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Geomechanical Evaluation of the Fractures Productivity in Geothermal Resources

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Abstract

Geothermal development has seen an increasing trend in the recent years in Indonesia to fulfill the increase in energy demand. Subsurface-related aspects in the development of geothermal resources is an integral part that requires a comprehensive analysis in order to expedite the geothermal development; one of which is their geomechanical aspect. This aspect is mainly associated with the in situ stress in the reservoir that plays an important role for a successful planning, drilling and production of the resources. Although the geomechanical aspect of geothermal may seem to be overlapped with petroleum, there are a subset of problems that is inherently unique to geothermal settings. For instance, the effect of the high temperature on the stability of the wellbore and the examination of the quality of the fractures affecting the productivity of the energy source. One needs to address these unique challenges to ensure the development of the geothermal resources can be optimised. In this paper, one of the cases that will be discussed is regarding the productivity assessment of fractures through geomechanical evaluation. The potential contribution of fractures to the production will be examined by assessing their tendency to open or close under shearing. The stress acting on each fracture will be first computed through which their slip tendency can be determined. Depending on the relative orientation between the fracture and the in situ stress, their slip tendency can be obtained. This integrated yet simple analysis is found to be meaningful in geothermal development. For a given fracture set, the relative magnitude of the in situ stress can potentially lead to a different conclusion if not accurately determined. To ascertain this, a profile showing the maximum shear stress acting for various fracture orientations is then overlapped with the fractures. It is confirmed that fractures will tend to open for the orientation associated with the high shear stress. Hence, detailed knowledge on the in situ stress magnitude and orientation is just as important as the knowledge on the distribution of the fractures.

Keywords: Fracture slip, Geothermal, In situ stress, Shear stress.

Introduction

Geothermal development has seen an increasing trend in recent years in Indonesia to fulfil the increase in energy demand. Based on the Geothermal Director of the Directorate General of EBTKE at the Ministry of Energy and Mineral Resources, geothermal energy had been produced around 8.9 % or 2130.6 MW in 2019. Meanwhile, the government targets an increase in geothermal utilization to 7241 MW or 16.8% in 2025. There are few challenges that come through this target, such as social issues, conservation area, funding, efficiency cost, and risk in the development stage.

Cost efficiency is also related to how much risk is involved at each stage in geothermal development. The exploration and power plant development stage has a higher cost than the other stages. Risk and cost can be diminished by development ini reservoir technology based on geomechanical principles. Reservoir geomechanical have significant processes through years, but mainly focused on the petroleum field. As geothermal energy is widely used and developed, technology for geothermal has started to thrive and geomechanics issues have become an interest. This aspect is mainly associated with the in situ stress in the reservoir that plays an important role for a successful planning, drilling and production of the resources. Challenges must be addressed to optimize the resources.

In this paper, one of the cases that will be discussed is regarding the productivity assessment of fractures through geomechanical evaluation. The potential contribution of fractures to the production will be examined by assessing their tendency to open or close under shearing. The stress acting on each fracture will be first computed through which their slip tendency can be determined. Depending on the relative orientation between the fracture and the in situ stress, their slip tendency can be obtained.

Geomechanics and Geothermal

Geothermal has a unique condition from the traditional oil and gas challenges. A number of geomechanical issues that arise in geothermal development have been identified, especially drilling and production. These issues are associated with the heating-cooling processes, fractures productivity, injection and production in the reservoir.

Drilling and well placement

Similar to oil and gas drilling, the geomechanical aspect has an influence on geothermal drilling, especially when it comes to managing wellbore stability. The most common problem faced in geothermal drilling is lost circulation due to the presence of fractures. On the other hand, the presence of fractures indicates good reservoir quality in a geothermal system. A geothermal wellbore is considered as high potential when it intersects major fracture systems. Therefore, in geothermal drilling, it is a common practice to directionally orient the wellbore to intersect as many fractures as possible. In other words, the more severe a lost circulation is, the better the wellbore would be. However, this may trigger wellbore instability because of the presence of fractures. According to Carson et al. (1982), fractures is a common feature in geothermal due to the vulnerability of hard rock formations in seismically active regions and abnormal thermal gradients due to convective groundwater flow through fractures. Although lost circulation is a good omen, it is also the most expensive problem and can even lead to increased cost, contributing to Non-Productive Time (NPT), and even well abandonment. On top of that, this problem can cause unbalanced formation pressure and induce borehole wall collapse, which can trigger other follow-up problems, such as casing failure and stuck pipe (Carson et al., 1982; Nugroho et al., 2017; Saleh et al., 2020).

