Rheological deformation and failure laws of boreholes in granite under thermo-mechanical coupling and its application in deep hole drilling of hot dry rock for geothermal energy exploitation

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Abstract. The key technology issue in deep hole drilling of hot dry rock (HDR) for geothermal energy exploitation is the stability of the surrounding rock. The temperature and in situ stress of the borehole play a significant role in its deformation and instability under high-pressure and high-temperature conditions. Based on the occurrence conditions of the granite reservoir of the Yangbajing geothermal field in Tibet, a research was conducted by means of experimental study, numerical simulation, and theoretical analysis, from which the following conclusions were drawn. (1) The deformation and failure laws of borehole are based on the physical experiment on granite specimen under high-temperature and high-pressure conditions. (2) The Weibull distribution of the thermal expansion coefficient is used for establishing rock heterogeneity, and the COMSOL software is used to reproduce the temperature and stress distribution of the borehole during physical experiment, thus demonstrating the distribution of the temperature field, stress field, and displacement field under thermo-mechanical coupling (TMC) condition. (3) Based on the complete analysis of the temperature field and stress field, combined with the conclusions of the deformation and failure of granite specimen under high-temperature and high-pressure conditions, the failure laws of borehole under the TMC condition were analyzed, as well as the critical conditions of borehole instability during deep hole drilling of HDR. (4) With the critical conditions of borehole instability during deep hole drilling of HDR, which the relation between the in situ stress σ and temperature T is σ = 241.9 – 0.3998·T. These conclusions have practical guiding significance to the stability control of the surrounding rocks of borehole in relation to projects such as geothermal energy exploitation from HDR, deep oil and gas resource extraction, and deep hole drilling in mainland China.

Keywords: hot dry rock; deep drilling construction; deformation and failure of borehole; instability critical conditions
1 Introduction

Deep hole drilling of hot dry rock (HDR) is not the only problem that needs to be solved but also the problem with humans exploring the earth to exploit geothermal energy\textsuperscript{[1,2]}. The key technology issue of deep hole drilling of HDR is the stability of the borehole\textsuperscript{[3,4]}. There is a significant difference between deep hole drilling of HDR for geothermal energy exploitation and deep hole drilling for oil and gas extraction\textsuperscript{[5]}. Because igneous rock mainly contains geothermal energy, deep hole drilling of granite is carried out under high-temperature and high-pressure conditions. Therefore, under the influence of temperature and in situ stress, some serious phenomena occur during the drilling process, such as a strong rheological property\textsuperscript{[6]}, drilling neck, deformation instability, and collapse\textsuperscript{[7]}. These can lead to borehole instability, which rapidly increases the drilling costs. Research revealed that drilling and other related subsurface activities for enhanced geothermal system (EGS) account for a significant portion (above 50\%) of the total cost of EGS development\textsuperscript{[8,9]}. Hence, the study of borehole stability and its destruction law under high-temperature and high-pressure conditions is key to solving the abovementioned problems. Furthermore, with the prevalence of oil resource exploitation and the development of drilling technology, oil and gas deep hole drilling engineering has been developed. However, this development has created increasing problems, such as the deformation and stability of the wellbore under high-temperature and high-pressure conditions. More than 10 countries, including Russia, the United States, Germany, and China, have made huge investments in continental scientific deep drilling, such as Russia’s 12262-m Kola superdeep borehole, CT-3\textsuperscript{[10]}, Germany’s 9101-m KTB-HB superdeep borehole\textsuperscript{[11]}, and China’s east sea science drilling\textsuperscript{[12]}. Study on the temperature and in situ stress in the deformation and destruction laws of drilling of the surrounding rock has an important scientific and engineering significance to solving problems in deep hole drilling and of drilling stability under high-temperature and high-pressure conditions. The results of the study will facilitate in the exploration of geothermal energy and other resources in the deep earth.

To solve this problem, numerous researchers have studied the physical and mechanical properties of rock under high-temperature and high-pressure conditions. It has been found that these properties change with temperature, for example, elastic modulus\textsuperscript{[13,14]} and compressive strength\textsuperscript{[15,16]} decrease with the increase in temperature, but permeability\textsuperscript{[17]} and the rheological properties\textsuperscript{[18,19]} increase. However, research on the stability control mechanism of borehole under high-temperature and high-pressure conditions has more guiding significance to drilling engineering\textsuperscript{[20,21]}. To study the borehole stability, physical experiment and numerical simulation can be employed. The thick-walled hollow cylinder (TWHC) test is a common way to study the failure laws of borehole under different stress and temperature conditions. The achievements of scholars are as presented follows: In a large number of vertical oil wells, the orientation of consistent breakouts was consistent with the direction of the regional minimum horizontal principal stress\textsuperscript{[22]}. Borehole breakouts form mainly through radial penetration into the rock mass without any circumferential extension\textsuperscript{[23]}. The effect of stress paths and the borehole size and grain bonding strength on the borehole failure in poorly cemented sandy formations were investigated via the TWHC test\textsuperscript{[24,25]}. The results revealed that in these weak formations, the confining pressure has a more significant effect on borehole instability than the content of the cement agent. A hollow cylinder (diameter 30 m and height 60 mm with a 5-mm borehole) specimen was utilized to study the effect of effective stress around a borehole on the formation instabilities and borehole stability\textsuperscript{[26]}. The result revealed that strain softening occurred as a result of the decrease in pore pressure. The effects of the confining stress, water injection flow rate, and temperature on the breakdown pressure and fracture permeability by granite hydraulic fracturing were investigated\textsuperscript{[27]}. However, the physical experiment can only reflect the deformation and damage to the surface of the specimen, not the interior of the specimen. Thus, it is important to use numerical simulation to further study the instability of the surrounding rock. The achievements of scholars are presented as follows: The
influences of the confining pressure, borehole diameter, and bedding orientation on the mechanical response of the hollow samples were investigated using numerical simulation. The result revealed that both peak stress and elastic modulus decreased with the increase in borehole diameter[28]. The effect of in situ stress ratio and discontinuity orientation on borehole stability in highly fractured rocks was investigated using the discrete element method[29,30]. The result revealed that when the in situ stress ratio increased, the rock blocks of the borehole wall tended to move toward the center of the borehole. Consequently, the yielded zone around the borehole increases and found high mud flow rates and high pore pressure increased the instability around borehole. The thermal cracking behaviors of rocks from boreholes subjected to heating were studied using a weakly coupled thermo-mechanical model[31]. The result revealed that crack initiation time and locations are strongly dependent on the geometrical conditions of the boreholes. Moreover, borehole stability and borehole breakout were studied using a thermo-poroelastic model[32]. The result revealed that the Mohr–Coulomb criterion offered the highest breakout depth, whereas the Drucker–Prager yield criterion provided the lowest estimation of the breakout depth. Shear failures occur either along or across the bedding planes, depending on the relative orientation between the wellbore trajectories and the bedding planes by a borehole stability model with anisotropic rock strengths[33]. Borehole stability in chemically active anisotropic formations of thermal, hydraulic, mechanical, and chemical loadings was investigated and what was used to assess time-dependent wellbore stability during and after drilling[34]. The dynamic shear and tensile failure condition in the near-wellbore zone were investigated using the thermo-poroelastic model. The results revealed that the pore pressure in the near-wellbore zone was extremely sensitive to the wellbore fluid temperature, which plays a significant role in the stress distribution of the near-wellbore zone and in its stability state[35]. The porothermoelastic effects on wellbore stability in transversely isotropic medium subjected to local thermal non-equilibrium were studied[35]. The numerical results revealed that heating tended to decrease wellbore stability (including shear failure and spalling), whereas cooling strengthened the shear failure of the wellbore.

