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A Methodology for the hydro-mechanical characterisation of EGS reservoirs

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Abstract

The development of an EGS power plant depends vitally on the understanding of hydraulic, thermal, chemical and mechanical processes and properties of a fractured reservoir. But it is a fact that the knowledge about the leading parameters of an EGS reservoir behaviour - especially the spatial distribution of fractures or flow paths - is usually rather poor. The treatment of this problem in the hydro-mechanical code HEX-S will be discussed.

Keywords: stochastic, hydro-mechanical processes, fractured reservoir

1. Introduction

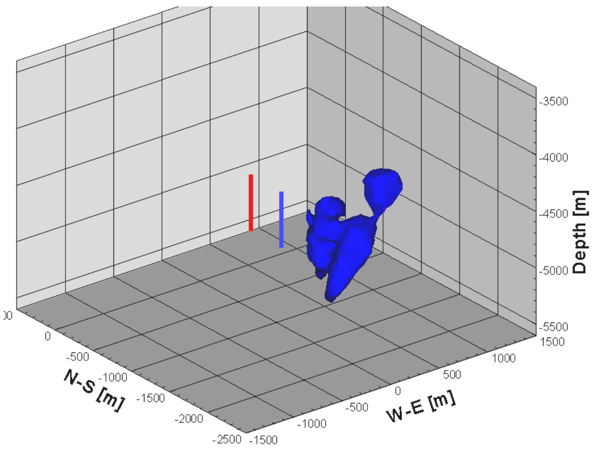
The development of an EGS power plant depends vitally on the understanding of hydraulic, thermal, chemical and mechanical processes and properties of a fractured reservoir. From an engineering point of view we would like to know all relevant parameters for characterising the actual state of a reservoir which would allow us to predict the results of a stimulation test and finally of long-term energy extraction.

Making predictions about a specific physical behaviour of a reservoir due to a change of boundary conditions - as e.g. during a stimulation test or during circulation - means applying a mathematical model in which as far as possible all existing information about the reservoir is integrated.

Despite the fact that a lot of progress has been made in the acquisition of information through hydraulic tests, microseismic measurements, well-logging and other methods, the underground system still remains highly under-determined during all phases of an EGS life-cycle. One method could be to integrate all known parameters deterministically into a model and treat unknown but relevant parameters in a stochastic manner. Especially the spatial distribution of fractures or flow paths is of crucial importance but usually very poorly known. How this problem can be treated shall be exemplified with the hydro-mechanical code HEX-S.

2. The hydro-mechanical code HEX-S

The hydro-mechanical code HEX-S has been developed to calculate the stimulation processes in a fractured reservoir during a massive injection into a borehole. The code takes into account the aperture change of each fracture in the model due to the corresponding overpressure resulting from the injection. The propagation of the overpressure in the reservoir as well as the development of the highly anisotropic reservoir permeability as a result of the fracture apertures is calculated as a time-dependent process. Hence the reaction of the reservoir permeability due to an arbitrary injection rate history can be calculated. Fig. 1 illustrates the typical transient development of a 0.1 mm aperture change in a fractured reservoir due to hydraulic injection.



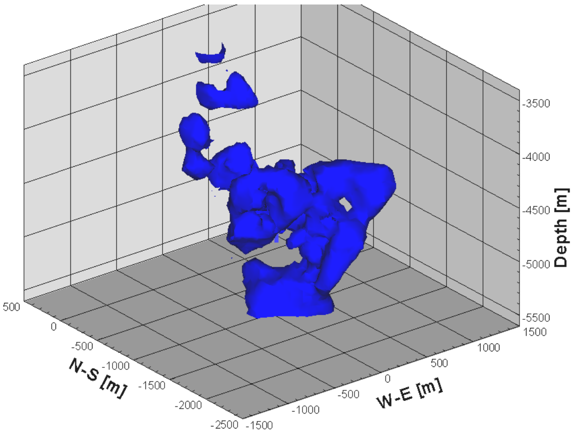


Fig. 1.: Calculated iso-surface of the 0.1 mm fracture aperture after 5 hours (top) and 20 hours (bottom) of injection into GPK4 for the 5 km deep reservoir domain at Soultz-sous-Forêts

2.1 Generation of the fracture network

The permeability distribution in a HEX S model depends essentially on the location, orientation and aperture of the incorporated fractures. HEX S allows defining an arbitrary number of both, stochastic and deterministic, fracture sets. Experience from various EGS test sites demonstrates that microseismic events often follow planar structures (i.e. Asanuma 2004, Evans et al. 2005; Cuenot et al. 2005). Since we assume that in most cases an induced microseismic event represents the shear failure of a along an area of a fracture ("slip patch"), the locations of the calculated shearing events can be compared with the microseismic clouds. In contrary, possible mode I events (normal stress variations) remain unidentified.

