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Deformation and instability failure of borehole at high temperature and high pressure in Hot Dry Rock exploitation

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ABSTRACT

Borehole stability at high temperature and high in-situ stresses is the key to Hot Dry Rock geothermal energy extraction. Upon drilling completion, borehole stability, its deformation and failure critical condition will be significant in deep HDR engineering design and construction. Using high temperature and high pressure servo-controlled triaxial rock testing machine, we performed experiments of borehole deformation and instability for three granite samples (200 mm in diameter and 400 mm long with a 40 mm opening in the center) at different hydrostatic stresses and temperature. The elastic and creep deformation data was analyzed. The results indicate that: 1) when the hydrostatic pressure is lower than 100 MPa and the temperature is below 400 °C, the specimens deform following the generalized Kelvin model. The critical condition for borehole stability is reached at hydrostatic pressure of 125 MPa and temperature of 500 °C, when creep deformation accelerates sharply. The failure mode is shear failure or a combination of shear and tension failure. The critical radial deformation ratio is about 20%; 2) Creep deformation at steady creep phase is derived based on the test data. The ultimate condition for drilling in granite is analyzed in regards to temperature and in-situ stresses.

1. Introduction

Hot Dry Rock (HDR) geothermal energy is mainly stored in granite. To exploit HDR geothermal energy, we need a great amount of drilling in granite, especially deep boreholes that are used to form artificial reservoir mainly through hydraulic fracturing technologies [1–3]. For other applications such as searching oil and gas resources, a lot of super-deep borings are located in the high temperature and high stress rock. Such projects have been carried out as Continental Scientific Drilling in more than ten countries, such as Russia, Germany, United States, and China. In Russia, the Kola SG-3 ultra-deep drilling at Kola Peninsula is 12262 m deep [4]. KTB-HB ultra-deep drilling in Germany is 9101 m deep [5]. Chinese continental scientific drilling conducted from June 2001 to January 2005 is 5118.2 m [6]. The first drilling for extracting hot dry rock geothermal energy at Fenton hill site in New Mexico is 4400 m [7,8]. Successful deep drilling under high temperature and high stresses is the key to explore energy and resources of the deep crust. At room temperature, the development of intra-and trans-granular dilatant microcracks in crystalline granite leads to borehole instability in the form of breakouts [9]. However, the physical and mechanical properties in rocks will change with temperature such as elastic modulus reduction [10], permeability enhancement [11], and mechanical strength decrease [12]. As a consequence, problems arise related to the borehole deformation and stability under high temperature and high stress, under which conditions, rock mass may lose its strength and exhibit rheological behavior [13].

Because of temperature and stress corrosion effects at depth [14], the drilling and completing cost is higher than that in oil and gas industry [15,16]. And the necking deformation, instability, and collapsing of boreholes in drilling always lead to a substantial increase in drilling costs and the borehole maintenance costs, and even sometimes prevent the project to be implemented [17]. Hence, in-depth study of borehole deformation and instability critical conditions under high temperature and high stress is of great scientific and engineering significance.

In this paper, the authors present the test results of granite rock specimens using the 20 MN servo-controlled high temperature and high pressure triaxial rock testing machine [18]. Three specimens were tested under less than 600 °C and 150 MPa hydrostatic stress. The deformation of the granite specimens, including elastic and

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creep deformation, was recorded and analyzed under steady and critical conditions for instability destroy of borehole.

2. Rock specimen testing under high hydrostatic pressure and high temperature

2.1. Experimental setup and monitoring equipment

The experimental setup shown in Fig. 1 has the following parameters:

1) Maximum axial load: 10,000 kN;
2) Maximum lateral load: 10,000 kN;
3) Maximum axial pressure on rock specimen: 318 MPa;
4) Maximum lateral pressure on rock specimen: 250 MPa (pseudo-triaxial confining pressure);
5) Maximum pore pressure: 250 MPa;
6) Specimen size: 200 mm × 400 mm;
7) Maximum drilling displacement: 450 mm;
8) Maximum drilling loading: 200 kN;
9) Maximum torque: 500 N m;
10) Maximum heating temperature: 600 °C;
11) Holding time of pressures: over 360 h;
12) Axial and lateral pressure offset: less than 0.3%;

The stress, deformation, pore pressure of inlet and outlet, temperature, torque and other parameters can be automatically recorded. The stiffness of the whole machine is greater than 9×10^{10} N/m.

The deformation of rock specimen and the borehole radial is measured using high temperature displacement sensor combined with static resistance strain gauge while temperature is under 240 °C. But the sensor cannot measure the displacement at the temperature over 240 °C for the serious changes of resistance with high temperature. So a specially designed optical instrument is used to measure borehole deformation during testing under high temperatures (seen in Fig. 2). Acoustic Emission (AE) is also monitored and recorded during the testing.

2.2. Specimen preparation

The granite used in the testing came from Pinyi, Shandong province in China. It is also called "Luhui" granite due to its characteristic of grey color. The samples were taken 50 m deep from a project site and contained no fractures. The three specimens were prepared as cylinders of 200 mm in diameter and 400 mm long. The specimens were cut smoothly on all sides. A hole of 40 mm in diameter was drilled

Fig. 1. 20 MN servo-controlled triaxial rock testing machine.

Fig. 2. Optical borehole deformation observation instrument.

along the cylinder axis of each specimen to simulate a borehole. The prepared specimen is shown in Fig. 3. Drilling of the holes was carefully controlled to ensure their verticality and concentricity. There were no apparent damages or fractures on any of the prepared specimens. The average uniaxial compressive strength (UCS), tensile strength, elastic modulus, and poisson's ratio of samples is 130 MPa, 18 MPa, 35 GPa, 0.25, respectively at normal temperature. The mineral composition is illite (25%), quartz (28%), feldspar (43%), calcite (1%), siderite (1%) and others (2%), respectively. The percentages in the bracket represent quality.

2.3. Testing procedure

The testing procedures are summarized as following:

1) Measure specimen height, diameter and the hole diameter.
2) Install a metal measuring rod in the middle point of the hole. Also install lighting at the bottom of the hole.
3) Seal the specimen and start testing by increasing temperature and hydrostatic pressure to the pre-determined values. The increment is 3–5 °C per hour for temperature.
4) At each pre-determined temperature (200, 300, …, 600), maintain the temperature and all-around pressure and continuously record the axial and radial deformation of the specimen as well as loading and temperature.
5) Measure borehole deformation every hour using the optical borehole deformation observation instrument.

2.4. Testing results of specimen 2

It is expected that the HDR geothermal energy resource exploration and other deep underground projects involve the high

Fig. 3. Granite specimen.