In deep hole drilling under high-temperature and high-pressure conditions, the physical, mechanical, and rheological properties, as well as the deformation law, stability and reinforcement technique, and rheological deformation, of drilling are different from the influence of the casing pipe at normal temperatures[36-39]. Therefore, using a combination of experimental research and numerical simulation, with the Yangbajing geothermal field in Tibet being used as an engineering background, extensive research on the stability of the wellbore during deep hole drilling of HDR and analysis of the effect of temperature and in situ pressure on the deformation and failure laws of drilling need to be conducted.

2 Experimental study on the deformation and destruction laws of granite drilling under high-temperature and high-pressure conditions

Based on the geological conditions of the granite reservoir of the Yangbajing geothermal field in Tibet, the fabric, ingredient, and temperature and pressure conditions of granite can be obtained through consulting literatures and site investigations. The granite obtained from the Gonghe Basin in Qinghai Province was selected as the experimental sample to study the deformation and destruction laws of deep hole drilling of HDR using experimental simulation.

2.1 The Introduction of the Experiment

2.1.1 The preparation of granite samples with a drill hole

The granite obtained from Longcaigou in the Gonghe Basin located in Qinghai Province, China, was used as the experimental sample. The current scholars generally use small-sized specimens to study the
rock creep\cite{9,20,21}. However, there were certain limitations. So, in this experiment, large-sized granite specimens were used.

Through a nondestructive process, three specimens from the same batch were prepared as cylinders with a height/diameter ratio of 2:1 (diameter, 200 mm; height 400 mm), and then a hole with a diameter of 41 mm was created into the axis of each cylinder specimen, as presented in Figure 1.

![Figure 1. The granite sample with a drill hole](image)

2.1.2 *High-temperature and high-pressure test equipment*

The 20 MN servo-controlled rock triaxial testing machine with high temperature and high pressure, which was independently developed by Project 211 of the key construction projects in China University of Mining and Technology, was used (Figure 2). The testing machine is mainly composed of host loading system, high-temperature triaxial compression chamber, temperature control system, auxiliary charging system, and test system. Figure 3 presents the high-temperature triaxial compression chamber. The deformation of the rock sample during the experiment was measured using a grating ruler, with an accuracy of 5/1000 mm, and the heating temperature was recorded using thermocouple temperature sensors. The relative data of temperature, loading, deformation, permeability, and sound emission of the rock sample during the experiment were automatically recorded using computer. The main parameters of the test machine are presented in the references\cite{40}. 

![Figure 2. The high-temperature triaxial compression chamber](image)
Figure 2. 20-MN servo-controlled rock triaxial testing machine with high temperature and high pressure

Figure 3. High-temperature triaxial compression chamber

2.1.3 The test instrument for observing the borehole deformation

A high-temperature displacement sensor combined with TS-3800 static resistance strain gauge was used to measure the borehole deformation from normal temperature to 240 °C. If the temperature is higher than 240 °C, due to the effect of the sensor on the temperature, the high-temperature displacement sensor is not stable. The borehole deformation observation instrument based on optical principle, which was developed by our group, was used to observe the borehole deformation, as presented in Figure 4. This instrument eliminates the influence of high temperature and has high magnification and accuracy. Moreover, it was proven to be effective.

Figure 4. Borehole deformation observation instrument based on optical principle

2.1.4 Experimental steps

First, measure the diameter and height of the samples. Second, strictly comply with the operating rules to for installing samples and then apply confining pressure and axial pressure that are equal to the stress condition of the model stratum. Next, heat the sample at 3 °C–5 °C/h. When the set temperatures are reached (200 °C, 300 °C …600 °C), maintain the loading stress and temperature for 48 h. Finally, certain
data, such as rock mass axial displacement, lateral displacement, and loading stress and temperature, are automatically recorded by the testing machine. Meanwhile, use the borehole deformation observation instrument to continuously observe the borehole deformation and then record particularly.

2.2 Experimental Results and Analysis

Considering the exploitation project of HDR geothermal energy is involved in deep buried and high-temperature rock mass, therefore, the temperature and burial depth have obvious influence on the deformation and failure of borehole in the process of deep hole drilling. The maximum loading stress used in the experiment was 150 MPa (considering that the volume-weight of the rock mass is 2.5g/cm³, that is to say, the self-weight stress at a depth of 1000 m is 25 MPa), which amounts to a stratum stress at a depth of 6000 m, and the maximum temperature was 600 °C. To truly reflect the temperature and stress fields and the damage scope of the wellbore under thermo-mechanical coupling (TMC) condition, the method based on experimental simulation and supplemented by numerical simulation was adopted. Numerical simulation was used for reproducing the data that cannot be measured during the test to study the temperature distribution, stress distribution, and damage range of the borehole. Then, the failure mechanism of the borehole under high-temperature and high-pressure conditions was explored, the deformation law of the borehole was determined, and the critical conditions of surrounding rock instability during deep hole drilling of HDR were identified.