In addition to the drilling challenges related to fractures and lost circulation, the high temperature inherent in a geothermal system can also promote other challenges. Zhou et al. (2018) discussed the thermal shock and tensile stress in rocks due to the cooling effect. The temperature difference between the drilling fluid and the surrounding rocks can induce shear failure or tensile failure around the wellbore (Dusseault, 1993). Wang et al. (1996) proposed a solution to model the effects of temperature and fluid flow on pore pressure and stress. They observed a substantial compressive stress being induced near a borehole when hotter fluid is circulated in the borehole. This may trigger shear failure around the borehole and increase its instability. On the other hand, circulating a cooler mud, such as in geothermal drilling, may improve the stability of the wellbore by reducing the near wellbore tangential stress. However, it is also recognise that the risk of tensile failure increases. Hence it is often observed that the downgoing cooler mud circulated through the drill bit nozzle will promote tensile fracture near the bottom of the hole while the upgoing hotter mud will potential induces breakout near the nearest casing shoe.

Production

One system that plays an important role in geothermal is enhanced or engineered geothermal system (EGS). EGS is very suitable for dry rock, geothermal energy production generally from dry reservoirs with low permeability that can be achieved by circulating water in an engineering fracture network consisting of artificial fractures and pre-existing fractures. Then, one of the important technologies in the development of geothermal resources, especially with the one with low permeability is hydraulic fracturing to improve productivity. The ultimate goal is to enhance the permeability of the reservoir sufficiently high to achieve the economic limit. Li and Lior (2015) developed a simplified model to qualitatively examined the required energy for a typical EGS reservoir. They concluded that the required energy to create a fracture is propotional to the volume of the created fracture represented by a propotionality coefficient that increases with depth due to a larger in situ stress. As an alternative of hydraulic fracturing, which requires the fluid pressure to overcome the minimum principal in situ stress and the tensile strength of the rocks, the hydro-shearing technique will requires a less pressure to induce pre-existing fractures to slip by increasing the pore pressure. Gischig and Preisig (2015) argued as to which mechanisms, i.e. hydrofrac or hydro-shearing, occurs during injection depends on the in situ stress state and the relative orientation of the fractures. The permeability enhacement induces by hydrofrac will tend to be reversible if proppant is not placed to keep the fracture open. Another approach that has gain a lot of attention is identification of an enhance fracture productivity by a so called critically stressed fractures. The concept and modeling of hydroshearing is similar to the evaluation of productivity asessment of a potentially slip fractures due to in situ stress. These are existing fractures that have slipped or has a potential to slip because of the in situ stress acting on them. Hennings et al. (2012) presented a study supporting the argument that fractures that were critically stressed are a good indicator for well productivity. Nygren and Ghassemi (2005) studied the impact of cold water injection on the productivity of critically stressed fractures of a geothermal field. They investigated the impact of injection on the shear initiation of a fractures networks and found that a large temperature difference can induce thermoelastic stress and cause the fracture to slip even below the critical injection rates. Such an approach of identifying the zones with critically stressed fractures can be implemented for predicting zones of enhanced permeability.

Brief methodology to examine fracture productivity by investigating their slip potential is presented in the following section followed by a case example using a hypothetical dataset.

Fractures and in situ stress

The presence of fractures plays an important role in determining the production in geothermal resources. Therefore, the identification of their presence becomes important. One of the best methods to recognize fractures is downhole image log; that allows geoscientists to study and analyze the fractures. The image log can provide a high-resolution image of the near-wellbore fracture from which fracture orientation, i.e. their dip azimuth and dip angle, can be obtained.

