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Downhole Stress Release Effect of Grooving by Means of Ultra-high Pressure Water Jet in Deep Geothermal Drilling

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ABSTRACT

Deep geothermal resources in dry hot rocks with high formation stress, high rock strength, and uniaxial compressive strength above 200MPa leads to worn commercial drilling bits and low rate of penetration in the drilling process of deep geothermal reservoirs. At present, the costs of drilling and completion account for about 50%-70% of the total development cost, which seriously restricts the development process of deep geothermal resources and becomes a major problem at present stage. To solve these problems in deep geothermal drilling, a new principle to "free" the rock from high confining stress concentrations by means of ultra-high pressure water jet is proposed. The distribution of effective radial stress, release degree of downhole stress by grooving, and the effect of grooving characteristics on the release of downhole stress are studied by means of numerical simulation at a depth of 5,000 meters. With depth, in-situ stress increases and is concentrated in the area of action of the drilling bit especially in the peripheral bottom-hole area. After grooving, in the peripheral bottom-hole area, the radial effective stress is reduced from 94.2MPa to 49.6MPa, and the axial stress is reduced from 19.8MPa to 5.3MPa. The groove method releases the mean effective stress, and it also allows the stress concentration zone to be pushed away from the cutting face while significantly lowering the effective stress in the area of action of the drilling bit. According to the mechanical characteristics of rock materials, the rock strength can be reduced by lowering the effective stress to improve the rock-breaking efficiency.

1. Introduction

Deep geothermal energy is a key development gateway for geothermal energy proliferation in the world. Geothermal electricity production is also beneficial for rich and poor economies alike with growing and diversified needs. Deep geothermal resources are mainly found in dry hot rocks with high formation stress, high rock strength, and the uniaxial compressive strength is generally above 200MPa, which leads to worn commercial drilling bits and low rate of penetration in the drilling process of deep geothermal reservoirs (Figure 1) (Zhou and Jin, 2018). At present, the costs of drilling and completion account for about 50%-70% of the total development cost, which significantly restricts the development process of deep geothermal resources (Simone and Enel, 2012).

Figure 1 Wear and failure of the peripheral cutters in drilling bits

Some scholars have studied the bottom hole stress distribution and found that the bottom-hole rock can be divided into three regions according to the stress state, three direction stretch zone, two direction compression area and three direction compression zone, each having increasing difficulty (Zhang and Li, 2018). This partly explains why the cutters on the peripheral area of commercial drilling bits are often the most worn and the most broken (Zhu and Liu, 2016). For the above-mentioned challenging rock formations, some scholars have proposed more cutters that should be arranged on the outside of PDC bits to improve the service life of bits and drilling footage (Peng and Shen, 2006). Other scholars have invented hybrid bits (Omar and Agawani, 2017) and weight-on-bit (WOB) self-adjusting bits which are important pioneers in drilling technology that have been put into use in recent years (Jain and Ricks, 2017).

Based on the above research, to address above problems in deep geothermal drilling a new principle to “free” the rock from high confining stress concentrations by means of ultra-high pressure water jet is proposed. To further understand the release effect, the stress field at bottom-hole is calculated based on Biot's poroelasticity theory, and the influence of the well depth on the stress-release effect and the degree of release efficiency are studied.

2. Calculation Method for Stress Field Distribution at Bottom-hole

The stress state of the rock after grooving by means of ultra-high pressure water jets in deep geothermal wells cans solve the problems with drilling that are shown in Figure 1. The rock is subjected to the combined action of overburden stress σ_{v}, maximum horizontal crustal stress σ_{H}, minimum horizontal crustal stress σ_{h}, liquid column pressure p_{h} and formation pore pressure p_{p}, the stress state of the rock at bottom-hole are shown in Table 1. The rock mass is assumed to be a homogeneous and isotropic porous, permeable, and elastic medium, and the pores of the rock are completely saturated with fluid.