Figure 5 and Table 1 present the results of the relative experiment on specimen 10#. Due to the high-temperature, displacement sensor was used for specimen 10# to measure the displacement of the borehole wall, and the confining pressure in the testing machine is loaded by solid NaCl. Therefore, the measured displacement of the lateral loading head includes the lateral deformation of the specimen and the deformation of NaCl. Thus, only the axial deformation and failure of the specimen under each temperature and in situ stress were analyzed. The experimental data shows that with the alternant increasingly of temperature and in situ stress, the axial deformation of granite specimens gradually increases; When the temperature increases, the axial deformation of the specimen exhibits the tendency toward elongation, and the deformation is a negative value. When the in situ stress increases, the axial deformation of the specimen tends to compress, and the deformation is a positive value. When the temperature reaches 500 °C and the in situ stress reaches 125 MPa (which amounts to 5000-m burial depth), the borehole is considered to be in the critical condition of instability. At this point, any change in temperature and in situ stress leads to the destruction of the borehole.
Figure 5. Relationship of temperature, stress, and axial deformation with time for 10# specimen

Table 1. Axial deformation and failure characteristics of 10# specimen

| Time/h  | Temp /°C | In situ stress /MPa | Axial deformation/mm | Note  |
|---------|----------|---------------------|----------------------|-------|
| 0–13.9  | 20–100   | 12.5                | -0.535               | 500   |
| 13.9–44.2| 100      | 12.5                | -0.52                | 500   |
| 44.2–58.7| 100–200  | 12.5                | -1.59                | 500   |
| 58.7–69.9| 200      | 12.5                | -1.38                | 500   |
| 70–119.8| 200      | 25                  | -0.455               | 1000  |
| 119.8–132.2| 200–300   | 25                  | -1.24                | 1000  |
| 132.2–181.1| 300      | 75                  | -0.44                | 3000  |
| 181.1–194.7| 300–400  | 75                  | -0.92                | 3000  |
| 194.7–244.1| 400      | 75                  | -1.12                | 3000  |
| 244.1–290.9| 400      | 100                 | -0.66                | 4000  |
| 290.9–336.8| 400      | 125                 | 0.2                  | 5000  |
| 336.8–350.1| 400–500  | 125                 | -0.935               | 5000  |
| 350.3–401.6| 500      | 125                 | -0.815               | 5000  |
| 401.6–404 | 500–150  | Abnormal            |                      |       |

Figure 6 presents the relationship between specimen axial deformation and the borehole wall deformation with time for specimen 11# under different temperatures and in situ stresses. The borehole deformation and axial deformation of specimen 11# are presented in Table 2. This experiment lasts 321 h. From Figure 6 and Table 2, it can be seen that the axial deformation of the granite body under the temperature of 400 °C and in situ stress of 100 MPa exhibits steady-state creep characteristics. When the temperature increases, the axial deformation decreases due to expansion. Moreover, the axial deformation increases when stress increases. When the temperature increases from 400 °C to 500 °C and the stress increases from 100 to 125 MPa, the axial deformation significantly increases. Under a constant temperature of 500 °C and constant stress of 125 MPa, the axial constant velocity creep of granite develops into accelerated creep, indicating that the granite sample with a drill hole enters the critical condition of failure or instability under the temperature of 500 °C and stress of 125 MPa. As can be seen from Figure 6, when the temperature is below 400 °C and the in situ stress is less than 100 MPa, the radial deformation of the borehole exhibits steady-state creep characteristic. When the temperature reaches 500 °C and the in situ stress reaches 125 MPa, the borehole deformation significantly increases. The borehole experiences steady-state creep – accelerated creep – steady-state creep – accelerated creep – damage within nearly 60 h. Then, this experiment is terminated due to severe borehole collapse.
Figure 6. Relationship of temperature, stress, axial deformation, and borehole wall deformation with time for 11# specimen

Table 2. Experimental data of temperature, stress, axial deformation, and borehole wall deformation of 11# specimen.

| Time/h | Temp /°C | In situ stress /MPa | Deformation/mm | Note       |
|--------|----------|---------------------|----------------|------------|
|        |          |                     | Borehole wall | Axial      |            |
| 0–19.23| 20–150   | 12.5                | 0.404         | −1.645     | Heating    |
| 19.23–23.3 | 150–200 | 25                  | 0.505         | −1.9       | Heating    |
| 23.4–74.5 | 200    | 25                  | 1.198         | −1.055     | Rheology   |
| 74.5–122.9 | 200    | 50                  | 1.325         | −0.545     | Rheology   |
| 122.9–129.3 | 200–250 | 50                  | 1.172         | −1.215     | Heating    |
| 129.3–177.5 | 250   | 50                  | 1.418         | −1.12      | Rheology   |
| 177.5–182.4 | 250–300 | 50                  | 1.510         | −2.025     | Heating    |
| 182.4–183.0 | 300    | 50                  | 1.751         | −1.63      | Rheology   |
| 183.0–231.1 | 300    | 75                  | 2.131         | −0.98      | Rheology   |
| 231.1–247 | 300–400 | 100                 | 2.361         | −0.57      | Heating    |
| 247–277.5 | 400    | 100                 | 2.377         | −0.605     | Rheology   |
| 277.5–279.2 | 400–450 | 100                 | 2.452         | −0.285     | Heating    |
| 279.2–284.8 | 450–500 | 125                 | 3.090         | −0.04      | Heating    |
| 284.8–321.3 | 500    | 125                 | 4.442         | 0.125      | Rheology   |

The experimental scheme of stress – temperature – time, which is different from specimen 11#, is adopted in specimen 12#, focusing on the deformation characteristics of drilling and the whole rock mass under a temperature of 500 °C, as presented in Figure 7. Figure 7 shows that specimen 12# experiences steady-state creep under a temperature of 500 °C and in situ stress of 125 MPa. At the later stages under the temperature of 500 °C and in situ stress of 150 MPa, some accelerated creep characteristics are exhibited. However, as the temperature increases from 500 °C to 600 °C at the stress of 150 MPa, the weakening and softening effects of the rock mass have remarkably improved, with marked accelerated
creep characteristics. Moreover, the same patterns have shown the change in borehole diameter and axial deformation of the rock mass.