To assess fractures productivity, in addition to the fractures orientation, one needs to also understand and quantify the in situ stress. The following equation can be used to estimate the magnitude of in situ stress in isotropic rocks considering the temperature effect (Zhang, 2019):

$$\begin{aligned} \sigma_h &= \frac{\nu}{1-\nu}\left(\sigma_v - \alpha P_p\right) + \alpha P_p + \frac{E}{1-\nu^2}\left(\varepsilon_h + \nu\varepsilon_H\right) + \frac{E\alpha_T}{1-\nu}\Delta \mathrm{T} \\ \sigma_H &= \frac{\nu}{1-\nu}\left(\sigma_v - \alpha P_p\right) + \alpha P_p + \frac{E}{1-\nu^2}\left(\varepsilon_H + \nu\varepsilon_h\right) + \frac{E\alpha_T}{1-\nu}\Delta \mathrm{T} \end{aligned} \quad (1)$$

The equation requires the knowledge of the rock elastic properties such as Young's modulus (E) and Poisson's ratio (ν), the vertical stress (σ_v) as well as the thermal expansion coefficient (α_T). The in situ stress will have to be projected into the fracture plan to obtain the normal and shear stress component acting on the plane. The following relation can be used for the transformation:

$$W = \begin{bmatrix} \cos(90-\beta) & 0 & \sin(90-\beta) \\ 0 & 1 & 0 \\ -\sin(90-\beta) & 0 & \cos(90-\beta) \end{bmatrix} \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where α and β are the dip azimuth and dip angle of the fracture. The stress acting on the fracture plane σ_f can then be obtained from the in situ stress:

$$\sigma_f = W\sigma_0 W^T \quad (3)$$

in which

$$\sigma_0 = \begin{bmatrix} \sigma_h & 0 & 0 \\ & \sigma_H & 0 \\ & & \sigma_v \end{bmatrix} \quad (4)$$

Result and Discussion

One of the key analyses in geothermal field development is associated with the knowledge of whether or not the fractures set tend to open and, hence, contribute to the production. This kind of analysis requires knowledge of the fracture orientations as well as the in situ stress state. Such a piece of information can be obtained from image log data. The natural fractures appearance from the image log can be identified and their dip angle and azimuth can be inferred.

The underlying concept to evaluate the slip potential of fractures follows that of the Jaeger's plane of weakness. The fractures shear strength limit is characterised by their cohesion and frictional coefficient. In most cases, the cohesion (S_w) of the fractures can be assumed to be zero. Hence, their strength depends only on the frictional coefficient (μ_w). The in situ stress will have to be projected into the individual fracture plane to obtain the normal and shear stress components. If the stress acting on the fracture plane exceeds the shear strength, then the fracture is said to have a tendency to slip.

$$|\tau| = S_w + \mu_w\sigma_n \quad (5)$$

Figure 1 shows an example of a hypothetical fracture set indicating a dominant azimuth orientation of 15-120 degree NE azimuth with varying dip angles. The in situ stress is assumed to be psi. The pore pressure is assumed to be 5000 psi The frictional coefficient is assumed to be . From Figure 1, it is obvious that some of the fractures tend to slip and it is expected the fractures to contribute to production. Most of the fractures that have a dip angle higher than 70 degree tend to be more stable than fractures that have a dip angle less than 70 degree. Moreover, it is also obvious that fractures whose dip is around 70-120 degree NE tend to open compared to the other fractures set. Such an analysis is important for well targeting to ensure the wellbore would primarily intersect those fractures that have a higher tendency to slip.

