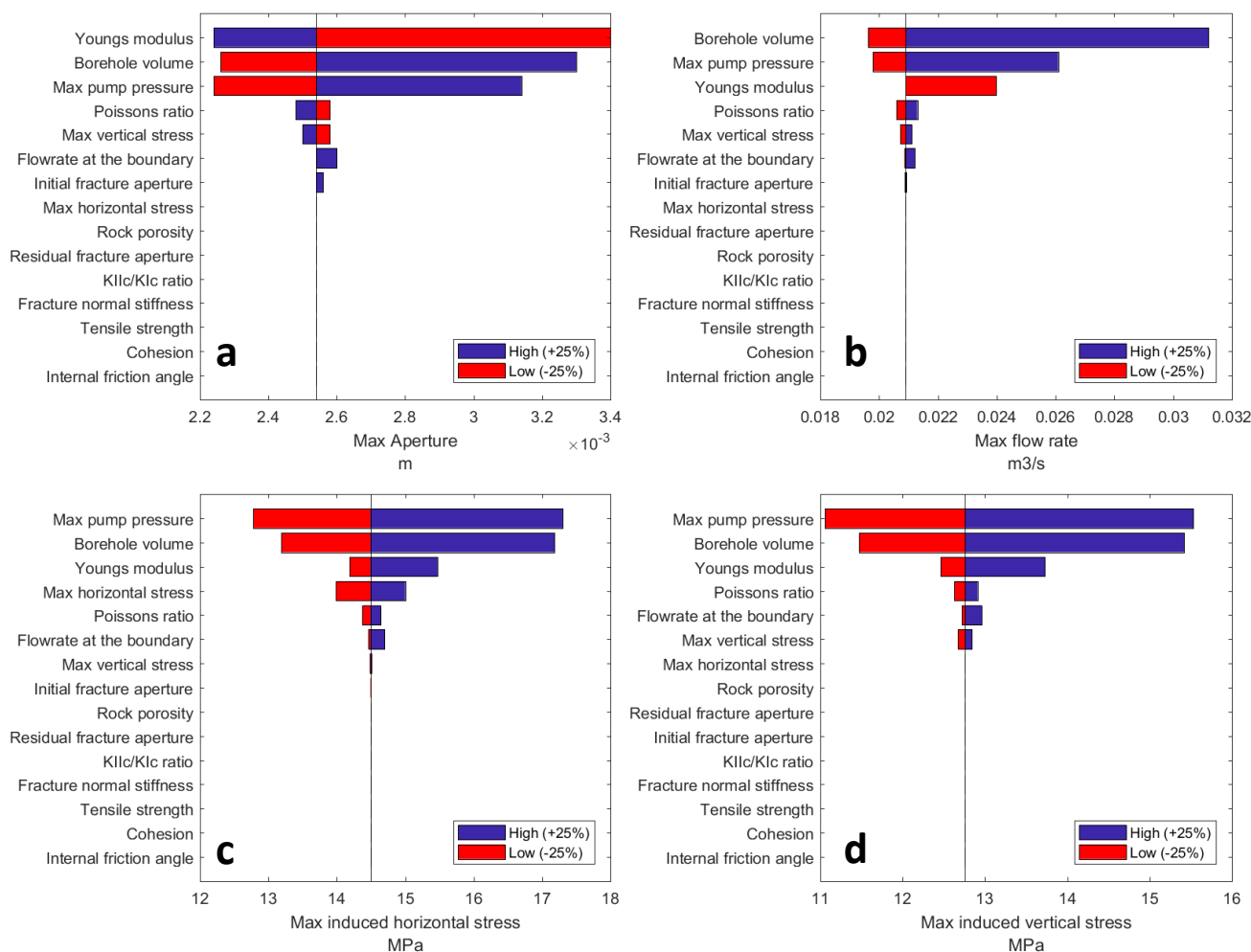


Figure 3. The sensitivity of fracture aperture (a), maximum flow rate (b), maximum induced horizontal stress (c), and vertical stress (d) to $\pm 50\%$ change of the input parameters in the hydraulic fracturing numerical model in FRACOD2D.