![Figure 7. Relationship of temperature, stress, axial deformation, and borehole wall deformation with time for 12# specimen](image)

Table 3. Experimental data of temperature, stress, axial deformation, and borehole wall deformation of 12# specimen.

| Time /h  | Temp /℃ | In situ stress /MPa | Deformation/mm | Note   |
|----------|---------|---------------------|----------------|--------|
|          |         |                     | Borehole  | Axial     |        |
| 0–21.5   | 20–350  | 12.5                | 1.822     | −1.51    | Heating|
| 21.5–28.9| 350–500 | 25                  | 1.824     | −3.14    | Heating|
| 28.9–29.9| 500     | 25                  | 1.822     | −0.865   | Rheology|
| 30–78.1  | 500     | 125                 | 2.766     | −0.26    | Rheology|
| 78.1–126.1| 500   | 150                 | 3.511     | −0.085   | Rheology|
| 126.1–140| 500     | 150                 | 3.301     | Abnormal | Rheology|

By analyzing the strain curve and deformation of the borehole wall of the three specimens under different loading conditions, it is found that when the in situ stress is the same, as the temperature increases, the specimen expands, and the axial deformation negatively increases. When the temperature is the same, as the in situ stress increases, the axial deformation decreases. When the temperature is below 400 °C and the in situ stress is less than 100 MPa, the axial deformation exhibits obvious stable creep characteristics. When the temperature increases above 500 °C and the in situ stress increases above 150 MPa, rapid creep occurs. With the increase in temperature and burial depth stress, the deformation of the inner wall of the borehole increases. In the stable creep stage, the deformation of the inner wall of the borehole slowly increases. In the rapid creep stage, the deformation of the inner wall of the borehole rapidly increases. In summary, it can be concluded that as the depth increases, the drilling surrounding rock enters several stages of stable creep, rapid creep, and destruction. Moreover, the critical depth of the drilling surrounding rock instability is about 5000 m.

3 Distribution Laws of Temperature and Stress at the Deformation and Failure of the Drilling Surrounding Rock
To reproduce the data that could not be measured in the experiment, and to deeply study the deformation and failure laws of the boreholes in the granite, using the COMSOL Multiphysics 5.2 and MATLAB software, a model based on heterogeneous granite specimens is established. The effects of temperature and in situ stress distribution of the borehole surrounding rock on the damage of the borehole surrounding rock under the TMC condition are investigated. Through experimental research, the relationship between the damage radius $R$ of the borehole surrounding rock and the loading stress $\sigma$ and loading temperature $T$ in the granite specimen under high temperature and high pressure can be determined, and the control mechanism of the borehole stability under the temperature and in situ stress can be revealed. Then, the critical conditions of borehole instability in deep hole drilling of HDR are derived.

3.1 The Physical Model

A numerical calculation model, with a size of $\Phi 200 \times 400$ mm, that is completely consistent with the granite specimen used in the experiment was established, and a drill hole, with a diameter of $\Phi 41$ mm, was created (see Figure 3). Moreover, the external loading conditions and constraints were completely consistent with the above physical test conditions. Using the probe provided by COMSOL Multiphysics 5.2, the corresponding monitoring points were set in the numerical calculation model. The coordinates were A (20.5,200), B (60.25,200), and C (100,200), which represent the inner wall of the borehole, the middle wall of the borehole surrounding rock, and the outer wall of the borehole surrounding rock, respectively. The temperature changes, stress changes, and displacement changes at monitoring points were observed and recorded.

3.2 Heterogeneous Construction of the Drilling Surrounding Rock

Brittle rocks, such as granite, are composed of various mineral crystal grains, and there are tiny primary cracks and pores over the granite. Crystal grains, primary pores, and cracks constituting granite exhibit random distribution. This is the origin of granite heterogeneity. Considering the need for calculation accuracy, considering the heterogeneity of related mechanical parameters in numerical calculation is more in line with the actual situation. Thermal expansion has an influence on thermal deformation and thermal stress and decide on the stability and safety of engineering. Therefore, it is important to determine a suitable thermal expansion coefficient of granite for the numerical calculation.

Studies show that the distribution characteristics of rock heterogeneity can be described by the Weibull function. In this numerical experiment, considering that the heterogeneous of coefficient-$\beta$ of thermal expansion of granite under high temperature has an influence on thermo-elasticity deformation of borehole.
The arbitrary point \( P (x, y) \) in the computational domain corresponds to the thermal expansion coefficient \( \beta (x, y) \). The probability density function of its distribution is presented in formula (1)[41,42]:

\[
f(\beta, \bar{\beta}, m) = \frac{m}{\bar{\beta}} \cdot \left( \frac{\beta}{\bar{\beta}} \right) \cdot \exp \left[ - \left( \frac{\beta}{\bar{\beta}} \right)^m \right]
\]

Here, \( \beta \) denotes the coefficient of the thermal expansion of rock; \( m \) denotes the randomly distributed parameter; \( \bar{\beta} \) denotes the average value of the thermal expansion coefficient of the rock when the heterogeneity parameter is \( m \); and \( E(\beta) \) denotes the expected value following the Weibull distribution.

![Distribution Map](image)

**Figure 9.** The distribution map of the thermal expansion coefficient under different \( m \)

Because COMSOL Multiphysics 5.2 has no built-in Weibull distribution function, MATLAB is used. First, the calculation area of the unit area is meshed using the MATLAB software. Next, a random number matrix that follows the Weibull distribution and has a thermal expansion coefficient of \( \beta \) and a homogeneity of \( m \) is generated. Then, the file is exported as a text file. Finally, the saved text file is imported into the COMSOL Multiphysics 5.2 software to realize the Weibull distribution of the thermal expansion coefficient using the interpolation function of the software.