In HEX S every fracture or fracture zone is represented by a number of circular slip patches with small, predefined radii, generated by subdivision of a planar, and so far circular fracture zone. The aperture of each specific slip patch contributes to the final permeability distribution in the model. Starting from an initial value (see below), the aperture change of a fracture depends on the orientation, the local effective stress field and its defined mechanical parameters.

Each fracture zone in HEX S can be generated from deterministic or stochastic data, with the following detailed properties:

1. Deterministic fracture zones of defined radii, orientations and classes of mechanical behaviour for their slip patches: The corresponding data is generally derived from borehole logs (e.g. FMS, UBI) but may also include post-experimental interpretation of individual, microseismically active planar structures (Fig. 2).

2. Stochastic generation of fracture zones with random location and orientation: The statistical distribution of the orientation of fracture zones seen in borehole logs is used as the input parameter for the stochastic generation. Each random seed number generates a new distribution of fracture zones in the model (Fig. 3). Each stochastically generated model, independent from the random seed number, has the same distribution of orientations of fracture zones. Stochastically generated fracture zones are generally reasonably used at locations with little information (i.e. at greater distance from the boreholes). The herewith-defined model domain is filled-up until a predefined fracture (or slip patch) density is reached. Generally, sets of >20'000 slip patches are generated in this way.

The initial aperture of each slip patch is proportional to its radius and adjusted with an overall factor in such a way that the whole reservoir model has a predefined average permeability.

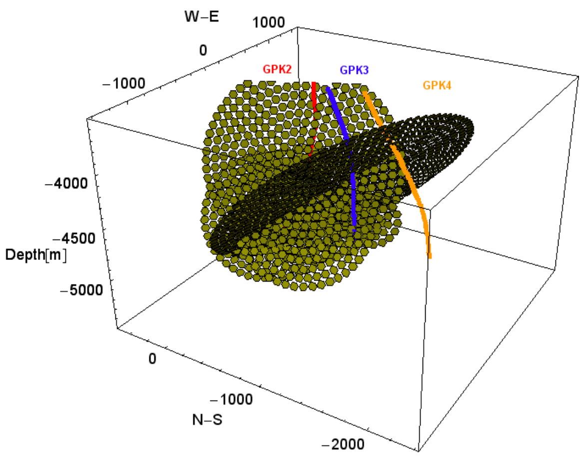


Fig. 2: Example of a model with deterministic fracture zones subdivided into slip patches for the 5 km deep reservoir domain at Soultz-sous-Forêts. Also indicated are the boreholes GPK2, GPK and GPK4

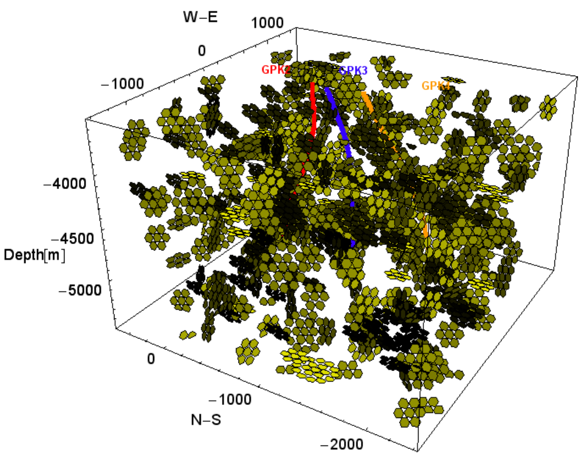


Fig. 3: Example of stochastically generated fracture zones for the 5 km deep reservoir domain at Soultz-sous-Forêts. Also indicated are the boreholes GPK2, GPK and GPK4

2.2 Implemented fracture aperture laws

The implemented aperture laws for the fractures or slip patches are basically of analytical kind (Willis-Richards et al., 1996, Jing et al., 1998, Bächler et al., 2001). The aperture of a fracture depends on three sets of parameters:

1. The mechanical properties of the fracture
2. The fluid pressure in the fracture space
3. The normal and the shear stress on the fracture plane

