Simulating the hydraulic stimulation of multiple fractures in an anisotropic stress field applying the discrete element method

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Abstract

The current study investigates hydraulic fracture stimulation for an Enhanced Geothermal System (EGS) in a petrophysical environment to evaluate stress shadowing and fracture interaction in a multi-fracture setup. Previous studies investigated the geothermal potential of the area around Freiberg (Saxony, Germany), which is therefore used as a case example. The commercial discrete element code 3DEC™ is applied to conduct the numerical simulations. The simulation results show that hydraulic fracture stimulation results in a strong stress field alteration, which significantly influences the propagation of subsequently stimulated fractures. The resulting deflection of fractures can be minimized applying an optimized stimulation concept.

1. Introduction

The hydraulic stimulation of a fracture results in stress redistribution, thereby creating a stress shadow around that fracture [1,2]. This effect is well known and extensively studied analyzing field data [3] and by conducting numerical simulations [4,5,6,7], for example to optimize hydrocarbon productivity from unconventional reservoirs. [8] measured fluid pressures during hydraulic fracture stimulation and their measurements indicate that stress...
shadowing is immediate, significantly influenced by geology, and cumulative. For example, during the last stimulation stages fluid pressure in an observation well increased by almost 2 MPa in more than 300 meters distance from the stimulation stage.

The presented research was conducted within the framework of the OPTIRISS project, in which a tool was developed to assess the investment risk for EGS projects in petrothermal environments based on geological, technical, economic and political aspects. One major goal of OPTIRISS was the optimization EGS designs based on the multi-fracture approach. In a first step the hydraulic stimulation of a single fracture was simulated to investigate fracture propagation and the alteration of the stress field. Based on the results a multi-fracture model was built to study fracture interaction. Finally, the setup for the hydraulic fracture stimulation was modified to minimize fracture interaction. The final stimulation concept provides an approach to engineer well aligned fractures, which can be easily connected by a second borehole for the later hot water production.

2. Methods and materials

2.1. Geology

In the current research the region of Freiberg (Federal state of Saxony, Germany) is used as a case example, which could be a suitable location for a geothermal power plant [9] with a HDR reservoir stimulated by applying the multi-fracture approach. The subsurface of Freiberg consists mainly of Augen gneiss and granite intrusions [10]. The target of the hydraulic stimulation process is a granite intrusion in a depth between four and five kilometres, which is indicated by an increase of seismic velocities. Typical properties of granite and gneiss measured by laboratory tests using samples from the Freiberg region are summarized in table 1. The stresses in the subsurface of Freiberg were evaluated by a numerical study [9] and the depth-stress relationship of the most likely case is shown in figure 1. The most prominent features of the stress field are a high anisotropy ($\sigma_1/\sigma_3 \approx 2$) and a lower $\sigma_3$ in the granite intrusion.

| Table 1. Properties of granite and gneiss (modified from [9]). |
|---------------------------------------------------------------|
| Parameter | Granite | Gneiss |
| Density [kg m$^{-3}$] | 2660 | 2700 |
| Young’s Modulus [Pa] | $6.5 \times 10^{10}$ | $5.5 \times 10^{10}$ |
| Poisson’s ratio [-] | 0.22 | 0.30 |
| Fracture toughness [Pa m$^{0.5}$] | $1.5 \times 10^{6}$ | $1.0 \times 10^{6}$ |
| Tensile strength [Pa] | $9.0 \times 10^{6}$ | $9.0 \times 10^{6}$ |
| Cohesion [Pa] | $3.8 \times 10^{7}$ | $3.1 \times 10^{7}$ |
| Friction angle [$^\circ$] | 40.8 | 35.5 |
| Dilation angle [$^\circ$] | 20 | 17 |

Fig. 1. Stress-depth relationship in the subsurface of Freiberg, plotted for the modeled depth (modified from [9]).
2.2. 3DEC software description

The simulations presented in this manuscript were conducted applying 3DEC™, which is a commercial software developed by Itasca™ Consulting Group Inc [11]. 3DEC™ is based on the discrete element method and models consist of rigid blocks of arbitrary shape, which become deformable after meshing. Moreover, meshing blocks subdivides contacts into sub-contacts with a sub-contacts area depending on the discretization size. Forces are transferred between blocks via contact-laws at their shared contacts and fluid transport as well as fracture propagation is limited to these contacts. In the simulations of the current study fluid transport is restricted to failed sub-contacts only. Among other properties, the strength of a contact is described by its tensile strength, normal stiffness and shear stiffness. In order to model an intact rock mass the properties of the gneiss and granite need to be converted into equivalent contact properties. For the conversion the mesh size needs to be taken into account as well. Following equations allow the calculation of the contact tensile strength $\sigma_{ts}$, normal stiffness $k_n$ and shear stiffness $k_s$ for hydro-mechanically coupled simulations in 3DEC™:

\[
\sigma_{ts} = 0.75K_{IC} l_D^{-0.49}
\]

\[
k_n, k_s = f \times (K + 4/3G)/l_D
\]

where $K_{IC}$ is the fracture toughness, K is the bulk modulus and G the shear modulus of the modelled rock mass, $l_D$ is the input discretization length for the meshing of the blocks, and f is an adjustment factor.