When the temperature of the rock reaches 400 \( ^\circ C \) and \( \varepsilon_{el} = 9.946593 \times 10^{-6}/^\circ C \), according to formula (1), we can assign to granite mesoscopic unit, specific distribution under different heterogeneity parameters \( m \) as presented in Figure 9.

3.3 Mathematical Model

The creep module and solid heat transfer module in the solid mechanics module in the COMSOL Multiphysics 5.2 software are selected. The constitutive equations used in the model are presented below. The constitutive equation of the solid mechanical interface is as follows:

\[
0 = \nabla \cdot S + F_v
\]

\[
S = S_{ad} + C : \varepsilon_{el}
\]
Here, $\varepsilon$ denotes the strain; $\varepsilon_0$ denotes the initial strain; $\varepsilon_{th}$ denotes the thermal strain; and $\varepsilon_{cr}$ denotes the creep strain.

In the numerical calculation, according to the relevant requirements in the above models and calculation conditions, the boundary conditions of stress and displacement are set in the calculation model.

The boundary load equation is:

$$S \cdot \vec{n} = F_A$$

(4)

The displacement boundary equation is:

$$W = u_{x=0} = 0$$

(5)

The heat transfer control equation for the heat transfer in solid interface is:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q + Q_{ted}$$

$$q = -k \nabla T$$

(6)

Using the heat flow boundary to heat the model in the numerical calculation is shown below:

$$-n \cdot q = Q_b$$

(7)

In addition, the heat source of the boundary of the model is set, and heat at a heating rate of 5 °C/h. A total of 100 h is selected as the calculation time. When the temperature is applied to the preset conditions, the temperature of the test piece remains constant.

In the calculation, the thermal expansion and temperature coupling in multi-physical fields need to be set. With regard to the thermal expansion term, the heat transfer term of the coupling interface is set to solid heat transfer, and the structural term is set to solid mechanics. The physical equation is:

$$\varepsilon_{th} = \alpha(T - T_{ref})$$

$$J_{th} = \left(1 + \alpha(T - T_{ref})\right)^3$$

(8)

Here, $\varepsilon_{th}$ denotes the thermal strain; $\alpha$ denotes the thermal expansion coefficient of the material; $T$ denotes the temperature; $T_{ref}$ denotes the strain reference temperature; and $J_{th}$ denotes the heat volume ratio. Furthermore, with regard to the temperature coupling item, the source item in the coupling interface is set to heat transfer in the solid interface, and the target side is set to solid mechanics.

The constitutive equation to obtain the steady-state creep rate of granite is as follows:

$$\frac{\partial \varepsilon_{cr}}{\partial t} = A_1 \left(\frac{\sigma_{eff}}{\sigma_{ref}}\right)^m + A_2 \left(\frac{\sigma}{\sigma_{ref}}\right)^n$$

$$\sigma = \frac{\sigma_{ref} + \sigma_2 + \sigma_3}{3}$$

$$\sigma_{eff} = \sigma_1 - \sigma_3$$

(9)

Here, $A_1$ and $A_2$ denote the coefficient of the creep rate; $Q$ denotes the creep activation energy; $R$ denotes the universal gas constant which is equal to 8.3143 kJ/mol; $T$ denotes the temperature (°F) of the experiment, 1 °C = 274.15 K; $\sigma_{eff}$ denotes the deviatoric stress (MPa); $\sigma_{ref}$ denotes the reference creep stress, $\sigma_{ref}$=1 MPa; and $m$ and $n$ denote the index of stress. These five parameters can be obtained by fitting the data from the creep experiment.
3.4 Selection of the Calculation Parameters

High temperature has an obvious influence on the mechanical parameters of granite. By analyzing the preliminary test data, it can be seen that the mechanical parameters, such as elastic modulus $E$ and Poisson’s ratio $\mu$, can be considered as functions with temperature variation. By dealing with the previous experimental data, using interpolation method to build elastic modulus and Poisson’s ratio to the temperature change into COMSOL Multiphysics5.2, which specific values refer to the literature (Zhao et al., 2015).

Granite is used as the surrounding rock material of the borehole. The specific settings of the mechanical parameters of granite at different burial depths and temperatures are presented in Table 4.

### Table 4 The relevant parameters of numerical calculation.

| Parameter                  | Value |
|----------------------------|-------|
| Heat transfer coefficient k/W/m·K | 2.9   |
| Specific heat capacity C/J/(kg·K) | 1080  |
| Density $\rho$/kg/m$^3$       | 2700  |
| Elasticity modulus $E$/GPa   | $E(T)$|
| Poisson’s ratio $\mu$        | $\mu(T)$|
| Heterogeneity $m$            | 3     |

3.5 Analyzing the Result of the Numerical Calculation

3.5.1 The temperature gradient distribution of the drilling surrounding rock during heating

The temperature gradient is the temperature increment per unit length in the direction of the isotherm normal and is a vector. In the temperature field, $\text{Grad } T$ indicates the degree to which the temperature changes from space. It can be expressed by Equation (10) as:

$$\text{Grad } T = \lim_{\Delta n \to 0} \frac{\partial T}{\partial n} \hat{n} = \frac{\partial T}{\partial n} \hat{n}$$  \hspace{1cm} (10)

Because rock materials, such as granite, are typical heterogeneous materials, the thermal conduction is not uniform during the heating process of the granite specimen. This results in a significant temperature gradient in the granite specimen. Moreover, it has been found that the greater the temperature gradient, the greater the thermal stress generated in the granite surrounding rock, and the greater the damage to the granite specimen.

