Modelling Reservoir Stimulation in Enhanced Geothermal Systems

Di Giuseppe, M.G [(1)*], Troiano, A. [(1)], Troise, C. [(1)], Perillo, G. [(2)] and De Natale, G.

[(1)] Istituto Nazionale di Geofisica e Vulcanologia - Osservatorio Vesuviano, Italy.
[(2)] Università Parthenope, Naples, Italy.

*Corresponding author: Maria Giulia Di Giuseppe
mariagiulia.digiuseppe@ov.ingv.it
Via Diocleziano, 328
80124 - Naples (Italy)

Abstract: Fluid injection in deep wells is a basic procedure in geothermal permeability enhancement. Numerical procedures to describe its potential to induce seismicity has already be presented in literature. These are based on the simulation of the thermodynamic evolution of the system where fluids are injected. The retrieved changes of Pressure and Temperature are subsequently considered as sources of incremental stress and strain changes, which are then converted to Coulomb stress changes on favored faults, taking into account also the background regional stress.

In this work, we upgrade this kind of procedures to consider the permeability enhancement obtained in the stimulation process. Actually, in fractured porous media subjected to external loads, the solid deformation changes the rock permeabilities. Assuming a conceptual model linking induced stress/strain and permeability changes, we can estimate the induced permeability variation during the stimulation process. In this way we adapt the medium behavior to mechanical changes and could possibly evaluate the effectiveness of stimulation process in enhancing a geothermal reservoir permeability.
Numerical results are applied to simulate water injection stimulation, used to create the fractured reservoir at the Soultz-sous-Forets (France) EGS site, to the aim of reproduce rock fracturing.

Keywords: Fracture and flow, Downhole methods, Controlled source seismology

1. Introduction

Geothermal systems represent a large resource that can provide, with a reasonable investment, a very high and cost-competitive power generating capacity. Considering also the very low environmental impact, their development represents, in the next decades, an enormous perspective (MIT Report, 2006). Despite this unquestionable potential, geothermal exploitation has always been perceived as limited, mainly because of the dependance from strict site-related conditions, mainly correlated to the reservoir rock's permeability, the amount of fluid saturation and, first of all, a convenient temperature-depth relationship. However, many of such limitations are overcome with the Enhanced Geothermal System (EGS, Majer et al., 2007), where massive fluid injection is performed to enlarge the natural fracture system of the basement rock. The permeability of the surrounding rocks results highly increased by pressurized fluids circulation and geothermal resource, in such way, become accessible in areas where exploitation, otherwise, could be not advantageous or even possible. Numerical procedures have already been presented in literature reproducing the thermodynamic evolution of the system where fluids are injected (Troiano et al., 2013). In such a way, changes of Coulomb stress can be computed from Pressure and Temperature changes; the correlation between computed Coulomb stress changes and observed induced seismicity patterns has been shown to be very effective for the Soultz-sous-forets case (Troiano et al., 2013) thus validating the procedure. We upgrade this kind of procedures to obtain an evaluation of the permeability enhancement obtained in the stimulation process. Assuming a conceptual model linking induced strain and permeability modification, we can estimate the induced permeability change during the water injection. In this way we adapt the medium behavior to mechanical changes and we could possibly evaluate the effectiveness of stimulation process in enhancing a geothermal reservoir permeability.

2. Method

Our method of analysis consists of a two-step procedure. In the first step, injection of water is simulated (Pruess, 1991) in a homogeneous medium, approximating a crystalline granite basement compatible with the deep structure of the Soultz-sous-Forets (France) EGS site. The modeled 3D physical domain and the imposed initial conditions are shown (Fig.1). Water at ambient condition is injected at a 100 kg/s rate for 10 days in a point located at -5 km depth. In such a way we obtain the pressure and temperature changes at each point in the medium, at the final time. Such P and T changes at any point are subsequently considered as elementary sources, heterogeneously distributed in the whole discretized volume, which generate an incremental stress tensor field estimated by using the Comsol Multiphysics finite element code (Troiano et al., 2011, Troiano et al., 2013). Once the complete field of stress changes is computed, a conceptual model linking induced stress and permeability modification in orthogonally fractured media is adopted, incorporating the influences of both normal strain and shear dilation on the effect of fluid flow. The permeability changes caused by the solid deformation may be expressed as (Peng and Zhang, 1989; Bai and Elsworth, 1994):

