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Using the migration of the induced seismicity as a constraint for fractured Hot Dry Rock reservoir modelling

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Abstract

The challenge for Hot Dry Rock technology is to develop a heat exchanger in deep hot rock masses and to circulate a fluid in order to extract its energy to be used at the ground surface. The present day strategy is to take advantage of natural fractures that pre-exist at these depths and to improve their hydraulic properties. The extension of the area with enhanced properties must then be evaluated so that the best locations for further boreholes can be proposed. To date, this development procedure is based on fluid injection at high rates, forcing hydro-mechanical interactions to take place along pressurised fractures. These pore-pressure-driven mechanisms are accompanied by seismic activity. Assuming the validity of poro-elastic theory in the fractured host rock, some authors have derived the virgin hydraulic diffusivity of the fractured reservoir from the analysis of the spatio-temporal growth of the induced seismicity. The present work is aimed at verifying this approach using a numerical code to solve directly for hydro-mechanical interactions in random fracture networks. Our approach assumes that the seismic activity is controlled by a Coulomb shear criterion and we show how the interpretation of spreading rate of the modelled shear activity in a given network coincides with the upscaled virgin hydraulic diffusivity of the same fracture network, calculated from an independent numerical procedure at the reservoir scale. Therefore, it is shown that the direct analysis of the seismicity migration is appropriate to give reliable estimates of virgin hydraulic and mechanic parameters. These parameters can then be used for performing any further quantitative analysis of a reservoir open to the far field. This is of importance, as fluid mass-balance in multi-well exploitation systems will include the contribution from areas surrounding the stimulated zone.

Keywords: Fracture network modelling; Microseismicity; Hydro-mechanical coupling; Shear failure; Macroscopic permeability

1. Introduction

Experiences from successive Hot Dry Rock projects during the last 30 years gradually led to the present conception of a reservoir consisting of the interconnection of boreholes over inter-well distances of commercial interest. The view is now accepted that this interconnection occurs through the pre-existing volumetric network of fractures, faults and joints of hydraulic significance. It is well established, in this particular field of engineered geothermal reservoirs [1–3], that any increase of the pore pressure in a pre-existing fracture can induce a shear rupture with a microseismic signature, as soon as a strength criterion for failure is met. Hydraulic experiments, better known as 'stimulation experiments', are undertaken, using fluid injections at high over pressures and elevated flow rates into the pre-existing conductive structures. The result is a general reduction of the shear strength of the rock mass where shearing and self-propping process can develop up to distances of hundreds of meters.

This stimulation strategy was adopted in the European Hot Dry Rock project run at Soultz sous Forêts (France), in the Rhine Graben extensional setting [4]. Regarding scientific and pre-industrial objectives, valuable results have been obtained at this site, at a depth of around 3.5 km [5]. Following this significant success at moderated depth, the project supported by the EC has evolved toward a three-well system at a depth of 5 km, and temperatures close to 200 °C [6]. Hydraulic tests obtained in the recent wells GPK2 and GPK3 during the 2000–2003 field campaign [7], and again during the development of the

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most recent well, GPK4, in late 2004 [8], have shown that fractures in the new targeted reservoir are still easy to reactivate, with over-pressure at the injection wells in the range of 14–18 MPa. Tens of thousands of seismic events were recorded during each stimulation phase. Thousands among them could be located in space, delineating a dense seismic cloud. In a plan view at reservoir depth, this cloud is elongated in shape in a direction close to that of the maximum horizontal stress component [9]. Seismic surveys are routinely used to delineate reservoir structure and evaluate cap-rock integrity in the field of petroleum engineering [10–12]. Much specific work in hard rocks can be found for a quantitative interpretation of the spatial structure of the seismic cloud, for mapping fault zones [13–15] and for discussing stress perturbation along sheared areas [16]. Such efforts to delineate and identify internal structures give geometrical constraints in reservoir models [17,18] that can integrate some fractures in a deterministic sense. Microseismic studies also provide at distance from observation wells a good insight into principal stress orientations from the inversion of focal mechanisms [19].