Lidman and Bobrowsky\[44\] believe that the thermal damage of brittle materials is controlled by the tensile strength of the material. When the material is affected by temperature and the internal tensile stress exceeds the material’s ultimate tensile strength, the material fails. The tensile thermal stress $p$ of the brittle materials is presented as follows:

$$p = \frac{1}{2} \alpha E \left( \frac{dT}{dx} \right)$$  \hspace{1cm} (11)

Here, $\frac{dT}{dx}$ denotes the temperature gradient in the direction of the heat flow, $\frac{dT}{dx} = \frac{h}{\lambda} \Delta T$; $h$ denotes the convection heat transfer coefficient between the different media; $\lambda$ denotes the thermal conductivity of material; $\Delta T$ denotes the temperature difference; $x$ denotes the distance from the material surface; $\alpha$ denotes the thermal expansion coefficient of the material; and $E$ denotes the elastic modulus of the material. Tensile thermal stress $p$ is simplified to:

$$p = \frac{aEh\Delta T}{2\lambda}$$  \hspace{1cm} (12)
Analyzing formula (12), it was found that tensile thermal stress $\sigma$ produced in the granite specimen was associated with $a$, $E$, and $\Delta T$. In a routine test, accurately recording the temperature gradient or the distribution of $\Delta T$ during heating is difficult. Therefore, the powerful post-processing function of the COMSOL Multiphysics 5.2 software was used to draw the temperature gradient distribution of the granite specimens during heating, as presented in Figure 10.

Figure 10(a) presents the temperature gradient distribution of granite drilling surrounding rock for 1 h. It can be seen from the figure that, under the condition of stable heat source, the maximum value of the temperature gradient is 57.43 K/m after heating for 1 hour in granite specimen, which is on the outermost part of the granite specimen. Moreover, the minimum value of the temperature gradient is 11.47 K/m, which is on the inner wall of the borehole. Figure 10(b) presents the distribution of the temperature gradient of the borehole heated for 10 h. It can be seen from the figure that the maximum value of the temperature gradient is 57.86 K/m, which is on the outermost part of the granite specimen. Moreover, the minimum value of the temperature gradient is 12.19 K/m, which is also located in the inner wall of the borehole. The heat source continues to provide heat during heating. Thus, a relatively stable temperature gradient is generated along the borehole radial direction in the granite specimen. When the specimen reaches a constant temperature (the 100th h), as presented in Figure 10(d), the maximum value of the temperature gradient in the granite borehole is $1.004 \times 10^{-5}$ K/m, the minimum is $8.102 \times 10^{-7}$ K/m, and the magnitude of the temperature gradient decreases to $10^{-5}$ to $10^{-7}$ K/m, which can be negligible. In addition, the maximum and minimum values of the temperature gradient exhibit a more random distribution in the granite specimen at this time, which differs from the tendency towards the heating process.

![Figure 10. The distribution figure of the temperature gradient at different heating times](image)
In summary, the temperature gradient inside the granite specimen is relatively large during the increase in temperature. At constant temperature, the temperature distribution of the specimen is relatively uniform, and the temperature gradient is mainly concentrated on the mineral particles. For the entire heating process, the largest temperature gradient is mainly at the position where the heat exchange is intense, that is, the outer surface of the specimen. On the basis of this conclusion, we know that in real hot dry rock drilling engineering, the boundary of heat exchange is the boundary between the drilling fluid and borehole wall, that is, the inner wall of the borehole. Therefore, it can be concluded that the location with the largest temperature gradient during drilling is the inner wall of the borehole. Moreover, the farther away from the inner wall of the borehole, the smaller the temperature gradient.

3.5.2 The thermal stress distribution of the drilling surrounding rock during heating

Formula (11) indicates that thermal stress is generated inside the test piece during heating. Figures 11 and 12 present the construction of thermal stress variables in the COMSOL software and the plot of thermal stress distribution at different times. Figure 11(a) presents the thermal stress distribution in the test specimen at the 10th hour of heating. As can be seen from the figure, the maximum thermal stress generated in granite is 2.28 MPa, which is on the outermost part of the granite specimen. The minimum thermal stress is 0.472 MPa, which is on the inner wall of the borehole, which is highly consistent with the distribution of the temperature gradient. Figure 11(b) presents the thermal stress distribution diagram when the test piece is at a constant temperature state, that is, at the 100th hour of heating. Moreover, the internal thermal stress of the specimen is greatly reduced. The maximum thermal stress is 0.61 MPa, and the minimum thermal stress is 0.11 MPa. From the figure, it can be seen that the thermal stress is mainly concentrated on the place where the temperature gradient is large.

![Figure 11](image_url)
Figure 12. Relationship between the thermal stress and time at each monitoring point under different TMC conditions

Analysis of the change in the thermal stress inside the borehole surrounding rock with time under different temperatures and burial depths is presented in Figure 12(a)–(e). From the figure, it can be seen that the thermal stress of the granite specimen gradually increases to the radial direction during heating.
The maximum thermal stress is on the outer side of the test piece, and the minimum is on the inner wall of the borehole, indicating that the thermal stress mainly occurs in places where heat exchange is intense. The thermal stress at the same coordinates inside the borehole surrounding rock decreases with the increase in the burial depth and temperature. This is mainly caused by the decrease in the elastic modulus and thermal expansion coefficient of the borehole surrounding rock as the burial depth increases. The details are presented in the literature[45]. From the literature, it can be realized that during the deep hope drilling of HDR, the thermal stress at the inner wall of the borehole is the largest, due to the intense heat exchange between the drilling fluid and the inner wall of the borehole surrounding rock, and thermal cracking mainly occurs at the inner wall of the borehole.

Therefore, where the heat exchange is intense, the temperature gradient is large, which greatly changes the thermal stress and causes the borehole surrounding rock to be damaged easily. Temperature is an important factor of borehole surrounding rock instability.