4. Conclusions

The hydraulic fracturing procedure for constructing an artificially fractured hard rock aquifer was successfully simulated numerically using FRACOD2D. It was found out that the most influencing input parameters in hydraulic fracturing numerical model are the operational parameters of the hydraulic fracturing equipment used (i.e. the maximum pump pressure and the borehole volume). Therefore, the

proper setting of the operational parameter of the fracturing equipment is crucial. Such finding is essential for the selection of appropriate hydraulic fracturing equipment for a construction of HYDROCK storage. Larger pump capacity can increase the resulting rock fracture aperture. Hence, the hydraulic conductivity of fracture planes will be higher, and the thermal performance of the system will improve.

The second group of input parameters that have a significant influence on the output are the elastic parameters (i.e. Young's modulus and Poisson's ratio). The higher the elastic properties, the more difficult is to create an open fracture with sufficient aperture and more pressure is required. This implies that selection of the site for HYDROCK construction and accurate site investigation will directly influence its performance. It is also crucial for numerical simulations of the hydraulic fracturing process as good quality laboratory data for the model input is needed.

In the future, a variety of scenarios will be tested to investigate the influence of different geological and geomechanical conditions, such as rock types, anisotropy, *in situ* rock stress, and presence of discontinuities. Additionally, a back-analysis of HYDROCK field test from the literature will be performed with an upgraded numerical model.

References

Amadei, B. and Stephansson, O. (1997), *Rock Stress and Its Measurement*, Springer Netherlands, Dordrecht, the Netherlands.

Eriksson, K.G., Larson, S.Å. and Haag, O. (1983), HYDROCK - en ny metod att lagra värme i berg (HYDROCK - a new method of storing heat in the bedrock), Technical Report R105:1983, Statens råd för byggnadsforskning, Stockholm, 117–123.

Hakami E (1995) Aperture distribution of rock fractures. PhD thesis, Royal Institute of Technology, Stockholm, Sweden

Hellström, G. and Larson, S.Å. (2001), Seasonal thermal energy storage – the HYDROCK concept. *Bulletin of Engineering Geology and the Environment* 60(2):145–156. doi:10.1007/s100640100101

Joshi, V. (1996), Borehole rejuvenation for sustainability, *Proceedings of the 22nd WEDC Conference*, 193–194.

Larson, S.Å. (1984), Hydraulic fracturing in the Bohus granite, SW-Sweden. Test for heat storage and heat extraction. *Geothermal Resources Council TRANSACTIONS* 8:447–449. <http://pubs.geothermal-library.org/lib/grc/1001215.pdf> Accessed 7 October 2016

Larson, S.Å., Fridh, B. and Haag, Ö. (1983), Hydrock - värmelager i berg. Anläggning av värmeväxlarytor med hjälp av hydraulisk uppspräckning; HYDROCK - metoden (Hydrock method - Heat Storage in Rock: The construction of heat exchanger surfaces by hydraulic fracturing), Technical Report Publ. B 222, Chalmers University of Technology/University of Göteborg.

Liu, H., Yang, T., Xu, T. and Yu, Q. (2015), A comparative study of hydraulic fracturing with various boreholes in coal seam, *Geosciences Journal*, 19(3), 489–502.

Nordell, B., Bjarnholt, G., Stephansson, O. and Torikka, A. (1986), Fracturing of a pilot plant for borehole heat storage in rock, *Tunnelling and Underground Space Technology*, 1(2), 195–208.

Ramstad, R.K. (2004), *Ground source energy in crystalline bedrock - increased energy extraction by using hydraulic fracturing in boreholes*. PhD thesis, Norwegian University of Science and Technology, Norway, <http://hdl.handle.net/11250/235848> Accessed 7 October 2016

Ramstad, R.K., Hilmo, B.O., Brattli, B. and Skarphagen, H. (2007), Ground source energy in crystalline bedrock-increased energy extraction using hydraulic fracturing in boreholes. *Bull Eng Geol Environ* 66: 493–503. doi:10.1007/s10064-007-0100-7

Shen, B., Stephansson, O. and Rinne, M. (2014), *Modelling Rock Fracture Processes: a fracture mechanics approach using FRACOD*. Dordrecht, The Netherlands: Springer. doi:10.1007/978-94-007-6904-5

Sundquist, U. and Wallroth, T. (1990), Hydrock - energilager i berg - slutrapport för etapp 1 & 2 (Hydrock - energy storage in rock: final report for phase 1 & 2), Technical Report Publ. B 349, Chalmers University of Technology/University of Göteborg.