Study on Thermo-Mechanical Coupling Characteristics of Surrounding Rock of HLW Disposal Repository in Clay Rock

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Abstract. With the long-term decay, releasing a large amount of heat is one of the main characteristics of high-level radioactive waste. Safe operation of high-level radioactive waste repository must consider the effect of thermo-mechanical coupling on repository stability. In this paper, core drilling samples and in-situ stress tests were performed systematically on clay rock in Tamusu area. Thermal conductivity and triaxial tests were operated on samples near the depth of target layer of repository, to obtain the thermal and mechanical characteristics parameters. According to these parameters, a repository model was established in FLAC 3D to simulate excavation of repository and thermo-mechanical coupling of surrounding rock within 100 years after it closed. Results reveal that thermo-mechanical coupling effect has a significant impact on stability of repository. Thermal field reaches a steady state when high-level radioactive waste releases for 20 years, and the temperature in surrounding rock decrease as negative exponential with the distance from the gallery increases of. Due the temperature of the surrounding rock increases, thermal stress is generated, and the stress level in the near field of repository is growing as a whole, thus, strain increases. After heating without support for 100 years, there is the possibility of shear failure at the top and bottom of the chamber. It is necessary to reinforce the chamber lining to ensure the safe and stable operation of the repository.

1. Introduction
With the use of nuclear energy, it is inevitable to produce radioactive waste that is toxic, has a long half-life, and emits a large amount of heat. Safe disposal of high-level radioactive waste in the use of nuclear energy is a key issue for the using nuclear energy. Deep geological disposal is an internationally recognized disposal method. About geological disposal, the stability of surrounding rock determines the safety and feasibility of the repository. Because the nuclides of high-level radioactive waste continuously release heat during the decay process, in the evaluation of the confining pressure stability of the repository, the situation under the thermo-mechanical coupling field has to be considered. Clay rock has a very low permeability and unique self-healing properties, and it has a good effect on the blocking of nuclide migration. Therefore, some countries choose clay rock as the surrounding rock of the disposal reservoir. Scholars at home and abroad have done a lot of research on the thermo-mechanical coupling characteristics of clay rock.

In France and Switzerland, researchers chose the highly consolidated Callovo-Oxfordian (COX) and Opalinus (OPA) clay rock layers as the repository rock[1]. The Belgian researchers chose the Boom clay rock and conducted a large number of laboratory tests and in-situ tests[2]; in 2011, Chen et al. explored the THM coupling characteristics of Boom clay rock based on ATLAS III small-scale in-situ heating test, and conducted numerical simulations; in China, researchers focus on Beishan high-level waste disposal repository which surrounding rock is granite, Liu et al. conducted numerical simulation in FLAC3D based on the mechanical and thermal characteristics of Beishan granite to study the effect
of thermo-mechanical coupling to Beishan granite\textsuperscript{[3]}; Liu et al. conducted a series of uniaxial compression tests on mudstone at room temperature to 800°C, studied the changes of mudstone mechanics and deformation characteristics with increasing temperature\textsuperscript{[4]}; Guo et al. conducted triaxial compression tests on sandstone at different temperatures and confining pressures, with temperature levels ranging from 0°C to 60°C. The results show that temperature influence is an important factor for engineering stability analysis\textsuperscript{[5]}.

In this paper, the thermal-mechanical coupling characteristics of the surrounding rock of the Tamusu Clay are investigated. The mechanical strength test and thermal conductivity test are carried out. According to the parameters obtained in tests, a two-dimensional numerical model of the repository was established in the finite difference software FLAC3D, and a 100-year thermal-mechanical numerical simulation was conducted.

2. In-situ stress tests

In order to obtain the state of geological stress in Tamusu area, applying the true level of geological stress to triaxial tests and numerical simulations. In-situ stress tests were carried out in Tamusu by hydraulic fracturing. The tests were conducted at different depths in both two boreholes to obtain changes in in-situ stress levels with depth. Results are shown in Fig.1.

It can be seen from Fig.1 that the principal stresses in all directions in the formation of the Tamusu region are continuously increasing with the increase of depth, and have a linear regression relationship with the depth, which is consistent with the existing research laws\textsuperscript{[4]}. The relationship between each principal stress and depth can be expressed by the following formula (1). The stress field is dominated by horizontal principal stress, and the principal stress relationship is generally expressed as $\sigma_H > \sigma_r > \sigma_h$.

