Numerical Modeling of Discrete Materials – Konietzky (ed.)

3D-hydromechanical modeling of hydraulic stimulation of deep geothermal wells in Hot Fractured Rock at Soultz-sous-Forêts (Alsace-France)

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ABSTRACT: The concept of Hot Fractured Rocks (HFR) has been developed in the Soultz-sous-Forêts geothermal site (France) to extract the heat of deep rocks and transform it into electrical energy. Stimulation of a well by pressurized hydraulic injection causes an irreversible increase in the permeability of the loaded fracture network. In this study, a numerical approach based on the distinct element method (*3DEC*-FLO code) is developed with the aim to understand and to explain the physical mechanisms which are responsible for the hydraulic behavior measured during stimulation tests conducted in the GPK1 and GPK2 wells. The model is designed to reproduce the observed behavior in terms of pressure-flow curves as well as in terms of the location of the stimulated fractures where the fluid is injected. First, the results obtained by the 3-Dimensional model have shown that the permeability increase is highly associated with shearing in fracture planes. The model also showed a significant correlation between the orientations of the permeable fracture and the in situ stresses, respectively.

1 INTRODUCTION

The experiments initiated at the Soultz-sous-Forêts site (France) in 1987 are aimed at progressively validating a new method for extracting heat from the deep fractured granite basement. Extraction must be carried out by forced circulation of a fluid between wells drilled at great depth (5000 m).

The experiments conducted so far on the site show that hydraulic stimulation techniques can considerably increase the local permeabilities in volumes which can extend up to several hundred meters around the well, thereby serving to establish connections between the wells. In 1997, a preliminary demonstration phase proved that heat could be extracted by circulation between 3000–3500 m depths in steady state conditions, between initially impermeable wells 450 m apart, with a perfectly balanced discharge of 25l/s, a temperature of 142°C, an available thermal power of 10 MW and a required pumping capacity of 0.2 MW.

In the last ten years, tests of stimulation injection and production were conducted in two wells (GPK1 and GPK2), in the upper part of the geothermal reservoir between 3200 m and 3900 m. The major result of the stimulations is the possibility of injecting higher flowrates for only small pressure increases (Gérard et al. 2000). Micro-seismo-acoustic events recorded during tests supply an image of the radius of influence of the hydraulic stimulation (300 to 400 m in the direction parallel to the major horizontal stress and 100 to 200 m in the perpendicular direction).

To help understand the mechanisms at play during the various hydraulic tests carried out at Soultz-sous-Forêts, the numerical approach had to account for the two following main points:

1 it must be able to take into account the fractures of the rock mass, and
2 it must be able to simulate interactions between the injected fluids and the rock mass, i.e. the hydromechanical coupling process.

Indeed, experimental data as well as geological investigations carried out in the GPK1 and GPK2 wells show that the geothermal reservoir is composed of a fractured granite basement.

From the hydraulic standpoint, two types of hydraulic tests were conducted in each of the two wells: “hydraulic stimulation tests”, where one injects very high pressure fluids in order to permanently increase fracture conductivities, and “injection tests”, where one injects fluids in order to determine the hydraulic characteristics of the fractures. The "hydraulic stimulation tests" showed that the fractured rock mass permeability could be significantly increased. Additional information obtained from the flow logs showed that the increase of permeability is associated with zones of privileged flow which have also been identified at this step.

The "injection tests" were performed after the stimulation tests and demonstrated that large increase in rock mass permeability is irreversible. This consolidates also the success of the hydraulic stimulations (Fig. 1).

Now, if we analyze qualitatively the Pressure vs. Flow rate stimulation curves (Fig. 1), we can approximately describe the observed hydraulic behavior in three main phases (Fig. 2):

– Phase 1: during which the mechanical deformations of the fractures induced by fluid pressures are small;
– Phase 2: during which significant deformations are developed in the zones located in the vicinity of the well;
– Phase 3: during which the deformations are developed and propagated in the fracture plane far from the well.

Thereafter in this study, the previous analysis is used as an essential support to better define the modeling procedure.