Table 1 Stress state of the rock at bottom-hole

Depth/m	Stress state /MPa			
	$\sigma_v > \sigma_H > \sigma_h$			P_p
	σ_v	σ_H	σ_h	
5000	120	110	100	52.50
5500	132	121	110	57.75
6000	144	132	120	63.00
6500	156	143	130	68.25
7000	168	154	140	73.50

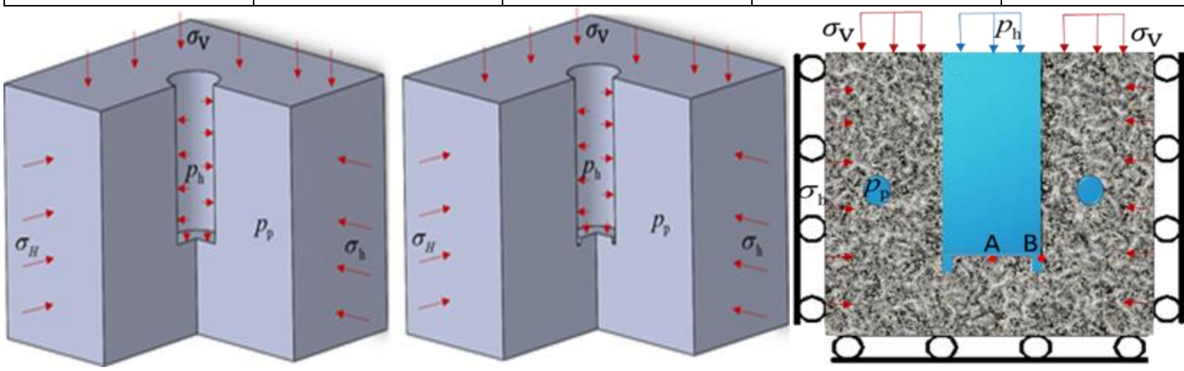

Figure 2: Petrophysical model of the rock at bottom-hole

The borehole model dimensions include a borehole size of 240 mm, well depth of 5000-7000 m, a regular cylindrical borehole wall, and the borehole bottom is a regular slotted plane (Figure 2). In order to reduce the influence of model size on the calculation results, the model size is set as 10 times the borehole radius. The model parameters are shown in Table 2:

Table 2 Numerical simulation parameters

Items	Symbol	Value	Unit
Young's modulus	E	60	GPa
Poisson's ratio	μ	0.25	/
Porosity	p	0.15	/
The density of rock sample	ρ_m	2500	kg/m^3
Overburden stress gradient	$\Delta\sigma_v$	0.024	MPa/m
Width of the groove	W	0.02	m
Depth of groove	D	0.04	m
Pore pressure gradient	ΔP_p	0.0105	MPa/m
Liquid column pressure gradient	ΔP_h	0.0111	MPa/m
Viscosity	v	0.001	Pa.s

3. Results and Discussions

3.1 Stress field distribution around the bottom-hole

In order to study the effect of grooving on the effective stress distribution of rock, the effective stress distribution of the bottom hole is analyzed when the depth of the well is 5000 m. Based on the numerical simulation of the stress field, the mean effective stress of the rock in different conditions is studied. As we can see from Figure 3, the effective stress of the rock near the axis of bottom-hole area is lower than peripheral bottom-hole area. The reason for this phenomenon is that the stress concentration is caused by the shape of the peripheral bottom-hole area before grooving. The presence of the groove results in a release of stress on the borehole bottom. It also allows the stress concentration zone to be pushed away from the cutting face while significantly lowering the value of stress in the area of action of the drilling bit.

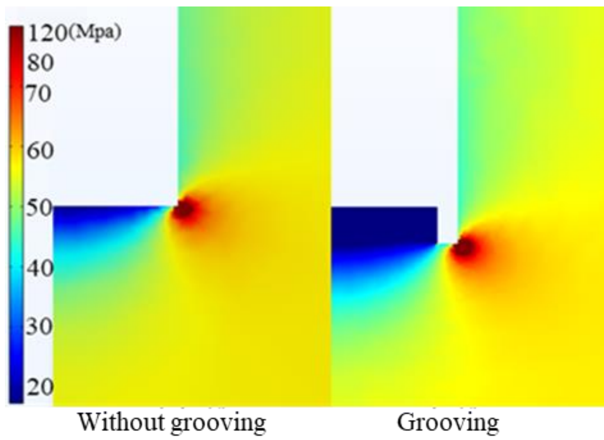

Figure 3 Mean effective stress contour at bottom-hole

Figure 4 shows the distribution of effective stress along the radial direction for a hole with and without grooving. The maximum value occurs at the junction of the bottom hole and wall, and decreases away from the borehole wall and finally stabilized at the in-situ stress (57 MPa). Because the groove cuts off the junction of the bottom hole and wall, the stress concentration phenomenon at the peripheral bottom-hole area disappears.