$$k' = k_0 \left\{ \begin{array}{l} 1 - \left(\frac{1}{K_n b} + \frac{1}{K_n s} + \frac{1}{E} \right) \left[\Delta\sigma_i - \nu \left(\Delta\sigma_j + \Delta\sigma_k \right) \right] + \\ - \left(\frac{1}{K_n b} + \frac{1}{K_n s} + \frac{1}{E} \right) \left[\Delta\sigma_j - \nu \left(\Delta\sigma_i + \Delta\sigma_k \right) \right] \end{array} \right\}^3 \quad (1)$$

where K_n represent the fracture stiffness, E the Young modulus of the granite (assumed as 10 GPa), s the fracture spacing, b the fracture opening and $\Delta\sigma_i$ represent the elements of induced stress tensor.

The simplified assumptions that the parameters s, b and K_n are independent on the coordinate system is applied. Furthermore, the value of K_n is imposed considering that from available informations the ratio of fracture stiffness to elastic modulus is highly variable, but a subset of results suggest that reasonable magnitudes are of the order of 0.1/cm (Bai and Elsworth, 1994).

Being the spacing and the opening of the fractures poor constrained, initially a parametric study is performed to evaluate the permeability changes as a function of s and b. A suitable couple of values is then adopted for such parameters, in order to impose, at the injection point, a permeability change of two order of magnitude, as experimentally recorded in well stimulation experiments. An estimate of the permeability change along the whole volume is successively obtained, using the (1). Due to the anisotropy of the induced stress tensor, permeability changes are, in principle, different in the three orthogonal directions, however, a mean value is assumed as k', the new medium permeability after fluid stimulation. Histogram of k' show a gaussian distribution of permeability values around the volume (Fig.2). The gaussian result centered around the k_0 value, with a standard deviation of about $k_0/3$.

To give an idea of the stimulation effects, it has to be considered that permeability at the injection point has been imposed as enhanced of two orders of magnitude. Furthermore, if values of k', are selected exceeding the mean of the gaussian more than 1 standard deviation, the corresponding points in the stimulated volume can be considered as the zone where permeability is effectively enhanced due to fluid injection (Fig.3). The mean value of k' in this zone results of $4.2*10^{-16}$ m^2, leading to a permeability about three times greater than k_0 in a spheric volume of about 0.5 km^3. The procedure can be re-iterated to reconstruct the permeability of the medium as function of the time, during stimulation process composed by different injection rates.

3. Conclusion

Our procedure rely on a very affordable basis, being a very good reconstruction of induced seismicity already been obtained. The new step that we are calibrating involve an estimate of the permeability enhancement correlated to stimulation process of geothermal boreholes. The proposed procedure lead to promising results, being the permeability enhancement estimated distributed in the space in a coherent way. The magnitude of this enhancement too, result coherent with the experimental data, once the wellbore overpressure and fluid flow has been imposed. The next step will involve the reconstruction of induced seismicity patterns, considering the permeability of the medium as a function of time, that changes during fluid injection due to induced stress tensor behavior.

4. References

Bai M, Elsworth D. Modeling of subsidence and stress-dependent hydraulic conductivity for intact and fractured porous media. Rock Mech Rock Eng, 27, 209-234 (1994).

Majer, E., Baria, R., Strak, M., Oates, S., Bommer, J., Smith, B. & Asanuma, H. Induced seismicity associated with enhanced geothermal sys- tems, Geothermics, 36, 185–222 (2007)

Massachussetts Institute of Technology. The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century: An Assessment, MIT Press, MA, USA (2006).

Peng, S., Zhang, J. Engineering Geology for Underground Rocks, 207-211. Springer (2007)

Pruess, K., 1991. TOUGH2—A General Purpose Numerical Simulator for Multiphase Fluid and Heat Flow, L.B.L. Report, Berkeley, CA.