3.5.3 Stress distribution law of the drilling surrounding rock

Figure 13(a)–(e) presents the relationship between the first principal stress at three monitoring points and time under different in situ stresses, wherein points A, B, and C represent the inner wall, middle wall, and outside wall, respectively, of the drilling surrounding rock. From Figure 13, it can be seen that as the temperature of the granite specimen increases, the compressive stresses at points A, B, and C have different rules. As the temperature increases, the compressive stress at point A gradually increases, and the compressive stress at the inner wall of the borehole in the steady state is 1–3 times that of the initial state. The compressive stress at points B and C is smaller than before. When in the constant temperature state, the compressive stress at points B and C returns to the stress state before heating, which is caused mainly by the expansion of the granite specimen as the internal temperature of the borehole surrounding rock increases. Moreover, the thermal stress generated in the granite specimen cancels out part of the loading stress. The compressive stress on the borehole gradually increases with the increase in the burial depth. Therefore, the temperature and in situ stress play a significant role in the drilling surrounding rock damage.
Figure 13. The relationship between the first principal stress and time under different in situ stresses

3.5.4 Analysis of the rheological displacement of borehole surrounding rock

Figure 14(a)–(e) shows that under different in situ stress and temperature, the rheological characteristics of the borehole surrounding rocks have evident rules: (1) Under the TMC condition, the creep deformation in borehole wall evidently increases with time, and the creep deformation of the internal surrounding rock far away from borehole slightly increases with time. Therefore, the rheological damage is most likely to occur at the borehole wall under the TMC condition. Also, along the radial direction of the borehole, the plastic radius further expands. (2) Under the TMC condition, when the burial depth stress is large and the rheological displacement at the borehole wall exceeds its limit value, evident damage occurs at the bore
wall, which leads to plastic failure of the hole diameter. When the plastic damage exceeds a certain range, it will lead to the complete damage to the drilling.
4 Analysis of the Fracture Characteristics of the Drilling Surrounding Rock Under the TMC Condition

By conducting experimental research on the deformation and failure of the drilling surrounding rock under high-temperature and high-stress conditions, and by analyzing the distribution laws of temperature and stress during the deformation and failure of the borehole, it can be realized that the temperature and in situ stress play a significant role in the deformation and failure of the drilling surrounding rock. To elucidate the failure mechanism and laws of the drilling surrounding rock under the TMC condition, further analysis on the following two aspects is necessary.

4.1 Analysis of the Failure Laws of the Drilling Surrounding Rock Under High-Temperature and High-Stress Conditions

Figure 15(a)–(b) presents the images captured using a borescope and a camera after the granite borehole was destroyed. Figure 16 presents the granule falling from the destroyed borehole wall, and Figure 17 presents the relationship between the bore diameter and axial height after the experiment. Combining the axial deformation curves and the borehole deformation curves in Figures 5–7, it can be realized that as the temperature and stress increases, the borehole deformation in granite exhibits distinct characteristics. Under the constant temperature and pressure state that in-situ stress of less than 100 MPa and temperature below 400 °C, the deformation of the drill hole exhibits obvious viscoelasticity. Although the diameter of the drill hole tends to be smaller, the drill hole is always at a stable state without damage. Under the combined effect of in situ stress of 125–150 MPa and temperature of 400 °C–500 °C, viscoelastoplastic deformation of the borehole surrounding rock occurs, and the borehole diameter decreases. With the increase in time, the surrounding rock of the borehole wall ruptures, and then the broken pieces fall, the borehole collapses and breaks, and the borehole deformation and the overall axial deformation of the rock enter the accelerated creep phase and fail.
Figure 15. Deformation of borehole in granite

Figure 16. The granule falling from the destroyed drilling wall

Figure 17. The changes in the borehole diameter along the axial height direction of granite specimen
Due to the friction in the upper and lower indenters, the end effect is obvious, and the affected length is 100 mm, which is about 1/4 of the test piece height. After the experiment of specimen 11#, the borehole diameter begins to increase from 109 mm from the lower end of the test piece and then stops at 95 mm from the upper end of the test piece. The most severe damage occurs in a height range of 90–300 mm, with a maximum hole diameter of 52 mm, and the residual outer wall of the borehole is still ruptured.

Figure 18. Rheodestruction pictures of granites with a drill hole (10#–12#) at high temperature and high pressure

Figure 18 presents the images of the rheological failure of drilled granite specimens (10#–12#) under high-temperature and high-pressure conditions. The critical conditions of borehole instability and failure of each specimen are summarized in Table 5. From Figure 18 and Table 5, it can be seen that the temperature conditions of failure and instability of the three test specimens are all 500 °C, and the in situ stress conditions are 125–150 MPa. The instability failure mode is compressive shear, or a combination of compressive shear and tension cracking. When the granite ruptured, the ruptured rock blocks of the borehole wall fell, and the rock sample exhibited an X-shaped and cone-shaped rupture. At the same time, numerous vertical cracks can be seen on the outside of the specimen, indicating that it was a composite failure mode of compressive shear and tension cracking. On the basis of the above experiments, from an engineering perspective, the temperature and stress composite conditions of the instability of the granite boreholes can be determined as 125 MPa and 500 °C.

Table 5. The destruction condition and characteristic of granite with a drill hole under high-temperature and high-pressure conditions

| Specimen | Damage mode | In situ stress /MPa | Temperature /°C | Failure mode description |
|----------|-------------|---------------------|-----------------|-------------------------|
| 10#      | Compressive shear | 150 | 500 | Hole shrinkage occurs at a height of 200–310 mm along the axial direction of the borehole, and its length is about 100 to 110 mm; the hole shrinkage diameter is 31.5 mm |
| 11#      | Compressive shear and tensile fracture composite form | 125 | 500 | The middle wall of the borehole experiences a series of changes: borehole shrinkage, crack, collapse, and diameter increase |
4.2 Analysis of the Numerical Simulation Result of Wellbore Destruction of Granite Under the TMC Condition

Under a high-temperature condition, due to the incoordination of the thermal expansion of the crystal particles constituting granite, the mutual displacement and cracking of the crystal particles occur within the granite, and the crystal particles soften at a high temperature, which directly leads to the decrease in the strength of granite and the enhanced mobility of the borehole surrounding rock. The thermal expansion caused by the temperature has a certain effect on the rheological displacement. The magnitude of the rheological displacement is mainly determined by the loading stress.