2.3. Model setup

Figure 2 illustrates the model setups for the single-fracture simulation (Figure 2a) and the multi-fracture simulation (Figure 2b). In both setups an intact rock mass is modeled consisting of the 1000 m thick granite intrusion and 500 m of gneiss above and below. In case of the single-fracture model only one wing of the fracture is simulated, whereas the complex fracture interaction due to stress shadowing in the multi-fracture simulation required the full model. Due to the high stress anisotropy fracture propagation is expected to be perpendicular to $\sigma_3$ [12,13]. Therefore, predefined fracture planes are introduced to the models with their normal parallel to $\sigma_3$. The models are meshed with the mesh size increasing with distance from the predefined fracture planes. Close to the predefined fracture planes the input discretization length is 25 m.

Fig. 2. (a) Single-fracture model setup for the simulation of one fracture wing. (b) Multi-fracture model setup for the simulation of five fractures with a spacing $d_x$. The orientation of the main stress components in the model are indicated by (c) and (d). Simulated is a depth between 3500 m and 5500 m. A plane is predefined for fracture propagation perpendicular to $\sigma_3$. The blocks and contacts are parameterized with properties equivalent to the modelled rocks.
A total of 5000 m³ of pure water are injected into the predefined fracture planes in a depth of 4900 m and at a rate of 5 m³ per minute. In the single-fracture model half the volume is injected at half the rate and in the multi-fracture model fractures are stimulated in row. According to [14] fluid loss is negligible in crystalline rocks. Therefore, a fluid efficiency of 100% is assumed. Neglecting temperature and pressure effects fluid density is set to 1000 kg/m³ and fluid viscosity to 1.0 mPa·s. Fluid backflow was simulated by applying a constant fluid pressure equal to the water column at the point of fluid injection and allowing unrestricted discharge.

2.4. Fracture deflection

In the multi-fracture simulations fractures are deflected due to stress field alterations. This fracture deflection renders it difficult (or even impossible) to connect all fractures by a second borehole for the later fluid circulation and hot water production. In the current study a measure for the deflection D is calculated applying following methodology (Fig. 3):

- Evaluate for each fracture a theoretical injection point (P_{th}) for the later fluid circulation, which is defined as the point 100 m below the upper fracture tip and in the middle of the fracture.
- Lay a line parallel to the stimulation borehole (line connecting all points of fluid injection) through P_{th}.
- Projecting P_{th} along this line on the next fracture plane in the row to get the projected point P_{pr}.
- Calculate the distance D_p between P_{pr} and P_{th}.
- Calculate the distance d between the points of fluid injection.
- Calculate the deflection D = D_p/d.

![Fig. 3. Sketch illustrating the calculation of the deflection D.](image)

3. Results and discussion

3.1. Single-fracture simulation

Fig. 4 shows a 3D representation of the simulations results from the single-fracture model (SF-Sim). After the hydraulic stimulation was finished the fluid was enclosed in the fracture. The locations of failed sub-contacts (colored points) indicate that the main propagation direction of the fracture is upwards towards lower stresses (point of fluid injection as a reference). In addition, the highest fracture apertures are located in the upper part of the fracture. Due to the higher stress acting normal to the lower fracture parts fracture closure is initiated as the fracture propagates and the fluid is forced upwards. The final fracture geometric properties are summarized in table 2.
The cutting planes in this figure show contour plots of the change in $\sigma_3$. In areas parallel to the fracture $\sigma_3$ is significantly increased up to a distance of more than 200 m. Such stress shadowing effects were also observed by [8] during the hydraulic stimulation of hydrocarbon reservoirs. The areas at the forefront of the fracture show a reduction of $\sigma_3$. Latter effect is the result of a material displacement towards the fracture and a related stress relief. The alteration of the stress field due to hydraulic stimulation, especially the increase of $\sigma_3$ parallel to the fracture might have a significant impact on the propagation of subsequently stimulated fractures.

Fig. 4. 3D illustration showing the simulation result of the single-fracture model. The points represent the location of failed sub-contacts with their coloring indicating the sub-contacts aperture. The cutting planes show the change of $\sigma_3$ due to the hydraulic fracture stimulation. Yellow to red areas indicate an increase and green to blue areas a decrease of $\sigma_3$. The solid black lines are the intersection between the fracture and the cutting planes.

3.2. Multi-fracture simulations

In the first multi-fracture simulation (MF-Sim#1) the setup for the hydraulic fracture stimulation followed the approaches commonly proposed in literature [14]. The stimulation borehole for the fluid injection is parallel to $\sigma_3$ and the spacing between the predefined fracture planes is 100 m. Similar to the single-fracture simulation the fluid is enclosed in the fracture after its hydraulic stimulation is finished.