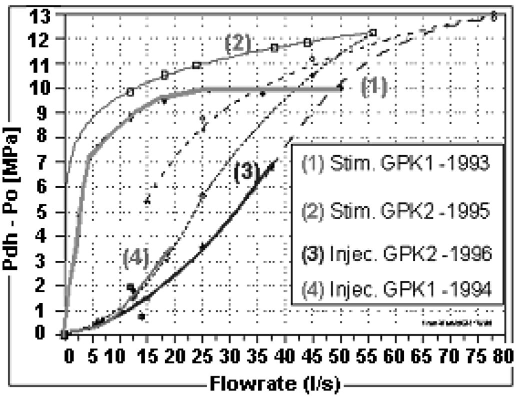

Figure 1. Over-pressure as a function of the flow obtained during hydraulic experiments conducted at Soultz-sous-Forêts in the two wells.

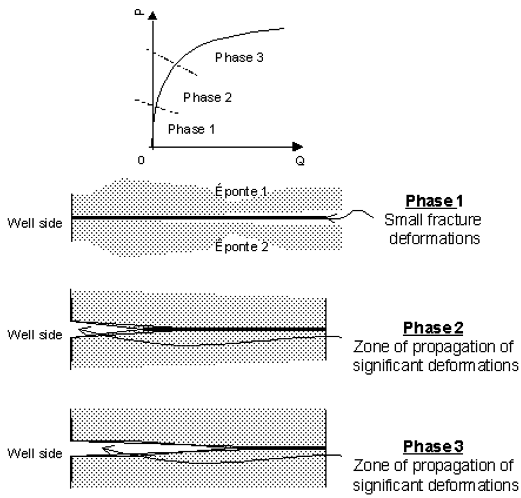

Figure 2. Propagation of the deformations induced by pressures on the fracture planes.

2 NUMERICAL APPROACH

The numerical approach developed in this paper used the calculation code *3DEC-FLO* (Itasca 1998) which is based on the distinct element method. Indeed, *3DEC-FLO* not only enables us to take into account the two main requirements described below, but it also offers a large choice of mechanical laws for the fracture behavior.

Thus, the qualitative analysis previously presented in this paper could be approached in the model by a continuously yielding law which is defined also by three domains depending on fracture shear strain (Fig. 3): an initial elastic domain, a second domain characterized by a decrease of the shear strength of the fracture induced by the degradation of the fracture sides due to the shearing mechanism, and a third domain which corresponds to residual deformations.

As a first approximation, the fluid circulates only via the fracture network. This assumption is considered true for the Soultz-sous-Forêts granite

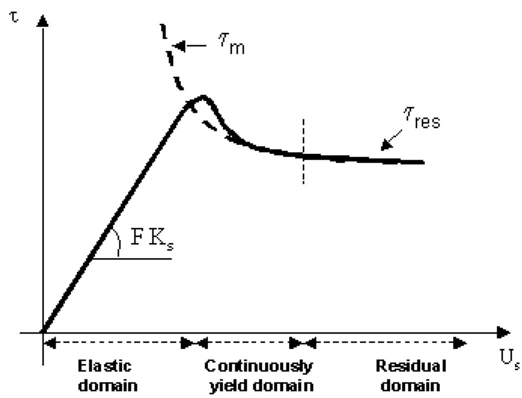

Figure 3. Continuously yielding law assumed for the fracture mechanical behavior.

because matrix permeability is negligible. The basic equations in the *3DEC-FLO* code with respect to hydro-mechanical coupling in each elementary domain are summarized below:

$$\sigma_{n,\,eff} = \sigma_{n,\,tot} - p \quad (1)$$

$$\Delta U_n = f(\Delta\sigma_n, k_n) \quad (2)$$

$$\Delta U_s = f(\Delta\tau, k_s) \quad (3)$$

$$a = a_0 + \Delta U_n \quad (4)$$

where, Eq. 1 is Terzaghi's expression, Eqs. 2 & 3 are the relations between normal ΔU_n (res. Tangential ΔU_s) strains, normal stiffness k_n (res. Tangential k_s) and normal $\Delta\sigma_n$ (res. Tangential $\Delta\tau$) stress variation, and Eq. 4 is the relation between the normal mechanical strain ΔU_n and the hydraulic aperture (a) of the fracture. The fluid flow obeys the cubic law.

