Experimental study on shear mechanical properties of through-step joints under direct shear

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Abstract

In this study, direct shear tests were carried out on artificial rock mass specimens with single-ladder, single-rectangular, and double-rectangular step joints. Consequently, the shear strength, cohesive force \( c \), internal friction angle \( \phi \), and crack shape of specimens with these through-step joints were analyzed, in order to understand the influence of the shape of the through-step joint on their direct shear mechanical properties. The results of the investigation were as follows: (1) Under the same normal stress, any increases in the height \( h \) of the step joint caused an initial-increase–decrease in the shear strengths of specimens with single-ladder and double-rectangular step joints, with a type-W variation pattern for the specimens with single-rectangular step joint. More essentially, when normal stress and \( h \) were constant, the shear strength of specimens with a single-ladder step joint was the greatest, followed by specimens with a double-rectangular step joint, whereas that for specimens with a single-rectangular step joint was the least. (2) For specimens with a single-ladder step joint, a small length of the bottom of the step joint with a large length of the rock bridge allowed \( c \) to dominantly influence the specimen shear strength. Conversely, a large length of the bottom of the step joint with a small length of the rock bridge caused \( \phi \) to play a key role in the specimen shear strength. For specimens with a single-rectangular step joint, when the length of the top of the step joint and that of the rock bridge were large, \( c \) had the dominant influence on the specimen. Otherwise, when the length of the top of the step joint and that of the rock bridge were small, \( \phi \) had the major influence on the specimen shear strength. (3) Furthermore, given a small \( h \) and low normal stress, specimens with a single-ladder step joint mainly experienced shear failure, whereas specimens with single-rectangular and double-rectangular step joints mainly generated extrusion milling in the step joints. Any increases in \( h \) caused specimens with the three types of step joints to have oblique cracks at the bottom and apex points of the step joint. The number of oblique cracks was expected to increase with greater normal stress.

1. Introduction

Actual engineering rock mass damage often depends on the distribution law and shear strength characteristics of the joint plane. Indeed, this relation justifies why the joint plane's direct shear mechanical properties have always been the focus of rock mechanics research.

Among those best exemplified include Yang & Chiang (2000), Jafari et al. (2003), Xue et al. (2003), Ghazvinian et al. (2010), Shen & Zhang (2010), Mohammad et al. (2012), Atapour & Moosavi (2013), Bahaaddini et al. (2013), He et al. (2014), Huang et al. (2014), Lee et al. (2014), Bahaaddini et al. (2015), Jahanian et al. (2015), Bahaaddini et al. (2016), Bahaaddini (2017), Mahdi Niktabar et al. (2017), Gutiérrez-Ch et al. (2018), Tian et al. (2018), and Zhang et al. (2019), who conducted tests and numerical simulation on the direct shear mechanical properties of joint planes with a serrated shape. Additionally, Bai et al. (1999), Hu et al. (2011), Zhou et al. (2015), Yang et al. (2019), and Cui (2019) carried out direct shear tests on joint planes with a straight shape.
In actual engineering rock mass, the shape of a joint plane may be serrated, straight, step type, or rectangular. The first two types are common topics of research studies involving the direct shear mechanical properties of joint planes, whereas studies for stepped or rectangular joint planes have been relatively rare. For example, Huang et al. (2016) used 2D particle flow code simulation to investigate the influence of the height-to-length ($H/L$) ratio in a rock step on shear deformation and strength for through-going discontinuity, whereas Kwon et al. (2010) analyzed the shear behavior of rectangular asperities on rock joints.

This study centers on direct shear tests carried out on artificial rock mass specimens containing single-ladder, single-rectangular, and double-rectangular step joints. It gives details on analyses of the shear strength, cohesive force ($c$), internal friction angle ($\varphi$), and crack shape of specimens in each through-step joint, and describes how the through-step joint shape affects the direct shear mechanical properties of the artificial rock mass specimen.