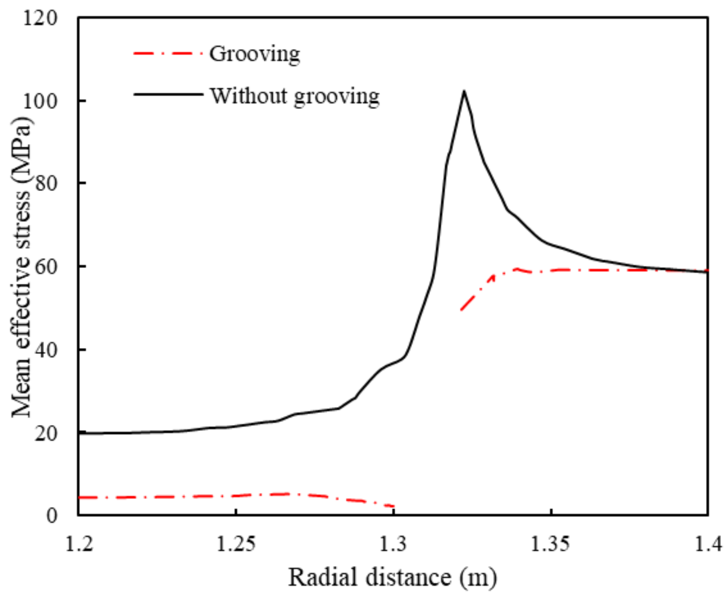

Figure 4 Distribution characteristics of effective stress at bottom-hole

3.2 Release mechanism of grooving

Before grooving by means of high pressure water jet, the stress condition of the rock at bottom hole is as shown in Figure.5(a), the rock is subjected to the combined action of maximum horizontal crustal stress, minimum horizontal crustal stress, liquid column pressure, and pore pressure. After the grooving, the groove cuts off the junction of the bottom hole and wall, the stress condition of the rock at well bottom is as shown in Figure.5(b), the rock is subjected to the combined action of liquid column pressure and pore pressure. In the process of grooving, the rock at well bottom will be subjected to a compress and unloading process. Since the horizontal crustal stress is greater than the liquid column pressure during the drilling, to a certain extent, the grooves releases the mean effective stress of rock at the bottom hole, and the process of compress and unloading of the rock during grooving can also promote the propagation of internal cracks in the rock. Further reduce the strength of the rock.

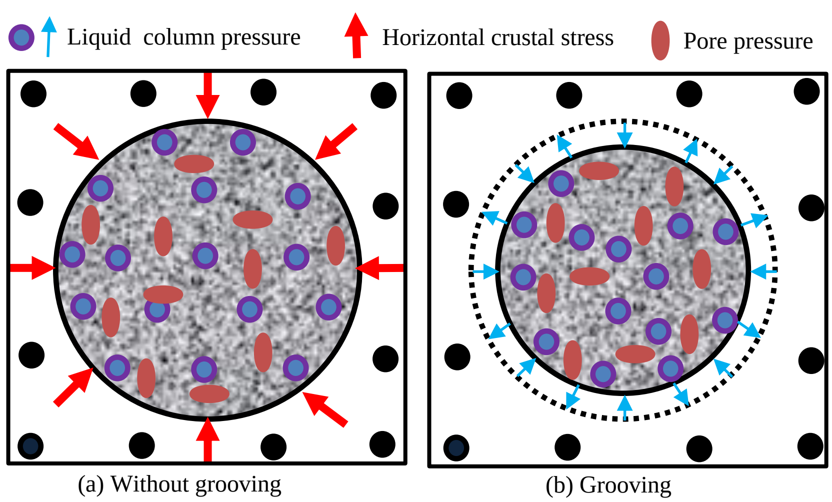

Figure 5 Release mechanism of grooving

3.3 Effective stress release efficiency of rock at different well depths

A total of 2 monitoring points are set up at the axis of bottom-hole area (Point A) and the peripheral bottom-hole area (Point B), to analyze the release efficiency of grooving on the effective stress at the bottom-hole in different well depths (5000 m-7000 m).

As shown in Figure 6, with the increase of well depth, the mean effective stress at the axis of bottom-hole area increases linearly. The reason for this phenomenon is that with the increase of well depth the in-situ stress and the drilling fluid pressure at the bottom-hole increases, which causes the mean effective stress at the bottom-hole to increase continuously. After grooving, the change of the mean effective stress is smaller than without grooving. With the increase of well depth, the release efficiency of groove on the effective stress at the axis of bottom-hole area increases gradually, and the rate of release efficiency increase tends to slow down. The modeled release efficiency at the well depth of 7000 m is 76.5%.