As we will see later, two assumptions for the fracture stiffness have been studied. First, a constant stiffness is assumed, and then the stiffness is assumed variable and proportional to the normal stress applied on the fracture sides. At this stage the granite mass is considered elastic. This seems sufficient to capture the mechanical behavior of the blocs and requires the definition of only two parameters: the Young's Modulus (E) and the Poisson's ration (ν), which are generally easy to determine. One of the main difficulties encountered in the model was the assignment of values for the hydro-mechanical parameters of the fractures. Indeed, two friction angles are needed to delimit the three domains (Fig. 3): an initial angle ($\phi_{initial}$), which characterizes the elastic threshold (τ_{max}) and a residual angle (ϕ_{res}), which indicates the beginning of the residual behavior (τ_{res}).

The deformation of the fracture sides is governed by the stiffnesses k_n and k_s for a constant law. When the stiffnesses are not constant, they must be related to the stresses by a law with new parameters as for example the maximum values, linear coefficients relating stiffnesses to stresses, etc.

Because of the strong non-linearity of the transmissivity vs. hydraulic aperture relationship ("cubic law"), hydraulic apertures must be bounded compared to the mechanical ones: the hydraulic aperture varies together with mechanical aperture as long as it stays between a residual hydraulic aperture and a maximal aperture (a_{max}) (see Eq. 4). It remains constant at the a_{res} – respectively a_{max} – value if the value given by Equation 4 becomes smaller – respectively larger – than these values. Finally, an initial hydraulic aperture (a_0) may be assigned.

It is difficult to determine the values of the various parameters described above – no data are available in the literature and the size of the fractured zones (some meters) eliminates laboratory results. To meet the challenge we have developed a progressive procedure which is summarized below step by step:

a) test different values for parameters and extract those which yield small flow rates for the first overpressures applied in the model i.e. pressures above hydrostatic pressure lower than 8 to 10 MPa.
b) improve the parameters obtained in step (a) by extracting those which yield higher flow rates when the value of overpressure becomes greater than 9 MPa.
c) improve the constitutive law for discontinuities, to obtain a progressive transition from case (a) to case (b).

Indeed, steps (a) & (b) were carried out using a constant stiffness law, therefore calibrating the constant stiffnesses and initial friction angle (ϕ initial). Step (c) was then carried out using a law taking into account variable stiffnesses.

3 RESULTS AND DISCUSSIONS

First, the results obtained from the simulation of the hydraulic stimulation test conducted in GPK1 in 1993 and the procedure developed for the calibration of the model will be presented. Then, the model developed for GPK1 will be used in the study of the stimulation test conducted in 1994 in GPK2. At this stage, the model is used to predict the measured behavior. It differs from the previous one only by the geometry of the fracture network identified in well GPK2. Note that the procedure and the hydro-mechanical parameters are unchanged.

3.1 *GPK1 stimulation test*

The fracture network taken into account in this study is the result of a combination of fracture data gathered by BRGM (Genter et al. 2001) and assumptions done because of the limitations imposed by *3DEC-FLO* capacities (Table 1).

The three-dimensional model explicitly accounts for seven fractures located at depths between 2867 m and 3498 m (Fig. 4). The model dimensions are 400 m × 400 m × 1000 m. It is centered on the well.

Flow logs performed during the stimulation test have established that the fluid is injected into the heat exchanger via only three main fracture zones (Table 1). In addition to the Pressure – Flow rate curves, the flow log data are used as a second reliable data to be verified by the model.

Initial and boundary conditions are needed in order to establish the reference state from which the effect of the injection pressures on the hydro-mechanical behavior is studied (Fig. 4). Hence, we assume as

Table 1. Geometric properties assumed for the fracture network in GPK1.

Fracture N°	Depth (m)	Dip (°)	Dip Direction (°)	Stimulated zone
F1	2867	70	297	Yes
F2	2898	48	122	No
F3	2903	78	318	No
F4	2965	80	248	No
F5	3224	71	088	Yes
F6	3339	83	274	No
F7	3498	63	257	Yes

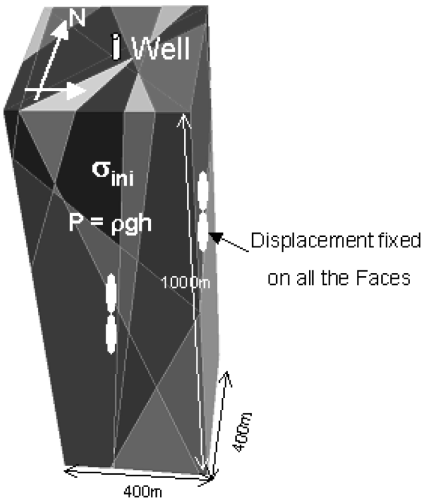

Figure 4. Geometry and initial hydro-mechanical conditions considered in the model.

