Study on hydro-mechanical coupling properties of clay rock in Tamusu - the pre-selected area of high-level radioactive waste repository

Haian Liang¹, Qingbo Hu¹*, Yu Wang¹, Haikang Chen¹, Longpeng Zhang¹, Chao Liu¹

¹Civil and Architectural Engineering, East China University of Technology. Jiangxi, Nanchang, China
hu_qingbo@126.com

Abstract. The research of hydro-mechanical coupling properties is of great significance for the design of high-level radioactive waste repository. In this paper, the permeability evolution test of Tamusu clay under full stress-strain condition is carried out. Based on the basic theoretical equation of hydro-mechanical coupling, the relationship between the permeability and stress of the Tamusu clay is analyzed. Combined with the results of in-situ stress measurement in the Tamusu area, the excavation simulation of the roadway with a burial depth of 500 m in the area is carried out, and the change law of pore water pressure in the surrounding rock near the field is analyzed. The results show that when the osmotic pressure is constant, the peak strength increases and the permeability decreases with the increase of confining pressure. When the confining pressure is constant and osmotic pressure increases, the result is reversed; The permeability of Tamusu clay is affected by confining pressure more than the osmotic pressure, and the relationship between permeability and axial stress follows the negative exponential function.

1. Introduction
In recent years, with the development of nuclear power industry, more and more high-level waste has brought about the inevitable disposal of nuclear waste. Choosing a reasonable deep geological disposal site has become the primary problem for safe disposal of high-level waste. Clay rock is one of the pre-selected surrounding rocks in China's high-level radioactive waste repository, and the study of hydro-mechanical coupling characteristics of clay rock is the key to the evaluation of repository sites.

At present, many scholars at home and abroad have studied the permeability characteristics of clay rock. Yu(2012), Jia(2016), et al. conducted a large number of experiments on Boom clay rock, analyzed the hydro-mechanical coupling characteristics and rheological characteristics of Boom clay, and established a mathematical model that could characterize the mechanical behavior of Boom clay rock. Bésuelle et al.(2014) discussed the effects of fracture development on the permeability characteristics of Boom clay rock, and analyzed the permeability changes under different stress states. Menaceur(2016), Seyedi(2017), Zhang(2018), et al. conducted a large number of hydro-mechanical coupling experiments on Callovo-Oxfordian clay rock. Based on the laboratory tests and in-situ tests, the hydro-mechanical coupling behavior of COX clay rock was discussed. Marschall(2017) and Bossart(2017), et al. conducted in-situ tests on the Oplinus clay to study the hydro-mechanical coupling characteristics of the excavation damage zone. Liu et al.(2018) conducted a study on the
water retention characteristics and gas permeability of Opalinus clay. However, the research on clay rock in China is relatively late. The research work on the surrounding rock of high-level radioactive waste repository is mainly concentrated on granite, and the research of the hydro-mechanical coupling characteristics of clay is rather little. Che(2012) and Hu(2014), et al. studied the basic physical properties and permeability characteristics of Longdong clay rock and Tamusu clay rock, respectively.

In view of this, this paper takes the Tamusu clay as the research object, and analyzes the relationship between permeability and axial stress of Tamusu clay based on the permeability evolution test under full stress-strain condition and the basic theoretical equation of rock hydro-mechanical coupling. Combined with the results of geostress measurement in the Tamusu area, the excavation simulation of the 500m buried depth of the Tamusu area is carried out, and the variation of pore water pressure and displacement field of the near-field surrounding rock is analyzed. It is expected to provide a reference for the study of clay rock in high-level radioactive waste repository.

2. Geostress level in the Tamusu area

The research group carried out hydraulic fracturing test on the site of Tamusu pre-selected area, and conducted in-situ stress test on ZK1 and ZK2 boreholes in this area. The test results are shown in Figure 1. It can be found that, in general, the principal stress of Tamusu area increases with the increase of the stratum depth; In this region, the horizontal stress $S_H$ and $S_h$ play a dominant role, and the overall performance of the principal stress relationship is $S_H > S_v > S_h$.

Since the high-level radioactive waste repository is mostly established in the deep underground with an embedded depth of 500 m or more, this paper mainly calculates the in-situ stress level according to the target buried depth, and only considers the most unfavorable factors: the maximum horizontal principal stress and vertical stress. According to the fitting function, the horizontal stress is about 15 MPa and the vertical stress is about 13 MPa at a depth of 500 m in Tamusu area.