According to in-situ stress test results, the dominant orientation of the principal stress in the borehole area is near the NE direction, which is basically consistent with the regional stress field.

$$\begin{align*}
\sigma_H &= 0.048H + 9.216 \\
\sigma_r &= 0.0265H \\
\sigma_h &= 0.028H + 3.815
\end{align*}$$

(1)

![Fig.1 Variation trend of borehole in-situ stress with depth](image_url)
3. Laboratory research

3.1. Triaxial test at room temperature

In order to study the mechanical properties of clay rock in Tamusu area, uniaxial and triaxial strength tests were conducted on the samples of the deep clay rock in Tamusu. The instrument used in this test is a TAW-2000 microcomputer-controlled triaxial pressure tester. The maximum axial force of the tester can reach 2000kN, the maximum confining pressure is 100MPa, the axial deformation measurement range is 0~10mm, and the radial deformation measurement range is 0~5mm. The rock sample is processed into a standard sample of Φ50mm×100mm.

Fig. 2 Samples of triaxial test at room temperature

For acquiring the mechanical properties of Tamusu clay, the triaxial test under different confining pressures was carried out on the Tamusu clay samples. The confining pressure settings were 0MPa, 5MPa, 10MPa, 15MPa, and two rocks were tested under each confining pressure sample, taking the average as the final value. During the test, first put the rock sample connected to the sensor into the confining pressure chamber, then close the confining pressure chamber, and fill the chamber with dimethyl silicone oil. After pressurizing the confining pressure chamber to the set value, axial pressure is applied at a certain rate in the axial direction until the rock sample fails, and the stress-strain curve of the rock sample is obtained. The stress-strain curve is shown in Fig. 3. Table 1 shows the mechanics and deformation characteristic parameters of Tamusu clay.

Fig. 3 Stress-strain curve of Tamusu clay

| Stress (MPa) | Radial Strain | Axial Strain |
|-------------|---------------|--------------|
| 0MPa-1      | -0.010        | 0.000        |
| 5MPa-1      | -0.005        | 0.005        |
| 10MPa-1     | 0.000         | 0.010        |
| 15MPa-1     | 0.005         | 0.015        |
| 0MPa-2      | -0.010        | 0.000        |
| 5MPa-2      | -0.005        | 0.005        |
| 10MPa-2     | 0.000         | 0.010        |
| 15MPa-2     | 0.005         | 0.015        |
Results show that as the confining pressure increases, the compressive strength of the Tamusu clay also increases, which increases approximately linearly, and the elastic modulus and Poisson's ratio also increase. The uniaxial compressive strength is about 34.41 MPa. With the increase of confining pressure, the change of Poisson's ratio is small, and its value is in the range of 0.18 ~ 0.40.

Table 1 Mechanical characteristic parameters of Tamusu clay

| Depth (m) | Confining pressure (MPa) | Elastic modulus (GPa) | Poisson's ratio | Compressive strength (MPa) |
|-----------|--------------------------|-----------------------|----------------|---------------------------|
| 1         |                          |                       |                |                           |
| T-2A      | 429                      | 0                     | 4.54           | 0.25                      | 31.36                      |
| T-2C      | 429                      | 0                     | 3.95           | 0.18                      | 34.16                      |
| average   |                          |                       | 4.23           | 0.22                      | 34.41                      |
| T-1B      | 559                      | 5                     | 6.94           | 0.26                      | 53.28                      |
| T-2H      | 565                      | 5                     | 7.76           | 0.30                      | 57.06                      |
| average   |                          |                       | 7.35           | 0.28                      | 55.17                      |
| 2         |                          |                       |                |                           |
| T-2D      | 530                      | 10                    | 10.88          | 0.28                      | 83.99                      |
| T-2N      | 530                      | 10                    | 10.02          | 0.38                      | 87.34                      |
| average   |                          |                       | 10.45          | 0.33                      | 85.67                      |
| T-3E      | 676                      | 15                    | 11.95          | 0.35                      | 105.57                     |
| T-3C      | 676                      | 15                    | 13.77          | 0.33                      | 113.37                     |
| average   |                          |                       | 12.86          | 0.34                      | 109.65                     |

3.2. Thermal coefficient performance test

In order to acquire the thermal properties of Tamusu clay, we conducted thermal conductivity tests on the dried clay samples by Hot Disk Thermal Constant Analyzer (TPS2500s) of the Beijing Institute of Geology of the Nuclear Industry through instantaneous planar heat source method.

Before this test, the cores were processed into pairs of Φ50mm × 25mm samples, the processed rock samples were placed in an oven and dried, and then placed in a drying dish to cool. Fix the flat surface of the Hot Disk sensor probe between the pair of rock samples so that the rock sample and the probe are in close contact. The temperature rise of the probe transfers the heat to the rock sample, and at the same time monitors the temperature change of the probe to obtain the thermal conductivity performance parameter of the rock sample. Each pair of rock samples is tested three times, and the average value is taken as the final test result. The results obtained from the thermal conductivity test are shown in Table 2.
Table 2 shows the thermal conductivity of Tamusu clay at 542m depth is 1.09~1.15 W/(m•℃) and the specific heat capacity is 694.13 ~ 775.71 J/(kg•℃); at 573m is 1.55~1.80 W/(m•℃). The specific heat capacity of Tamusu clay is 615.35~686.57 J/(kg•℃).