initial stresses in the model, the natural stress field (σ_{ini}.) determined by the expression below for depths between 1450 m and 3500 m (Klee & Rummel 1993):

$$\sigma_h = 15.8_{[MPa]} + 0.0149_{[MPa/m]} * (z_{[m]} - 1458)$$

$$\sigma_H = 23.7_{[MPa]} + 0.0336_{[MPa/m]}\ (z_{[m]} - 1458) \qquad (5)$$

$$\sigma_v = 33.8_{[MPa]} + 0.0255_{[MPa/m]}\ (z_{[m]} - 1377)$$

We also assume a hydrostatic pressure field, described by the expression below:

$$P = \rho\, g\, z \qquad (6)$$

where ρ is the density of water, g is gravity and z is the depth.

Fixed zero displacements, associated with a fixed hydrostatic pressure, are assumed at the boundaries of the model.

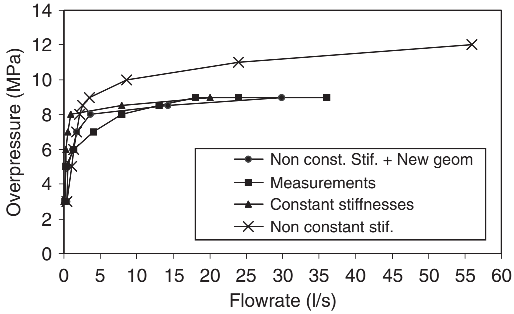

Figure 5. Comparison of measured and calculated Pressure vs. Flow rate curves (GPK1 model).

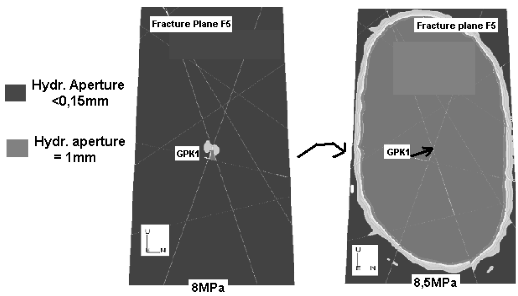

Figure 6. Distribution of hydraulic apertures in the fracture plane (F5) at pressures 8 MPa and 8.5 MPa.

The simulation of the hydraulic test is carried out in the model by adding an overpressure (ΔP) in the open part of the well and by calculating the flow rate injected throughout the fracture network when hydro-mechanical equilibrium is reached. The simulation is conducted in eight stages, each one corresponding to an overpressure step.

Examples of results obtained for the study of the stimulation test in GPK1 are presented below. For the model with a constant stiffness the Pressure vs. Flow rates curve is qualitatively similar to the measured one (see curve 1 in Fig. 5). We note also that only a small quantity of fluid is injected into the rock mass via the fracture network as long as the overpressure applied in the well is lower than 8 MPa.

When this value is exceeded, a spontaneous increase is calculated for the flow rates injected in fracture (F5), which jump to 7 l/s when the overpressure is equal to 8.5 MPa. This phenomenon is due to the increase of the hydraulic aperture, which appears and propagates far from the well in the fracture plane (Fig. 6). The model also shows that fractures (F4) and (F6) absorb the fluid when the overpressures are much increased in the well. The increase in the permeability of the fractures (F4), (F5)

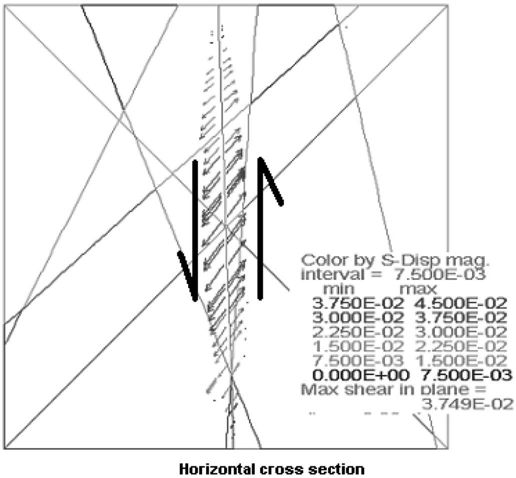

Figure 7. Shearing mechanism associated with the increase of the permeability of the fractures (example of the fracture F5).