![Figure 1 Trend of geostress in the Tamusu area](image)

3. Hydro-mechanical coupling test of Tamusu clay

3.1. Basic equations of hydro-mechanical coupling

Based on the following assumptions: the fluid in the rock medium follows the Biot seepage theory; the rock is a kind of elasto-brittle material, and the mechanical behavior of the loading and unloading process conforms to the elastic damage theory; the damage of the rock is subject to the maximum tensile strength criterion and the Mohr-Coulomb strength criterion. The basic equations of hydro-mechanical coupling under Biot theory are

Stress balance equation:

$$\sigma_{ij,j} + F_i = 0 \quad (1)$$

The geometric equation:

$$\varepsilon_{ij} = \frac{1}{2} (u_{j,i} + u_{i,j}) \quad (2)$$

Constitutive equation:
\[ \sigma'_{ij} = \sigma_{ij} - \varphi p \delta_{ij} = \lambda \delta_{ij} \varepsilon_t + 2G \varepsilon_{ij} \]  

Seepage continuity equation:

\[ k \nabla^2 p = \frac{1}{Q} \frac{\partial p}{\partial t} - a \frac{\partial \varepsilon_{ij}}{\partial t} \]  

Where \( F_i \) is volume force, \( \varepsilon_{ij} \) is the strain, \( u \) is the displacement of the solid skeleton, \( \rho \) is density, \( t \) is time, \( v \) is the actual seepage velocity, \( n \) is porosity. \( \sigma'_{ij} \) and \( \sigma_{ij} \) are the effective stress and total stress of the solid skeleton of the porous medium respectively, \( \varphi \) is the pore water pressure coefficient of the porous medium, \( \delta_{ij} \) is the Kronecker symbol, and \( \varepsilon_t \) and \( \varepsilon_{ij} \) are the total strain and the bulk strain respectively.

Compared with the continuity equation of fluid mechanics, the seepage continuity equation contains more parameters. If the rock is isotropic and the porosity is constant, the two functions are the same.

Hydro-mechanical coupling equation:

As the rock begins to break, its structure changes greatly, and the hydro-mechanical coupling equation and coupling parameters also change. So far, there is no regular understanding of the phenomenon after the failure, so only the transient method is used to analyze the relationship between permeability and stress before the peak strength of the rock.

Yang et al. (2004) summarized the relationship between permeability and stress obtained by some scholars. The relationship can be expressed by the following four functions.

Negative exponential function:

\[ k = k_0 e^{-a\sigma} \]  

Negative power exponential function:

\[ k = k_0 (\sigma')^{-a} \]  

Power exponential function:

\[ k = k_0 \left( 1 - \frac{\sigma}{a+b\sigma} \right)^4 \]  

Hyperbolic function:

\[ k = \frac{a}{b+\sigma'} \]  

Where \( k \) is permeability, \( k_0 \) is the initial permeability, \( \alpha \) is a constant, \( \sigma \) is stress. \( \sigma' \) is the effective stress, \( a \) and \( b \) are constants.

The coupling parameters in the above four functions are assigned, and the relationship curves between permeability and stress are drawn as shown in figure 2.

![Figure 2](image.png)

Figure 2 The relationship curves between permeability and stress (k1-k4)

3.2. Hydro-mechanical coupling test

To study the hydro-mechanical coupling characteristics of the Tamusu clay, this paper adopts the indoor hydro-mechanical coupling test, and obtains the H-M coupling full stress-strain curves of the Tamusu clay. The relationship between the permeability evolution, the permeability and stress of the clay rock under full stress-strain is analyzed. These efforts provide the basis for the study of high-level radioactive waste repository.
The test adopts a cylindrical standard sample of $\Phi 50 \times 100$ mm. These samples are taken from the 500 m buried depth in the high-level waste repository pre-selected area of Tamusu, Inner Mongolia. The TAW-2000 microcomputer controlled rock triaxial testing machine is used to test the hydro-mechanical coupling of Tamusu clay under different confining pressure and osmotic pressure according to the test standard. The confining pressure is set to 10 MPa and 15 MPa, respectively, and the osmotic pressure is set to 2 MPa, 5 MPa and 8 MPa, respectively. The axial displacement control loading is used in the test, the loading rate is controlled to 0.005 mm/min, and the confining pressure and osmotic pressure are loaded to the design values. The test process ensures that the confining pressure is greater than the osmotic pressure, which prevents the heat-shrinkable tube from being broken due to excessive osmotic pressure. After the test, the water flow data is derived from the test system and the permeability is calculated. The test results are shown in Table 1 and Figure 3.