The discussion now focuses on the possibility of deriving not only geometry but also some additional hydraulic knowledge from the shear failure mechanism, considered as the source of the acoustic emissions. A quantification of the pre-stimulation hydraulic diffusivity of the fracture network is already under discussion. Shapiro's approach [20] uses a spatio-temporal analysis of the induced microseismicity to derive an in situ estimate of the hydraulic diffusivity tensor of the virgin rock mass. It is also shown in [21] that this tensor is proportional to the permeability tensor. The main assumption of the so-called SBRC approach (seismicity-based reservoir characterisation) is that the triggering front of the hydraulic-induced events propagates like the process of pressure relaxation in an isotropic poro-elastic saturated medium. According to these authors, the spatial position d of the triggering front at time t in a fractured medium with a scalar diffusivity D is given by $d = (4\pi Dt)^{1/2}$. The method has been used again at Soultz site [22] to derive a scalar permeability of the deeper part of the rock mass of about $2 \times 10^{-16}\,\mathrm{m}^2$. The understanding of the growth of the seismic cloud during an injection phase remains, however, a matter of debate. A structuration at large scale in the seismic cloud is generally observed after a period of nearly axisymmetrical growth. It can be argued that it reflects the reactivation of weaker fracture zones away from the well, with a particular orientation. It may also be a general rupturing process, aggregating local ruptures along local discontinuities and mostly controlled by the far field stress tensor [23,24]. Therefore, the growth of the seismic cloud reflects these couplings between mechanic and hydraulic processes and suggests macroscopic cohesion and friction coefficients.

The present paper is a numerical contribution to the above debate and we will concentrate on the early phase of the seismic cloud development. We simulate the hydraulic behaviour of a set of fracture networks under various hydro-mechanical conditions in such a way that its permeability, its hydraulic diffusivity and the diffusivity of the shearing migration can be separately obtained. This method offers the opportunity of comparing the magnitudes of both diffusion processes. It will complement and extend efforts of running an inversion for hydraulic properties of rocks performed in [25] that was based on a pore-pressure relaxation model in a 2D homogeneous isotropic background with randomly distributed critical zones, but that did not integrate a real fluid flow model in a discrete system of fractures. Thanks to calculations in a set of generic networks, we will also show that small hydraulic conductivities can explain delayed shear ruptures by simple mechanical rules. This work forms part of the basis required for the evaluation of the overall impedance of a circulated HDR system at flow rates compatible with an economic exploitation scheme.

2. Forward modelling of the shearing process and derivation of the virgin hydraulic diffusivity

2.1. Overview of the FRACAS numerical tool used for the verification of the SBRC approach

A description of rationale and concepts behind the discrete fracture network (DFN) model, FRACAS, used in the present paper to model fluid migration in 3D random networks of fractures can be found [18,26]. Our DFN approach assumes that fluid flow in deep hard rocks occurs in disc-shaped fractures, that assemble into a 3D network, and that in comparison the contribution of blocks of intact rock to the overall flow is negligible. Many works on boreholes, outcrops, lineament maps and seismic profiles highlight the presence of faults at all scales, and point to fractal characteristics [27–30]. For our purpose, the networks generated hereafter will exhibit fracture sizes following a power law distribution where formal representation of the Complementary Cumulative Density Function is expressed as

$$G(x) = (x_0/x)^{\mathrm{a}}, \tag{1}$$

where x_0 is the minimum radius value, x is any fracture radius between x_0 and infinity, a is the exponent of the power law, and $G(x)$ the probability that a radius is greater than x. Fracture sizes are generated through a Gaussian anamorphosis as in [31].

Depending on its own size, each fracture is recursively meshed into a sub-set of smaller disc-shaped cells, and the flow equations, namely the equations relating volumetric fluxes to hydraulic head gradients computed between adjacent cell's centres and the mass conservation equations at each cell, are solved in a transient manner for the set of connected cells to obtain detailed time-dependent pressure and velocity fields.

The numerical package accounts for some hydro-mechanical interactions, and shear slip along unstable cells