Direct shear experiment on salt rock incorporating loading rate effect

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Abstract. To investigate the shear behavior of salt rock under different loading rates, direct shear testing was conducted on high-purity salt rock obtained from Pakistan using a YZW-100 apparatus. The experimental results of the shear stress, deformation, and failure characteristics of the salt rock showed that the loading rate is an essential factor influencing the shear strength parameters of the rock. When the shear loading rate was increased, the cohesion of the salt rock significantly increased; however, the internal friction angle slightly decreased, nearly remaining unchanged. The shear failure mode of the salt rock manifested by shear stress-displacement curves tended to be ductile failure with increased normal force. The residual stress of the salt rock was large, indicating its high friction-bearing capacity. The dilatancy deformation was also subjected to shear loading. The fracture section of the salt rock exhibited visible local scratch marks. These experimental results are helpful for further understanding the failure mechanism of salt rock and the stability of underground gas storage under different gas injection and production scenarios.

1. Introduction
Salt rock, with its low permeability, good creep, and self-healing properties, has become an ideal medium for underground energy storage and has thus been rapidly developed and widely used in various countries [1-3]. In China, the first salt cavern developed for gas storage is located in Jintan, Jiangsu. Since its initiation in 2007, nearly 50 rounds of gas production and injection cycle have been completed in 12 years. Salt mines in Wanzhou, Chongqing; Yunying, Hubei; and Pingdingshan, Henan have also been considered for site selection and construction.

In the existing research of the short-term strength theory of salt rock and gas storage engineering, most studies evaluated the yield failure of salt rock based on the Mohr–Coulomb strength theory and analyzed the stability of gas storage in deep salt rock media. Li et al. [4] compared the strength parameters of the interface between salt rock and salt–gypsum and concluded that the shear strength of the interface is slightly stronger than that of pure salt rock. Yao et al. [5] analyzed the relationship among shear strength, dilatancy, and normal stress of salt rock through direct shear testing. The shear characteristics of rocks under different loading rates have been well studied Fukui et al. [6] studied the relationship of the peak and residual shear strength and the loading rate of andesite through direct shear testing at different low displacement loading rates and found that both types of shear strength increased with an increase in the loading rate. Gong et al. [7, 8] reported that in the low strain rate range of $10^{-5}$–$10^{-1}$ s$^{-1}$, the cohesion of rock increased as the strain rate increased, and the internal friction angle remained almost constant. In the high strain range of $10^{0.5}$–$10^{2}$ s$^{-1}$; however, the rock
Cohesion was positively correlated with the strain rate, whereas the internal friction angle was negatively correlated. Zhao [9] analyzed the strength of several different rocks under medium and high loading rates and determined that the rate effect of rock strength is mainly caused by the rate effect of cohesion. Qian et al. [10] proposed the Mohr–Coulomb criterion to consider the intensity–strain rate effect for evaluating the dynamic failure characteristics of rocks. Li et al. [11] studied the microscopic mechanism of the strength rate dependence of rock materials, proposed a sliding crack model, and reported that the rate dependence of strength is caused by the velocity dependence of crack propagation velocity and fracture toughness.

During gas reservoir operation, rocks near the cavity are subjected to shear action at different rates owing to the different rates of cyclic injection and gas production. In addition, the pure gas injection or production rate changes according to changes in supply and demand. Therefore, the strength and deformation characteristics of salt rock under different loading rates are crucial to the operational stability of gas storage. In this study, direct shear testing of salt rock under different displacement loading rates is conducted to investigate the rate effects of peak shear strength, residual shear strength, shear dilatability, and the strength parameters of the salt rock. The experimental results are helpful for further study of the failure mechanism of salt rock and the stability of underground salt rock gas reservoirs.

2. Specimens and test device

To reduce the influence of impurities on the test results, the salt rock specimens used herein are high-purity evaporative sedimentary salts occurring in Pakistan under deep burial. These specimens have a dense structure, and the main component is NaCl with a content of more than 95%. The size of the cylindrical specimens is $\phi 50 \times 100$ mm$^2$, which conforms to the test specifications. The samples were divided into four groups of five specimens each. The shear velocity values of the groups were 0.01, 0.03, 0.06, and 0.1 mm/s, and the five specimens were subjected to normal force of 10, 15, 20, 25, and 30 kN, respectively.

The test was conducted using a YZW-100 direct shear test apparatus controlled by an electro-hydraulic servo system. The main performance indices of the system are as follows: the maximum output force of both vertical and horizontal hydraulic cylinders was 1000 kN, and the strokes of the vertical and horizontal pistons were 400 and 300 mm, respectively. The device can record the force and displacement in the normal and shear directions. The specimen installation and loading are shown in Figure 1. The normal stress and shear stress of the direct shear test can be expressed as

$$\sigma_n = \frac{P}{A},$$

$$\tau = \frac{Q}{A},$$

where $P$ is the normal force, $Q$ is the shear force, and $A$ is the cross-sectional area of the specimen.
3. Test results and analysis

3.1. Shear deformation characteristics

3.1.1. Relationship between shear stress and shear displacement. Figure 2a shows the shear stress–shear displacement curve of the salt rock specimens at the loading rate of 0.1 mm/s, the results of which occurred in the following three stages.

