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Multi scale numerical modelling related to hydrofracking for deep geothermal energy exploitation

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Abstract

Prediction of fracture propagation through rock masses is investigated in this paper by adopting the Distinct Element Method (DEM) and the Voronoi tessellation. A microstructure-based model was created. Microparameters governing Voronoi sub-blocks contacts behaviour were calibrated against laboratory tests results for different rocks. An upscaling procedure is proposed to build reliable and representative numerical models at in situ scale to study fracture propagation for deep geothermal wells.

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Keywords: Fracture process; Voronoi tessellation; geothermal wells

1. Introduction

Enhanced Geothermal System (EGS) are engineered reservoirs created to extract heat from economically improductive geothermal resources, typically known as Hot Dry Rock (HDR). An EGS uses drilling, fracturing and injection to provide fluid and permeability in areas that have hot but dry underground rock [1]. Heat is the only component that needs be natural. Insufficient permeability is remedied by artificial means such as hydraulic fracturing, by means of which high-pressure water is injected from the surface through wells into a body of deep, hot, compact rock to enlarge preexisting sealed fractures or to create new ones. Water permeates these fracture

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system, flows along permeable pathways, extracting heat from the surrounding rock. This reservoir is later penetrated by a second well, which is used to extract the heated water. Upon leaving the plant, the fluid is returned to the reservoir through injection wells to complete the circulation loop.

Despite hydraulic fracturing technology having been used for more than 30 years in the context of energy exploitation, underground formations represent a complex system of variables (both rock and well properties) that make fracturing processes a not fully understood problem that requires further investigation [2-4]. Prediction of the effectiveness of the fracturing process can be investigated by numerical simulations [5-8]. For problems in which large-scale phenomena (e.g. rock slides or reservoir stimulation) are strongly influenced by processes occurring at much smaller scales (e.g. fracture initiation and propagation), it is not practical to generate comprehensive simulations that include an explicit representation of the fracturing processes over a wide range of scales. To address this problem, numerical methods may be used with a multi-scale approach combining multiple models defined at fundamentally different length scales within the same overall spatial domain [2, 9-13]. For example, a small-scale model with high resolution can be utilized in a fraction of the overall domain and linked to a large-scale model with coarse resolution over the remainder of the overall domain, providing necessary efficiency of characterization and computation that will render solution of these problems practical.

This paper will focus on the simulation of hydrofracking processes for the creation of an EGS system by a multi-scale approach. The Voronoi tessellation [14] and the Distinct Element Method (DEM) [15] will be used to reproduce rock behavior at the laboratory scale. An upscale procedure will be presented to finally model the fracturing process at the site scale. The theoretical but realistic case study of a man-made geothermal field concerning a granitic rock mass will be discussed.

2. Multi scale modelling approach

The multi scale modelling approach was implemented with the DEM and the UDEC software [16]. Voronoi tessellation was used to generate the synthetic rock material. The Voronoi tessellation is a special joint generator that creates randomly sized polygonal or triangular (option Trigon) blocks. The grain boundaries in the poly-crystal structure produced by Voronoi tessellation can be used to represent flaws in intact rock and therefore allow for simulation of crack damage development through initiation and propagation of fractures along grain boundaries [16].

The parameters governing the behavior of Voronoi elements have to be calibrated and verified against reliable laboratory experiments. To this extent, uniaxial compression tests (UCS) and indirect tensile strength tests were simulated for a number of rock types. Synthetic specimens of 50 mm in diameter and 100 mm in height were prepared (Fig. 1a), in which a Voronoi edge of 3 mm was chosen. Five different rocks were considered: Plaster of Paris [17], Transjurane sandstone [18], Tagikistan siltstone, Augig granite [18] and Barre granite, allowing to assess the differences in the calibration of the Voronoi sub-blocks contacts microparameters.

The constitutive model of the sub-blocks is assumed as isotropic elastic, while an elasto-plastic behavior with softening and a Mohr-Coulomb failure criterion is assigned to the Voronoi contacts. A constant loading rate of 0.001 m/s was applied to the top and bottom platens to simulate uniaxial loading tests. The loading rate was found to be a good compromise between computational time and precision of the results in previous studies.

The calibration process was performed by means of a trial-and-error procedure where the material macro properties are modified by two factors S and R defined as follows:

$$k_{n,trial} = S \cdot k_{n,mat} \qquad k_{s,trial} = k_{n,trial} / 2 \tag{1}$$

$$c_{trial} = R \cdot c_{mat} \qquad tg\Phi_{trial} = R \cdot tg\Phi_{mat} \qquad \sigma_{t,trial} = R \cdot \sigma_{t,mat} \tag{2}$$

where k_n and k_s are the normal and shear stiffnesses, c is the cohesion, Φ the friction angle and σ_t the tensile strength.

At first, R is kept constant and S is gradually increased in order to match the deformability measured during triaxial laboratory tests. Then, the calibrated S value is kept constant and R is modified to match the proper strength. Table 1 shows the results of the calibration process.