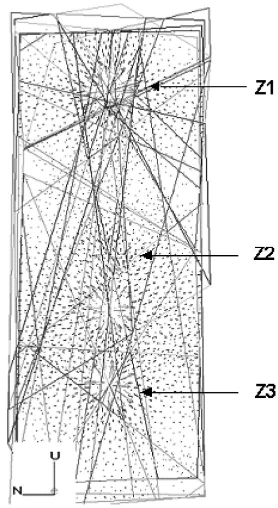

Figure 8. Distribution of the flow rates in the GPK1 fracture network.

and (F6) is always associated with the apparition of shearing in the fracture planes (Fig. 7). However, the dramatic increase of the flow rate is not in good agreement with the measurements.

Only one of the three "main injection fractures" computed is in agreement with flow log data (Table 1), which indicates fractures F1, F5 and F7 (Table 1).

The use of a law with non-constant stiffness qualitatively improves the hydraulic behavior calculated by the model (curve 2 in Fig. 5), but a quantitative difference remains also true in comparison with the measurements. At this step, fractures (F5) and (F7) are stimulated. This is in good agreement with the flow log results, but the model shows that fracture (F4) is also stimulated, instead of fracture (F1) as observed on the flow log.

We studied different hypotheses to try to understand why the permeability of fracture F1 in the model didn't increase as observed on the site. Only one assumption, among all those which were tested, resulted in a good consistency between the model and measurements. This assumption concerned the orientation of fracture F1. Its dip direction was changed from 297° to 283°. Using this hypothesis, the main injection fractures are calculated to be F1, F5 and F7 (Fig. 8) and the Pressure vs. Flow rate curve is similar qualitatively and quantitatively to the measured one (see curve 3 in Fig. 5).

Up to now, the results obtained with the model enable us to conclude that:

- the shear mechanism appears as a possible phenomenon responsible for the increase fracture permeability,
- the relative orientation of in situ stresses and fractures plays a major role in the increase of permeability.

Table 2. Geometric properties assumed for the fracture network in GPK2.

Fracture (N°)	Depth (m)	Dip (°)	Dip Direction (°)	Stimulated zone
A1	3247	65	68	Yes
A2	3350	76	236	Yes
A3	3470	70	68	Yes
A4	3508	70	288	–
A5	3566	70	68	–

3.2 *GPK2 stimulation test*

The previous model has been used to study the stimulation test conducted on well GPK2 in 1994 (Fig. 1). The fracture network present in the upper part of GPK2 has been established by BRGM geologists (Genter et al. 2001). The flow log performed during the hydraulic test showed that fluid is injected into the heat exchanger via only three main fracture zones (Table 2). The percentage of flow rates injected in each permeable fracture is around 25%.

The following results were obtained by the model for the previous fracture network of GPK2:

- the Pressure vs. Flow rates curve calculated by the model is in good agreement with the measurements (Fig. 9).

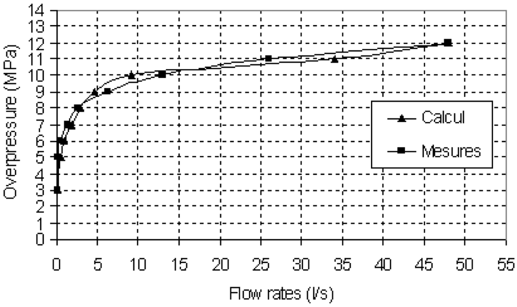

Figure 9. Measured and calculated Pressure vs. Flow rates curves for the upper part of GPK2.

– as confirmed by the flow log data, the model also shows an increase in the permeability of the fractures A1, A2 and A3.
– the increase in permeability of the stimulated fractures is associated with a shear mechanism in the fracture planes.

4 CONCLUSION

Numerical modeling is in progress to study the hydraulic behavior observed during stimulation tests conducted in the two wells GPK1 and GPK2 at Soultz-sous-Forêts HFR site.

Indeed, this approach permits better understanding of the physical mechanisms which are responsible for increases in fracture permeability and to study why most of the flow occurs in only a subset of the fracture network.

Thus, the model was useful to establish that a shear mechanism induced by the injection pressures is probably responsible for the increase in fracture permeabilities.

The model demonstrates also the good correlation between stimulated fractures orientations and the in situ stress tensor orientation.

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