(1) At the initial stage of loading, the shear displacement rapidly increased, whereas the shear stress slowly increased. The slope of the curve did not significantly increase until the shear displacement reached a particular value of about 1–2 mm. This stage is mainly designated to close the gaps between the specimen and the shear box and to seal the cracks in the specimen.

(2) With an increase in shear displacement, the slope of the curve increased, and the curve steepened. Then, the slope of the curve gradually became gentle until reaching peak stress, which was caused by dislocation movement and crack propagation in the salt crystals.

(3) After the shear stress peaked, the slope of the curve transitioned from positive to negative, and the shear stress gradually decreased. In this process, the cohesion between the grains of the salt rock continuously decreased until the specimen was destroyed. However, the salt rock specimen still showed a certain bearing capacity, which is the friction between the failure surfaces under the normal force, also known as the residual stress.

Figure 2a shows that the post-peak segment of the shear stress–shear displacement curve flattened as the normal force increased at a certain loading rate. Therefore, the shear failure of the salt rock transitioned from brittle to ductile with an increase in normal force. The shear stress–shear displacement curves at different loading rates are shown in Figure 2b. When the normal force was 30 kN, the form of the shear stress–shear displacement curve of the salt rock was roughly the same as that with an increase in loading rate from 0.01 to 0.1 mm/s. However, the shear resistance of the salt rock samples was improved to some extent, and the peak shear stress increased from 10.67 to 13.03 MPa.

![Figure 2](image)

Figure 2. Force diagram of specimens including shear stress–shear displacement curves: (a) curves at a loading rate of 0.1 mm/s; (b) curves with a normal force of 30 kN

3.1.2. Relationship between normal displacement and shear displacement. The displacement zero point is the moment at which the shear force begins to be applied. The normal displacement is positive when the specimen is compressed. The relationship between the normal and shear displacement is shown in Figure 3. A decrease in normal displacement indicates the occurrence of dilatancy. As indicated in Figure 3a, the salt rock showed different degrees of dilatancy under different normal forces. The normal displacement decreased as the normal force increased, which means that the
dilatancy was inhibited. Figure 3b reflects the influence of the loading rate on the dilatancy characteristics. The normal displacement gradually decreased when the loading rate increased, which indicates that the dilatancy was negatively correlated with the loading rate.

![Figure 3](image)

**Figure 3.** Normal displacement–shear displacement curves: (a) curves at a loading rate of 0.1 mm/s; (b) curves with a normal force of 30 kN

### 3.2. Shear strength characteristic

#### 3.2.1. Peak shear strength.

The peak shear strength $\tau_p$ at different loading rates $\dot{d}$ is shown in Figure 4. Under different normal stresses, the peak shear strength of salt rock increased with the loading rate. Thus, the strength value had a linear relationship with the logarithm of the loading rate.

![Figure 4](image)

**Figure 4.** Shear strength–loading rate curves

#### 3.2.2. Shear strength parameters.

The shear strength of a rock refers to its ability to resist shear failure, which can be expressed by the internal friction angle $\varphi$ and cohesion $c$. The Mohr–Coulomb strength theory holds that when the normal stress is small, a linear relationship exists between the rock shear strength and the normal stress, which can be expressed as

$$\tau = \sigma_n \tan \varphi + c . \quad (3)$$
The shear strength curves of the salt rock at different loading rates are shown in Figure 5. By fitting the normal stress–shear strength relationship shown in the figure with different loading rates, the shear strength parameters of the salt rock samples at different loading rates can be obtained, as shown in Table 1. Figure 6a shows that the cohesion $c$ of the salt rock increased as the loading rate increased, whereas the internal friction angle $\phi$ remained almost constant, as shown in Figure 6b. When the loading rate increased from 0.01 to 0.1 mm/s, the cohesive force $c$ of the salt rock increased from 6.338 to 8.546 MPa at a rate of 33.7%. The internal friction angle changed from 44.348° to 43.601° at a rate of only 1.6%, which can be considered as remaining almost unchanged. This indicates that an increase in the shear strength of salt rock is mainly achieved by increasing the cohesion with the increase in the loading rate.

The shear strength parameters of the Pakistani salt rocks used in this test were compared with those of Chinese salt rocks obtained from Jintan, Jiangsu, and Yunying, Hubei, at the same loading rate of 0.01 mm/s, as shown in Table 1. The cohesion of the Pakistani salt rocks was more than 6 MPa, whereas that of the Chinese salt rocks was 3–4 MPa [4, 5]. The internal friction angle $\phi$ was about 44° for all cases; no significant difference was noted. The purity of the Pakistani salt rock is higher than that of Chinese salt rock; the structure form is much simpler; the grain cohesiveness is higher; and the grain interface impurity is lower. In contrast, the structure of Chinese salt rocks is complex with abundant impurities in the grain interface, which is not conducive for grain bonding. Moreover, the grain size in the Pakistani salt rock is significantly smaller than that of the domestic salt rock, as shown in Figure 6.
You [12] reported that the strength of fine-grained salt rocks is higher than that of coarse-grained salt rock, which is consistent with the results of the present study.