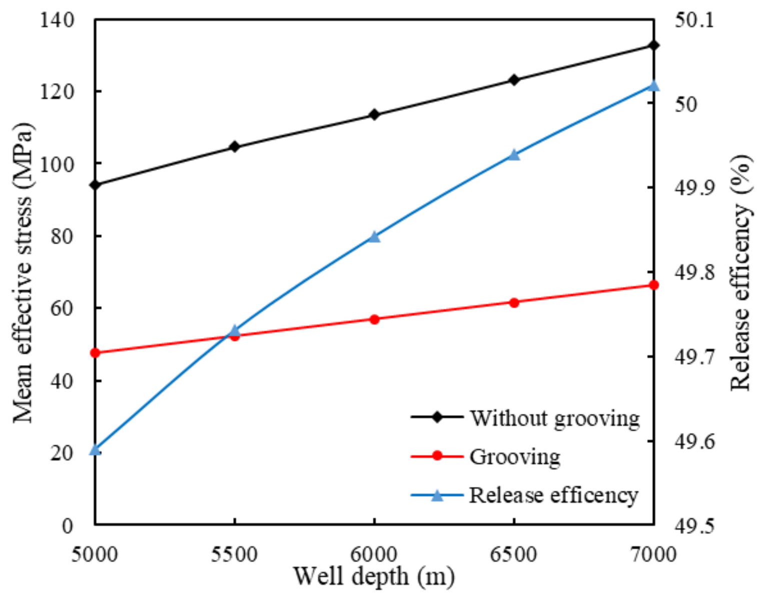

Figure 6 Mean effective stress release efficiency in the axial bottom-hole area（Point A)

Figure 7 shows the mean effective stress release efficiency in the peripheral bottom-hole area. With the increase of the well depth, the phenomenon of stress concentration is more significant in the peripheral bottom-hole area, and the value of mean effective stress increases linearly. According to the mechanical characteristics of rock material under the condition of confining pressure, the rock strength can be increased, partly explaining why the cutters on the peripheral area of commercial drilling bits are often the most worn and the most broken. After grooving the mean effective stress is significantly reduced, and with the increase of well depth the mean effective stress shows a trend of increase, but the increase is not significant compared with the condition of without grooving. Within the scope of study, the presence of this groove releases the mean effective stress in the peripheral bottom-hole area significantly, and with the increase of well depth the release efficiency of mean effective stress increases slightly, and is basically stable at about 50%.

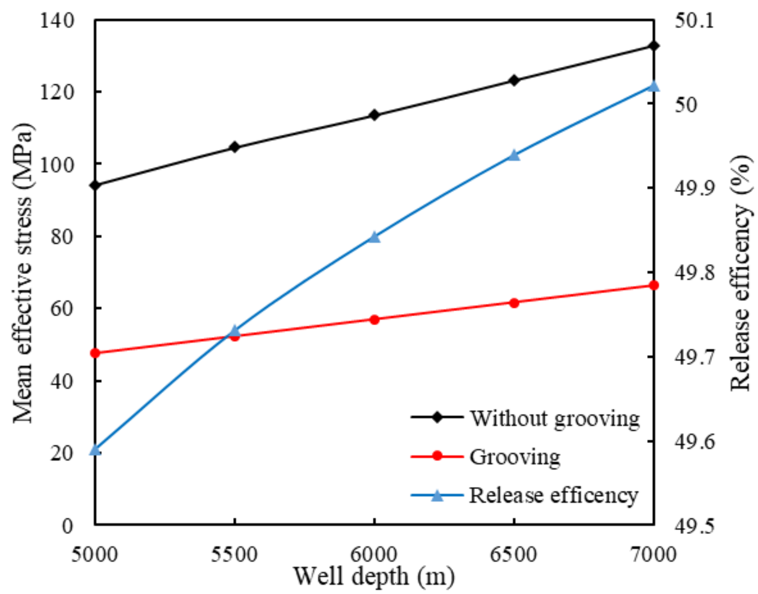

Figure 7 Mean effective stress release efficiency in the peripheral bottom-hole area (Point B)

4. Conclusion

1、With the increase of the well depth, in-situ stress increase and are concentrated in the area of action of the drilling bit especially in the peripheral bottom-hole area. This phenomenon also increases the yield strength of the rock which causes significant wear on drill bits.

2、The presence of this groove releases the stress, it also allows the stress concentration zone to be pushed away from the cutting face, while significantly lowering the value of stress in the area of action of the drilling bit.

3、With the increase of well depth, the release efficiency of groove on the effective stress increases gradually, and the release efficiency of groove on the effective stress in the axis of bottom-hole area is greater than the peripheral bottom-hole area by 23%.

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