The effective normal stress $\sigma_{n,eff}$ and the effective shear stress τ_{eff} on the plane of a fracture are derived from the three regional principal stress components and the fluid pressure P at the fracture location. Depending on the pore and fracture fluid pressure P, the fracture aperture at a given location is assumed to react:

a) By compliance only

b) By compliance and shearing

c) By jacking and shearing

a. Compliance only

Under the condition of low effective shear stress, τ_{eff} , only a compliant reaction of the fracture walls to fluid pressure will affect the aperture. The conditions for this behaviour are

$$\sigma_{n,eff} > 0$$

$$\Delta\tau = \tau_{eff} - \sigma_{n,eff} \cdot \tan(\Phi) \quad < 0$$

(Mohr-Coulomb criterion)

As convention, stress is positive for compression. The friction angle Φ of the fracture walls is implemented as a function of $\sigma_{n,eff}$. The aperture increase is treated as reversible and vanishes as soon the pressure declines after the end of injection.

b. Compliance and shearing

If the effective shear stress τ_{eff} at the fracture walls exceeds the friction resistance, i.e. $\Delta\tau$ >0, and the effective normal stress $\sigma_{n,eff}$ still is positive, the fracture fails. The additional "shear" aperture change, a_s, due to the shear offset, U, is

$$a_s = U \cdot \tan(\Phi_{dil})$$

The shear dilation angle of the fracture wall, Φ_{dil}, is also implemented as function of $\sigma_{n,eff}$. The shear offset is defined from fracture shear stiffness, K_s, as:

$$U = \Delta\tau / K_s$$

This portion of the aperture increase is considered to be irreversible when injection test has stopped and the pressure field in the reservoir has reached its ambient value.

c. Jacking and shearing

In the case the effective normal stress, $\sigma_{n,eff}$, becomes negative, the fracture walls separate and the friction forces acting on them disappear. In addition to the shear aperture change, a contribution from jacking conditions, a_j, arises. Clearly, a_j is considered to be fully reversible.

Although the shear induced, mode II, aperture change of a fracture is the only permanent effect after an injection test has ended, the contributions from jacking and compliance are also of major importance for the propagation of the pressure front during the stimulation process.

2.3 *Hydraulic processes*

The time-dependent pressure calculation in HEX-S is performed with a new finite element (FE) algorithm which is a further development of the FRACTure code (Kohl & Hopkirk, 1995). The main advantages of the FE algorithm are in efficient and flexible formulations:

- Local mesh refinement at specified locations in the reservoir domain such as boreholes,
- Utilization of an implicit time-step procedure for the transient calculation
- Easy extension to further physical processes or constitutive laws

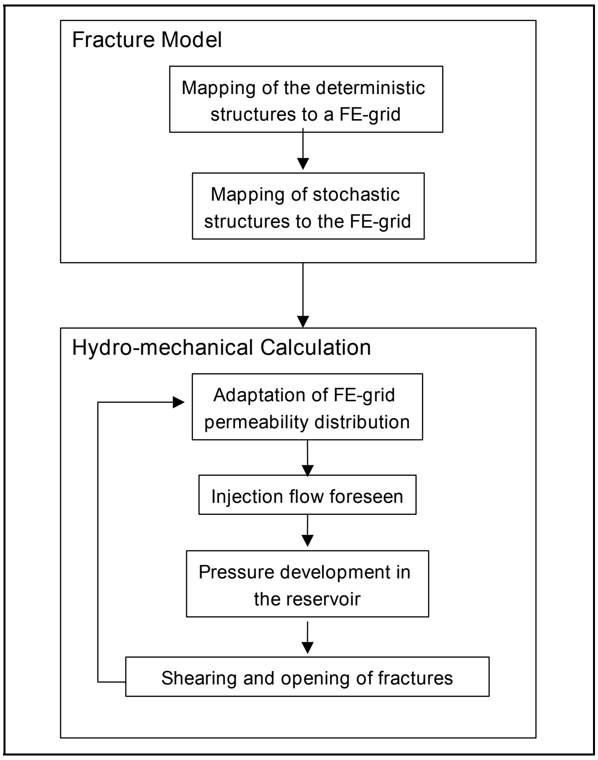


Fig. 4: Principle flow chart of HEX-S

The hydraulic conductivity for each element is derived from the apertures of the intersecting slip patches by a specific mapping procedure. The intersection of the discrete fractures with the continuous FE grid is calculated using a "Rock-to-Fracture volumetric index", RFVI. The mapping results in individual FE volumes of strongly anisotropic properties. Thereby, the hydraulic properties of the FE grid are modified after each time-step. HEX-S calculates the pressure in the model and determines the new apertures of the slip patches. When the hydraulic conductivities of the elements have been updated from the corresponding slip patch apertures, a next time-step is carried out (Fig. 4).

3. References

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4. Acknowledgements

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