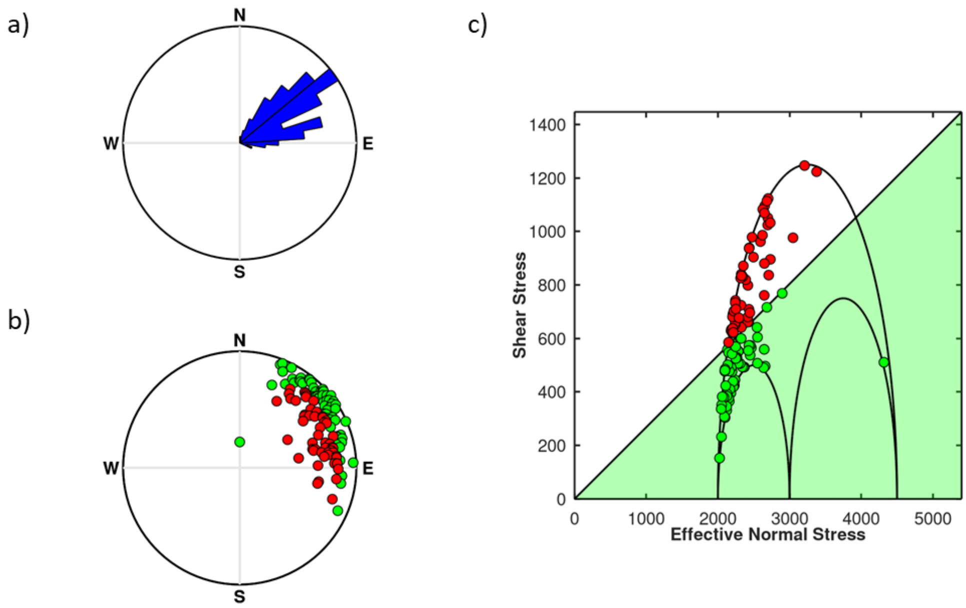

Figure 1. (a) Stereonet indicating the fracture set orientations. (b) Individual fractures orientation is shown as a point reflecting the dip azimuth and dip angle. The red coloured circles are fractures that have a higher tendency to slip and open and the green coloured circles are the stable fracture set. (c) The shear stress vs. effective normal stress plot indicating the unstable fractures (red circle) that lie above the Coulomb failure envelope.

A more detailed examination shown in Figure 2 revealed the distribution of the shear stress acting on the failure plane. The plot suggests that fractures with orientation of SE-NW with a dip angle between 30 to 70 degree will likely to be under stressed and has a higher potential to slip.

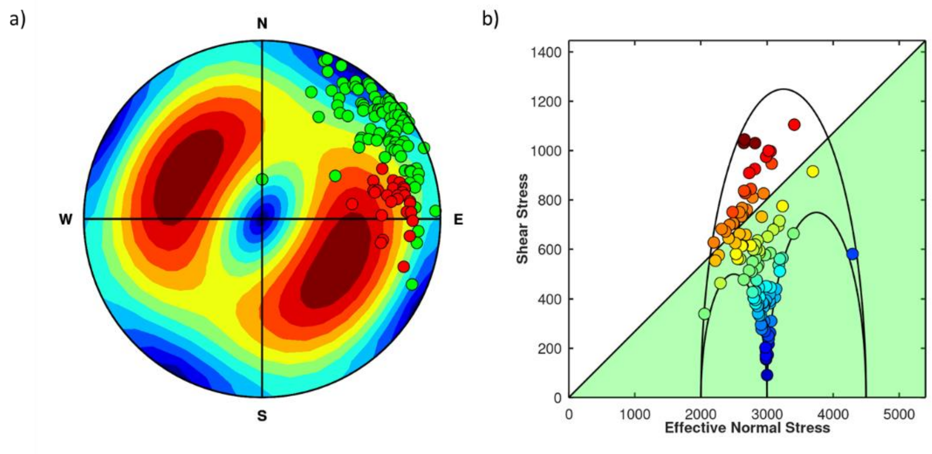

Figure 2. (a) The stereonet plot showing the shear stress overlaid with the potentially open (red circles) and closed (green circles) fractures. (b) The shear stress vs. effective normal stress plot color-coded by the magnitude of the shear stress acting on the fracture plane.

Conclusions

Productivity of a geothermal resources can be assess by studying the quality of the fractures. One approach that can be integrated in fractures evaluation is by examining their slip potential due to the in situ stress. The potential contribution of fractures to the production can be examined by assessing their tendency to open or close under shearing.It is understood that fractures opennes tendency will be associated with the high shear stress. The profile of the shear stress acting on the fracture plane, for all possible fracture azimuth and dip angle, may provide an insight on the preferable orientation of fractures that may contribute to productivity. The concept and modeling of hydroshearing is similar to the evaluation of productivity asessment of a potentially slip fractures due to in situ stress presented in this paper.

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