Fig. 5a is the 3D representation of failed sub-contacts. As observed in the single-fracture simulation, the main direction of fracture propagation is towards lower stresses and the highest fracture apertures are located in the upper fracture parts. However, the fractures do not align in a row, but develop a complex fracture pattern by alternating more or less randomly to the left and right. This complicated fracture alignment is caused by the stress shadowing of previously stimulated fractures. Fig. 6 shows a horizontal cutting plane at half fracture height, which indicates the
alteration of $\sigma_3$ in the range of approximately $\pm$ 12 MPa. Equivalent to the single-fracture simulation, the hydraulic stimulation of a fracture results in an increase of $\sigma_3$ in the areas parallel to that fracture. Moreover, the area of increased $\sigma_3$ extends well beyond the predefined plane of a subsequently stimulated fracture, which is deflected by the higher $\sigma_3$ values. A high fracture deflection of 4.85 m m$^{-1}$ was evaluated for this first stimulation setup and fracture geometries show high variances (Table 2).

For the second multi-fracture simulation (MF-Sim#2) the setup for the hydraulic fracture stimulation was modified to counteract the fracture deflection observed in MF-Sim#1. The stimulation borehole for the fluid injection is at a horizontal angle of 45° to $\sigma_3$ and the spacing between the predefined fracture planes is 200 m. After the hydraulic stimulation of a fracture is finished an unrestricted fluid backflow is allowed by applying a constant water pressure equal to a water column of 4900 m at the point of fluid injection.

Fig. 5b is the 3D representation of failed sub-contacts. Apart from fracture #5, which propagated into a part of the model with coarser meshing and is therefore neglected, fractures are well aligned. Fig. 7 shows a horizontal cutting plane at half fracture height, which indicates the alteration of $\sigma_3$ in the range of approximately $\pm$ 7 MPa. This significantly lower change in $\sigma_3$ is a result of the fluid backflow. By increasing the spacing between fracture planes and by applying a horizontal angle between stimulation borehole and $\sigma_3$ the overlap between fractures is minimized. Although, fracture deflection cannot be completely avoided, this second stimulation setup effectively reduces fracture deflection to 0.57 m m$^{-1}$ and provides more consistent fracture geometries than the first stimulation setup (Table 2).
Fig. 6. Contour plot showing the change of $\sigma_3$ for simulation #1 in a horizontal cutting plane at half fracture height. The snapshots are taken after the hydraulic stimulation of a fracture is finished. Yellow to red areas indicate an increase and green to blue areas a decrease of $\sigma_3$. The location of the subsequently stimulated fracture is indicated by the dotted line.
Fig. 7. Contour plot showing the change of $\sigma_3$ for simulation #2 in a horizontal cutting plane at half fracture height. The snapshots are taken after the hydraulic stimulation of a fracture is finished. Yellow to red areas indicate an increase and green to blue areas a decrease of $\sigma_3$. The location of the subsequently stimulated fracture is indicated by the dotted line.

Table 2. Fracture geometric properties for the single-fracture (SF-Sim) and the two multi-fracture simulations (MF-Sim#1 and MF-Sim#2).

| Fracture property     | SF-Sim | MF-Sim#1   | MF-Sim#2   |
|-----------------------|--------|------------|------------|
| Length [m]            | 400    | 300 – 380  | 329 – 368  |
| Height [m]            | 660    | 639 – 952  | 712 – 842  |
| Fracture area [km²]   | 0.19   | 0.18 – 0.23| 0.19 – 0.21|
| Average aperture [mm] | 26     | 22 – 28    | 11 – 12    |
| Fracture deflection [m m⁻¹] | -     | 4.85       | 0.57       |
4. Conclusions

Both, the single-fracture and the multi-fracture simulations show that fractures tend to propagate towards lower stresses, which results in a preferential height growth. Mechanical and hydraulic barriers might help limit fractures to the targeted geological formation. Moreover, the hydraulic stimulation significantly altered the stress field around the stimulated fractures. Especially the increase of the minimum stress component $\sigma_3$ strongly influenced the propagation of subsequently stimulated fractures. Allowing fluid backflow out of finished fractures reduced the magnitude of the change in $\sigma_3$ from $\sim 12$ MPa to $\sim 7$ MPa, but the area over which the stress field alteration extended did not change.

Stimulating multiple fractures in a row with the stimulation borehole parallel to $\sigma_3$ and a low spacing between fractures caused strong fracture interaction, resulting in fracture patterns which are difficult or even impossible to connect with a second borehole for later fluid circulation during hot water production. Varying the stimulation setup could not prevent fracture deflection completely, but increasing the spacing between fractures and setting the stimulation borehole at an angle of 45° to $\sigma_3$ reduced fracture overlap and therefore also fracture deflection. Moreover, if fluid backflow is allowed after hydraulic stimulation is finished, fracture geometries tend to be more consistent.

Acknowledgements

The research presented in this article was conducted within the framework of the OPTIRISS project. The project was funded by the “Europäische Fond für Regionale Entwicklung” (EFRE). We thank our project partners at JenaGeos and at the Geoscience Department at the University in Jena, as well as at Dynardo GmbH in Weimar for many fruitful discussions and their feedback on our research. We are especially grateful to Prof. Dr. Michael Kuehn and the whole committee organizing this Energy Procedia.

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