![Fracture morphology of different salt rock types after failure: (a) salt rock from China; (b) salt rock from Pakistan [4]](image)

**Figure 6.** Fracture morphology of different salt rock types after failure: (a) salt rock from China; (b) salt rock from Pakistan [4]

| Salt rock origin | d/mm/s | c/MPa | φ/° |
|------------------|--------|-------|-----|
| Pakistan         | 0.01   | 6.34  | 44.35 |
|                  | 0.03   | 7.47  | 43.96 |
|                  | 0.06   | 8.12  | 43.77 |
|                  | 0.1    | 8.55  | 43.60 |
| Jintan [4]       | 0.01   | 3.16  | 44.7  |
| Yunying [5]      | 0.01   | 4.17  | 42    |

3.2.3. **Discussion on the mechanism of the loading rate effect.** The visco-elastic model [13] shown in Figure 7 can explain the loading rate effect. The model comprises two springs ($E_1$ and $E_2$) and a viscous element ($\eta$). At low strain rates, spring $E_1$ will lose its function owing to the release of the viscous element, and only spring $E_2$ will be subjected to external force. At high strain rates, the external force is borne by spring $E_1$, spring $E_2$, and the viscous element. The external work must be increased to break the material so that the strength of the rock increases with the increase in strain rate.

![Visco-elastic model [13]](image)

**Figure 7.** Visco-elastic model [13]

The propagation and polymerization of inherent cracks in rock material under external forces are the fundamental causes of rock material failure and macroscopic mechanical properties. The crack propagation can be expressed as [11]

$$K_1(t) = k(v)K_1,$$

where $K_1(t)$ is the dynamic stress intensity factor of the material, $v$ is the crack growth rate, $k(v)$ is a function of the crack growth rate, and $K_1$ is the static stress intensity value of the crack tip. Equation (4) shows that with an increase in the loading rate, higher fracture toughness is required to make the microcracks expand. The rate effect of the rock material strength is caused by the crack growth rate and the rate-related characteristics of the rock material fracture toughness.

3.2.4. **Shear failure mode.** The fracture morphology of the specimens at different confining pressures and loading rates after failure is the same as that with no apparent differences, as shown in Figure 8. The fracture morphology is not a plane; rather, it is uneven and gully shaped, as shown in Figure 9. When the failure of the salt rock specimen was removed from the direct shear box, a large number of
salt rock particles were scattered at the failure point. The edge of the section was not completely broken because the grains on both sides of the shear plane underwent plastic deformation owing to excessive pressure under the load and were embedded into each other. Under shear force, the grains of salt rock slide and squeeze against each other to produce such concave and convex gullies, which is similar to the ploughing effect in tribology [14] and can improve the shear strength of the salt rock.

| d (mm/s) | 0.01 | 0.03 | 0.06 | 0.1 |
|---------|------|------|------|-----|
| P (MPa) |
| 10      |      |      |      |     |
| 15      |      |      |      |     |
| 20      |      |      |      |     |
| 25      |      |      |      |     |
| 30      |      |      |      |     |

**Figure 8.** Fracture morphology of salt rock after failure under different actions

**Figure 9.** Friction traces on broken sections

4. Conclusions

In this study, a YZW-100 direct shear testing apparatus was used to conduct direct shear testing on four groups of high-purity Pakistani salt rocks at different loading rates, and the influences of the loading rates on the shear strength and deformation characteristics of rock are analyzed. The main conclusions are given below.
(1) The shear failure mode of the salt rock is ductile; the shear stress–displacement curve is relatively gentle; and the ductility increases with an increase in normal stress.

(2) The influences of the loading rate on the direct shear characteristics of the salt rock are mainly reflected in the shear strength and dilatancy. The shear strength of the salt rock increases and the dilatancy decreases with increasing shear rate.

(3) Based on the Mohr–Coulomb strength theory, the shear strength parameters of salt rocks under different shear displacement rates are obtained. When the shear rate increases from 0.01 to 0.1 mm/s, the cohesion $c$ significantly increases from 6.34 to 8.55 MPa, representing an increase of 33.7%. The value of the internal friction angle $\phi$ changed from 44.35° to 43.6°, indicating almost no change. The effect of the loading rate on the strength of the salt rock is mainly realized by increasing the cohesion. Compared with domestic salt rocks containing more impurities, the crystal size of the Pakistani high purity-salt rock is smaller, and the shear strength is higher.

(4) The shear fracture surface of the salt rock is not smooth, which is attributed to grain squeezing and friction under the action of the load. Increasing the ploughing effect improves the shear strength of the salt rock.

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