| Sample | Depth/m | $\sigma_3$/MPa | $\Delta P$/MPa | $\sigma_c$/MPa | $\varepsilon_c$ | $E$/GPa | $\mu$ |
|--------|---------|---------------|---------------|---------------|--------------|---------|------|
| TPK-11 | 539.05  | 10            | 2             | 84.27         | 0.026        | 3.24    | 0.22 |
| TPK-12 | 539.05  | 10            | 5             | 78.94         | 0.011        | 5.43    | 0.30 |
| TPK-22 | 539.05  | 10            | 8             | 74.26         | 0.023        | 2.31    | 0.28 |
| TPK-21 | 556.43  | 15            | 2             | 112.64        | 0.033        | 4.52    | 0.25 |
| TPK-13 | 556.43  | 15            | 5             | 104.30        | 0.034        | 3.07    | 0.35 |
| TPK-14 | 556.43  | 15            | 8             | 101.11        | 0.029        | 4.47    | 0.32 |

$\sigma_3$—Confining pressure; $\Delta P$—osmotic pressure; $\sigma_c$—peak stress; $\varepsilon_c$—peak strain; $E$—elasticity modulus; $\mu$—Poisson's ration.

![Figures](image1.png)

Figure 3 Stress-strain and strain-permeability curves under different confining and osmotic pressures

3.3. Analysis of test results

Figure 3 shows that permeability of Tamusu clay is on the order of $10^{-20}$ m$^2$. When the osmotic pressure is the same, as the confining pressure increases, the peak strength increases and the permeability decreases. The increase of confining pressure leads to the increase of lateral restraint. Then the expansion of micro-cracks and micro-cavities in clay rock is inhibited, and the bearing capacity increases, that is, the peak strength increases. Initially, the clay rock is in the compaction
stage of fracture and pore, in which the seepage channel will decrease, the permeability will decrease. When the confining pressure is the same, as the osmotic pressure increases, the peak strength of the clay rock decreases and the permeability increases. With the increase of osmotic pressure, the rock damage rate is accelerated, and the existence of osmotic pressure reduces the crack initiation stress. Under the same deformation condition, the rock damage is advanced and the peak strength decreases.

When the confining pressure is 10 MPa and 15 MPa, the osmotic pressure increases from 2 MPa to 8 MPa, and the peak strength of the rock decreases by 11.84% and 10.31%, respectively. When the osmotic pressure is 2 MPa, 5 MPa and 8 MPa, the confining pressure increases from 10 MPa to 15 MPa, and the peak strength of the rock increases by 33.79%, 32.13% and 36.16% respectively. It can be seen that the confining pressure plays a leading role in the peak strength of the clay rock.

In the early stages of deformation, the permeability of Tamusu clay is mainly affected by the axial pressure. The initial pores of the sample are compacted, and the permeability is at a low level and has a decreasing trend. As the axial stress continues to increase, the micro-cracks and micro-cavities inside the rock sample begin to expand, and new cracks begin to form and penetrate, then the permeability rises to the peak. There is a sudden change point in this process, and the permeability increases sharply at this point. Since the sample is destroyed in an instant and the change in permeability after the peak cannot be measured, only the relationship between the permeability and the stress before the peak strength of clay is analyzed, the relationship curves and the fitting curves are shown in Figure 4.

![Figure 4 Relationship curve and fitting curve of permeability and stress](image)

(d) $\sigma_3=15$ MPa, $\Delta P=2$ MPa  
(e) $\sigma_3=15$ MPa, $\Delta P=5$ MPa  
(f) $\sigma_3=15$ MPa, $\Delta P=8$ MPa

Table 2  Fitting results of permeability and stress of clay rock from Tamusu pre-selected area

| No. | $\sigma_3$/MPa | $\Delta P$/MPa | Fitting equation | $R^2$ |
|-----|--------------|--------------|-----------------|------|
| 1   | 10           | 2            | $k=1.21\times10^{20}\sigma^{0.25}$ | 0.97 |
| 2   | 10           | 5            | $k=1.56\times10^{20}\sigma^{0.24}$ | 0.96 |
| 3   | 10           | 8            | $k=2.39\times10^{20}\sigma^{0.47}$ | 0.96 |
| 4   | 15           | 2            | $k=2.13\times10^{20}\sigma^{0.52}$ | 0.95 |
| 5   | 15           | 5            | $k=5.44\times10^{20}\sigma^{0.69}$ | 0.97 |
| 6   | 15           | 8            | $k=4.96\times10^{20}\sigma^{0.56}$ | 0.96 |