Troiano, A., Di Giuseppe, M.G., Petrillo, Z., Troise, C. and De Natale, G. Ground deformation at calderas driven by fluid injection: modelling unrest episodes at Campi Flegrei (Italy). Geophys. J., 187, 833-847 (2011).

Troiano, A., Di Giuseppe, M.G., Troise, C., Tramelli, A., and De Natale, G. A Coulomb stress model for induced seismicity distribution due to fluid injection and withdrawal in deep boreholes. Geophys. J. Int., 195, 504-512 (2013).

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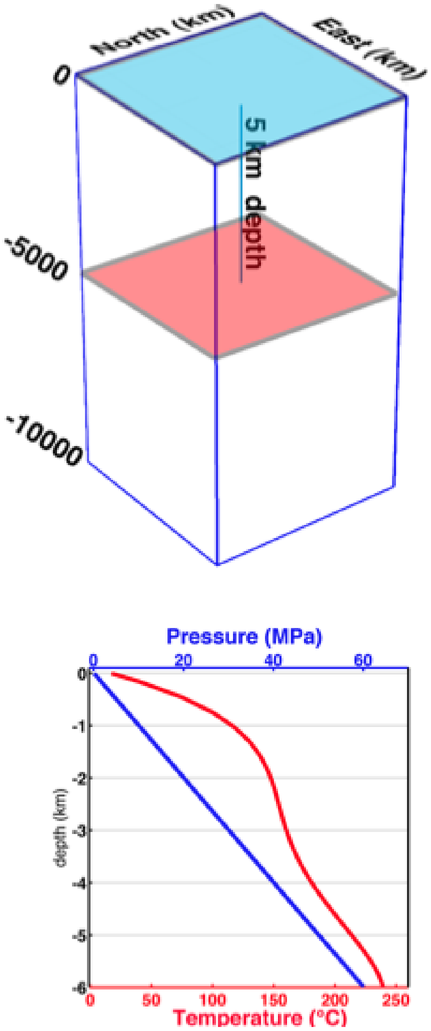

Fig. 1. Top: Sketch of the simulation volume. Blue plane, Earth surface; red plane, injection plane. Bottom: pressure and temperature initial conditions are indicated. Initial pressure (blue) and temperature (red) conditions as a function of depth.

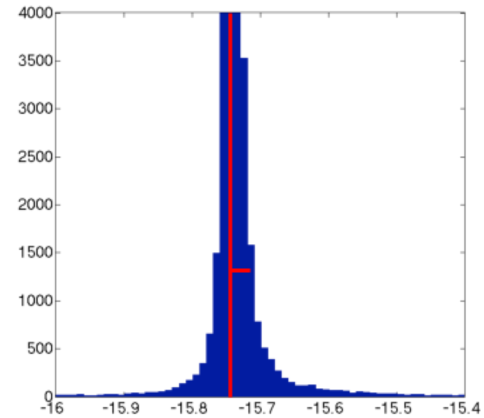

Fig. 2. Histogram of k', the new medium permeability after fluid stimulation. The histogram show a gaussian distribution of permeability values around the volume, centered around k_0, the initial permeability value. Mean value and standard deviation are represented with the red lines.

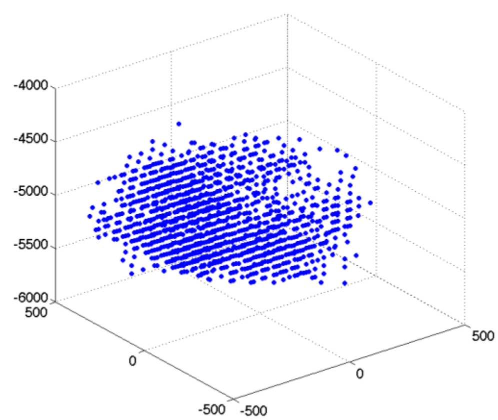

Fig.3. Points in the stimulated volume corresponding to values of k' exceeding the mean of this gaussian distribution more than 1 standard deviation. This area is considered as the zone where permeability is effectively enhanced due to fluid injection. The enhancement is estimated considering the mean value if this point.