The Drucker–Prager yield criterion was adopted to analyze the calculated results. Under the in situ stress of 1000 m and the temperature of 100 °C, the plastic failure zone was not generated within 100 h. Only the rheological displacement evidently increases at the borehole wall. When in situ stress of 2000 m and temperature of 200 °C are applied, the borehole surrounding rock begins to produce plastic regions. The rheological failure zone of the borehole surrounding rock at the 100th hour under different TMC conditions is illustrated in Figure 19. As the stress and temperature of the granite specimen increase, the radius of the plastic failure zone significantly increases. Especially at a depth of 5000 m and a temperature of 500 °C, the radius of the plastic zone produced by the rheology of the borehole surrounding rock is the largest. This indicates that a larger area of the borehole wall is unstable, causing damage to the inner wall of the well.
5.1 Determining the Destruction Radius of the Wellbore in Granite Specimen Under the TMC condition

From the above analysis, it can be realized that, under the TMC condition, the rheological failure zone mainly expands on the radial direction of the borehole, and the expanded radius \( R \) is closely related to the loading temperature \( T \) and loading stress \( \sigma \). According to the result of the numerical calculation, it can be concluded that the radius of the rupture \( R \) at the time of borehole instability under different temperatures \( T \) and loading stress \( \sigma \), as presented in the Table 6.

| Destruction radius \( R \)/mm | Stress \( \sigma \)/MPa | Temperature \( T \)/℃ |
|-------------------------------|----------------------|-----------------------|
| 0                             | 25                   | 100                   |
| 2.278                         | 50                   | 200                   |
| 10.466                        | 75                   | 300                   |
| 17.892                        | 100                  | 400                   |
| 28.648                        | 125                  | 500                   |

By fitting the above data, the relationship between the radius \( R \) of the failure zone and the stress \( \sigma \) and temperature \( T \) is expressed by the following equation:
\[ R(\sigma, T) = 0.1716\sigma + 0.06862T - 10.0162 \quad R^2 = 0.96191, \] 

(13)

5.2 Critical Conditions of Borehole Instability Under the TMC condition

Under the TMC condition, the rheological displacement of the borehole surrounding rock gradually increases as the rheological time increases, and the plastic failure zone on the inner wall of the borehole also gradually increases. When the damage area exceeds the limit value, instability damage occurs at the borehole, causing the rock particles on the inner wall to fall off, the diameter of the borehole to rapidly increase, and the borehole to be completely damaged. From Figure 17, we can conclude that the drilling diameter \( R_1 \) is equal to 52 mm when \( z = 200 \) mm. At this moment, the radius \( R \) of borehole destruction in granite is equal to \( R_1 - r \), namely, 31.5 mm. When put it into formula (13), the relationship between the in situ stress \( \sigma \) and the temperature \( T \) under the critical conditions of borehole destruction and instability can be expressed as follows:

\[ 0.1716\sigma + 0.06862T = 31.5 \] 
(14)

By arranging formula (14), the relationship between the loading stress \( \sigma \) and the temperature \( T \) at the critical condition of borehole instability under the TMC condition can be expressed as follows:

\[ \sigma = 241.9 - 0.3998T \] 
(15)

The \( \sigma-T \) relationship curve under the critical condition of failure and instability of the borehole surrounding rock under the TMC condition is illustrated in Figure 20.

**Figure 20.** Relationship between stress \( \sigma \) and temperature \( T \) at the critical conditions of wellbore instability

5.3 Critical Conditions of Borehole Instability and Its Application and Research Significance Under High-Temperature and High-Stress Conditions

The drilling surrounding rock stability control technology is a complex worldwide problem. On average, up to 1 billion dollars are spent on the handling of wellbore instability around the world annually, and the wasted time accounts for about 5%–6% of the total drilling time. According to relevant data, the phenomenon of wellbore instability mainly occurs in deep hole drilling, and the stage of open hole, and the most serious losses are caused by the instability of the wellbore. With the high temperature and high in situ stress in deep hole drilling of HDR, how to effectively deal with the loss caused by the deformation and instability of drilling is a major technical problem that needs to be solved urgently.

Formula (15) and Figure 20 present the relationship between the burial depth stress \( \sigma \) and temperature \( T \) during the critical condition of borehole failure instability under high-temperature and high-pressure conditions. This has important guiding significance to deep hole drilling of HDR. When the formation stratum temperature \( T_0 \) is obtained from the geological data, the in situ stress at the maximum open-hole depth of the well can be obtained by using formula (14). By converting the in situ stress into the
equivalent drilling depth, one can infer the ultimate depth to maintain stable deep hole drilling of HDR under different temperatures. Moreover, effective protective measures should be taken to reduce the risk of damage and instability of the borehole surrounding rock.

6 Conclusions

Based on the storage conditions of the granite thermal reservoir of the Yangbajing geothermal field in Tibet, we employed experimental study, numerical simulation, and theoretical analysis to study the mechanism and laws of deformation and failure of drilling surrounding rock in deep hole drilling of HDR and deduce the critical conditions of wellbore instability under high-temperature and high-pressure conditions. The main conclusions drawn from this study are as follows:

(1) The deformation and failure laws of the borehole are determined via simulation experiment of the deformation and failure of granite under high-temperature and high-pressure conditions;

(2) The COMSOL software was used to establish the heterogeneity of the drilling surrounding rock, and numerical simulation was conducted to reproduce the temperature and stress distributions of the borehole deformation and failure under the experimental conditions. Moreover, it was conducted to reveal the distribution laws of the temperature field, stress field, displacement field, and thermal stress in the interior wall of the drilling surrounding rock under high-temperature and high-pressure conditions;

(3) Based on the full analysis of the temperature field and the stress field, combined with the experimental results of the borehole deformation and failure of granite under high-temperature and high-pressure conditions, the failure characteristics and rules of the borehole surrounding rock under the TMC condition are analyzed. It has been pointed out that the temperature and in situ stress of the borehole surrounding rock in deep hole drilling of HDR play a significant role in its deformation instability;

(4) At the critical conditions of drilling surrounding rock instability in deep hole drilling of HDR, the relationship between the in situ stress $\sigma$ and temperature $T$ is $\sigma = 241.9 - 0.3998 \cdot T$. It is possible to deduce the ultimate depth to maintain stable drilling of HDR under different temperatures.

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