$\sigma_3$—Confining pressure; $\Delta P$—osmotic pressure; $R^2$—Fitting correlation coefficient
Figure 4 shows that before the peak of clay, as the axial stress increases, the permeability gradually decreases and eventually stabilizes. The fitting results indicate that the negative power exponential function fits well to the relationship between stress and permeability. The results are shown in Table 2.

4. Numerical simulation of disposal roadway

In this simulation, the finite difference software FLAC 3D is adopted to simulate the excavation of the underground disposal roadway with a depth of 500 m in Tamusu. Since the length of the roadway has little influence on the simulation results, the model is established as two-dimensional. The model size is 40×40 m and the roadway radius is 2m, and the excavation simulation of the roadway is carried out under pore water pressure of 2, 5 and 8 MPa, respectively. The rock mass parameters are obtained from field test and laboratory test, as shown in Table 3. The mechanical boundary conditions are: horizontal displacement constraint on both sides, horizontal displacement and normal displacement constraint on the bottom, and free boundary on the top. The excavation part is set to the null model, and the seepage model is an isotropic model. The boundary around the model is permeable. After excavation, the pore water pressure on the wall is equivalent to the atmospheric pressure.

Table 3 Model parameters

| G/GPa | K/GPa | c/MPa | φ(°) | σt/MPa | σh/MPa | σv/MPa | E_f/GPa | σ_f/MPa | P | k×10^20 |
|-------|-------|-------|------|--------|--------|--------|--------|--------|----|--------|
| 4.0   | 5.2   | 6.9   | 42.2 | 3.4    | 15.0   | 12.0   | 2.0    | 0.5    | 0.14| 1.0    |

G—Shear modulus; K—Bulk modulus; c—Cohesion; φ—Internal friction angle; σ_t—Tensile strength; σ_h—Horizontal stress; σ_v—Vertical stress; E_f—Fluid modulus; σ_f—Fluid tensile strength; P—Porosity; k—Coefficient of permeability.

(a) Pore water pressures is 2MPa  (b) Pore water pressures is 5MPa  (c) Pore water pressures is 8MPa

Figure 5 Pore water pressure dissipation cloud diagrams under different initial pore water pressures

(a) Pore water pressures is 2MPa  (b) Pore water pressures is 5MPa  (c) Pore water pressures is 8MPa

Figure 6 Vertical displacement cloud diagrams under different pore water pressures

It can be seen from Figure 5 and Figure 6 that the excavation of the roadway leads to the dissipation of pore water pressure of the surrounding rock in the near field, and the pore water pressure at the cave wall is the minimum. With the increase of the distance from the cave wall, the pore water pressure of the rock mass gradually approaches to the original rock’s. With the increase of initial pore pressure, the maximum displacement caused by excavation gradually increases from 4.0 mm at the pore pressure of 2 MPa to 6.6 mm at 8 MPa, and the maximum displacement appears at the top of the roadway. The difference of initial pore water pressure has little influence on the uplift displacement at the bottom of the roadway, and the maximum displacement is 1.6 mm at the pore pressure of 8 MPa.
5. Conclusion
The principal stress of Tamusu area increases with the increase of the stratum depth; In this region, the horizontal stress play a dominant role, and the overall performance of the principal stress relationship is $S_H > S_p > S_v$. The horizontal stress is about 15 MPa and the vertical stress is about 13 MPa at a depth of 500 m in Tamusu.

The permeability of Tamusu clay is on the order of $10^{-20} \text{m}^2$. When the osmotic pressure is the same, the peak strength increases and the permeability decreases with the increase of the confining pressure. When the confining pressure is constant and osmotic pressure increases, the result is reversed; The confining pressure plays a leading role in the peak strength of the clay rock. The negative power exponential function fits well to the relationship between stress and permeability of Tamusu clay.

With the increase of initial pore pressure, the maximum displacement caused by excavation gradually increases from 4.0 mm at the pore pressure of 2 MPa to 6.6 mm at 8 MPa, and the maximum displacement appears at the top of the roadway. The difference of initial pore water pressure has little influence on the uplift displacement at the bottom of the roadway.

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