Table 2  Thermal parameters of Tamusu clay

| Depth (m) | Density (g·cm⁻³) | Thermal Conductivity (W·m⁻¹·℃⁻¹) | Specific heat capacity (J·kg⁻¹·℃⁻¹) |
|----------|------------------|-------------------------------|-------------------------------------|
| T-3B     | 542.58           | 2.31                          | 1.09                            | 775.71                           |
| T-3C     | 542.68           | 2.51                          | 1.11                            | 728.69                           |
| T-3D     | 542.78           | 2.48                          | 1.15                            | 691.13                           |
| T-2E-1   | 573.02           | 2.27                          | 1.55                            | 727.75                           |
| T-2E-2   | 573.07           | 2.28                          | 1.80                            | 868.57                           |
| T-2C     | 573.80           | 2.48                          | 1.57                            | 615.35                           |

4. Thermal-mechanical coupled numerical simulation

To study the thermal-mechanical coupling characteristics of the surrounding rock of HLW disposal repository, a 100-year numerical simulation was conducted. According to the research of domestic and foreign scholars on the heat release process of solid waste with the decay of nuclides, the nuclides have the strongest heat releasing intensity in the first 100a, and then decay seriously after 100a. Therefore, within 100 years after the waste is placed in the repository, the thermal effect on surrounding rock is maximized[6]. Therefore, this time value simulation is the excavation of the Tamusu clay and the thermo-mechanical coupling within 100a after excavation. Because the compactness of the filling material is not large[7], the influence of the backfill material is not considered in the numerical simulation in this paper.

4.1. Model parameters and boundary conditions

The numerical simulation model is based on the conceptual model of the claystone repository in Belgium, a typical claystone repository country [8-9]. This model is a horizontal disposal model with a tunnel diameter of 2m, and the model size is 100m×100m, as shown in Fig.5. The rock mass strength constitutive model uses the Mohr–Coulomb model, and the thermal model uses the isotropic heat conduction model. The numerical simulation parameters are selected according to the parameters obtained from the experiment, as shown in Table 4.

![Fig. 5 Numerical simulation model](image-url)
Table 4 Numerical simulation parameters

| Shear modulus (GPa) | Bulk modulus (GPa) | Cohesion (MPa) | Friction angle (°) | Tension strength (MPa) | Thermal conductivity (W·m⁻¹·C⁻¹) | Specific heat capacity (J·kg⁻¹·C⁻¹) | Thermal expansion coefficient (°C⁻¹) |
|---------------------|-------------------|---------------|-------------------|-----------------------|-----------------------------------|-----------------------------------|----------------------------------|
| 4.0                 | 5.2               | 6.9           | 42.2              | 3.4                   | 1.38                              | 620.4                             | 1×10⁻⁵                           |

4.2. Analysis of numerical simulation results

4.2.1. Evolution law of temperature field
It can be seen from Fig.6 that due to the heat release of the heat source, there is an obvious heat regulation circle in the surrounding rock. As the distance from the wall is increased, the temperature of the surrounding rock decreases rapidly to the original surrounding rock temperature; according to the temperature changing of the monitoring point in the surrounding rock. Isothermal circle expands with time rising. Temperature grows fast in the first 20a of heating, and then reaches a stable state slowly. According to the distribution trend of temperature in surrounding rock when heating for 100a, temperature varies with the distance away from the chamber, it is a nearly first-order exponential decay.

Fig. 6 Temperature field distribution after heat release for 100 years (unit: °C)

Fig. 7 Temperature field distribution along radial direction away from gallery at different times

4.2.2. Evolution law of stress field
Fig.8 and Fig.9 show the distribution of the maximum and minimum principal stress in the surrounding rock after excavation and heat source heat release. It can be seen from Fig.8 that after excavation, the maximum principal stress is concentrated at the top and bottom of the chamber about 29MPa, and the maximum principal stress gradually decreases to the in-situ stress level as it moves...
away from the chamber; the minimum principal stress is 0MPa on the surface of the surrounding rock. Far from the chamber, the minimum principal stress rises to the original minimum principal stress level. The stress concentration factor is $1.83 \sim 2.41$. After source releases heat for 100a, the distribution of principal stresses is approximately the same as that after excavation, but the maximum and minimum principal stress values have improved overall. The maximum principal stress concentrated at the top and bottom of the chamber increases to 35.7MPa, an increase of 23.1%, which is close to the uniaxial compressive strength of the Tamusu clay; the minimum principal stress on the surface of the surrounding rock of the chamber increases from 2.12MPa To 2.4MPa, an increase of 13.2%.

4.2.3. Evolution low of deformation field

Fig.9 and Fig.10 are the deformations of the surrounding rock at different stages of treatment, and Fig.11 is vector diagram of the deformations of the surrounding rock at different stages. It can be seen from the figure that after the excavation of the disposal pit, because $\sigma_H > \sigma_v$, the surrounding rock of the chamber is squeezed towards the center of the gallery, the deformation on both sides of the chamber is larger, the maximum displacement of the side wall of the chamber is 2.06mm, and the bottom of the chamber top The maximum displacement is 1.37mm, forming a near-ellipse with a long diameter in

Fig. 8 Stress distribution of surrounding rock after excavation (unit: Pa)

(a) Maximum principal stress (b) Minimum principal stress

Fig. 9 Surrounding rock deformation after stable excavation (unit: m)

Fig. 10 Surrounding rock deformation after heat release for 100 years (unit: m)
After excavation and heating for 100a, the deformation of the surrounding rock is 2.95 ~ 8.00mm, and the horizontal displacement is smaller than the vertical displacement, and the overall movement trend is upward.

4.2.4. Distribution of zone state

Fig. 12 shows the distribution of zone state in surrounding rock after excavation and heating for 100 years. In this figure, none indicates that there is no plastic zone; shear-p indicates that it has experienced shear failure but is currently in elastic state; tension-p indicates that it has experienced tensile failure but is in elastic state. It can be seen from Figure 12 that after the excavation of the disposal roadway, the surrounding rock mass does not appear plastic zone, and the surrounding rock state is stable; after the disposal repository is closed and the heat source is heated for 100a, the surrounding rock is mainly subject to shear failure, and the failure area is mainly distributed at the top and bottom of the chamber.

4.3. Thermal-mechanical coupling characteristics analysis

According Fig. 3 that surrounding rock rapidly heats up within 20a of heat source heat release. At 20a, the temperature field basically reached a steady state. The distribution law of the temperature field in the surrounding rock is that the temperature of the surrounding rock decreases exponentially from 100 °C to 15 °C of the original surrounding rock as it moves away from the heat source. As the temperature of the rock mass rises, the rock minerals thermally expand, and the contact relationship between the rock mineral particles changes, thereby generating thermal stress in the rock mass due to temperature changes\(^{[10]}\). The thermal stress obviously changes the stress state of the rock mass, which makes the stress in the surrounding rock rise. In the surrounding rock close to the heat
source, the temperature is higher and the stress changes greatly; as the distance from the heat source increases, the stress state of the surrounding rock approaches the original stress state. Before the heat source is added, due to the excavation of the chamber, the surrounding rock of the chamber is extruded into the center of the chamber into a vertical ellipse with a maximum displacement of 2.95mm; Strain. The effect of temperature on the deformation of the surrounding rock is obvious. After 100a of heating, the maximum displacement of the surrounding rock deformation of the chamber is 9mm. Before and after the heat source releases heat, the strain of the surrounding rock does not exceed 1%. According to Hoek's deformation support theory of surrounding rock[11], support problem can not be considered.

![Fig.12 Classification standard of extrusion deformation of surrounding rock][11]

According to the distribution of zone state, there is no plastic zone after excavation, the surrounding rock is safe and stable. However, when the chamber without lining support is heated 100 years, plastic zone appears in the stress concentration area at the top and bottom of the chamber. there is a possibility of shear failure in the stress concentration zone. Therefore, the influence deformation and thermal stress caused by temperature raising on the stability of surrounding rock should be considered. The inner lining of the disposal tunnel should be reinforced to ensure the safe operation of the repository.

5. Conclusion
For the deep geological repository of high-level radioactive waste, the thermal damage of surrounding rock caused by the temperature, generated in the decay process of high-level radioactive waste, is crucial to the nuclide migration and long-term stability, safety of the repository. The thermomechanical coupling effect has a significant impact on the stability of the repository. In the process of heat release, the temperature raising is a changing process in the surrounding rock of the repository. The temperature in the surrounding rock reaches a stable state about 30 years, and the distribution of the temperature field in the surrounding rock decreases with the increase of the distance from the heat source. The thermal stress caused by thermal expansion changes the stress state of surrounding rock and affects the deformation of surrounding rock. According to the strain of surrounding rock, the strain of surrounding rock of the chamber is less than 1%, support problem can not be considered. However, from the perspective of the plastic zone, there is a possibility of shear failure in the stress concentration zone at the top and bottom of chamber. Therefore, inner lining of the disposal tunnel should be reinforced to ensure the safe operation of the repository.
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