2. Experimental Setup

2.1. Specimen preparation

Cement mortar was the model material used in the test. The strength of the cement material was 32.5 MPa, and the sand was mainly quartz sand. A specimen with a joint plane (dimension: 10 cm × 10 cm × 10 cm) was prepared by pouring and casting the cement mortar (water–cement ratio: 0.65) into a mold. Approximately 2 h after the vibration, a 1-mm-thick pre-made thin plastic piece was inserted into the specimen, and then pulled out vertically to form an empty joint in the specimen after about 12 h. Figure 1 displays a model diagram of the artificial jointed rock mass specimen with a double-rectangular step-joint plane.

2.2. Test instruments

Subsequently, specimens with through-step joints were placed on a direct shear tester shown in Fig. 2.

2.3. Test sequence

(1) Uniaxial compression test of intact specimens

Three intact specimens were subjected to a uniaxial compression test at a 1-kN/s loading rate, to obtain their uniaxial compressive strength ($\sigma_c$), which provides the basis for determining normal pressure in the direct shear test. Figure 3 displays the uniaxial compressive stress–strain curve for each specimen.

Accordingly, the specimens displayed uniaxial compressive strengths of 15.335, 15.289, and 14.785 MPa, averaged at 15.136 MPa.

(2) Shear test of specimens with a stepped joint plane
Next, the three intact specimens with a stepped joint plane were subjected to a shear stress, yielding four categories of normal stress: $0.2\sigma_c$, $0.3\sigma_c$, $0.4\sigma_c$, and $0.5\sigma_c$ corresponding to 3.03, 4.54, 6.05, and 7.57 MPa. The shear test under each normal stress was repeated with the specimens, taking the average of their shear strength values. In this test, the normal and tangential loading rates were both 1 kN/s.

### 2.4. Shear test group

#### 2.4.1. Shear test group of intact specimens

The three intact specimens were labeled with respect to the four categories of normal stress above, as follows. (i) normal stress: $0.2\sigma_c$ (3.03 MPa); specimen number: # F0.2-WS-1, # F0.2-WS-2, and # F0.2-WS-3; (ii) normal stress: $0.3\sigma_c$ (4.54 MPa); specimen number: # F0.3-WS-1, # F0.3-WS-2, and # F0.3-WS-3; (iii) normal stress: $0.4\sigma_c$ (6.05 MPa); specimen number: # F0.4-WS-1, # F0.4-WS-2, and # F0.4-WS-3; (iv) normal stress: $0.5\sigma_c$ (7.57 MPa); specimen number: F0.5-WS-1, # F0.5-WS-2, and # F0.5-WS-3.

#### 2.4.2. Shear test of specimens with a single-ladder step joint

Figure 4 shows a shear test diagram for specimens with a single-ladder step joint.

In the figure, parameters $l_1$, $l_2$, and $h$ indicate the respective lengths of the bottom and top of the step joint, and its height.

Two scenarios were considered for this test: (1) at a fixed value of $l_1 = l_2 = 5.0$ cm, $h = 1.0, 1.5, 2.0, 2.5$, and 3.0 cm; (2) at a fixed value of $h = 2$ cm, $l_1 = 2.0, 3.0, 4.0, 5.0, 6.0, 7.0$, and 8.0 cm. The test groups are shown in Table 1.
Table 1
Shear test groups of artificial jointed rock mass specimens with a single-ladder step joint.

| Study | $l_1$ / cm | $l_2$ / cm | $h$ / cm | Normal stress / MPa | Amount of specimens |
|-------|------------|------------|----------|--------------------|--------------------|
| 1     | 5.0        | 5.0        | 1.0      | 3.03, 4.54, 6.05, 7.57 | 12                 |
| 2     | 5.0        | 5.0        | 1.5      | 3.03, 4.54, 6.05, 7.57 | 12                 |
| 3     | 5.0        | 5.0        | 2.0      | 3.03, 4.54, 6.05, 7.57 | 12                 |
| 4     | 5.0        | 5.0        | 2.5      | 3.03, 4.54, 6.05, 7.57 | 12                 |
| 5     | 5.0        | 5.0        | 3.0      | 3.03, 4.54, 6.05, 7.57 | 12                 |
| 6     | 2.0        | 8.0        | 2.0      | 3.03, 4.54, 6.05, 7.57 | 12                 |
| 7     | 3.0        | 7.0        | 2.0      | 3.03, 4.54, 6.05, 7.57 | 12                 |
| 8     | 4.0        | 6.0        | 2.0      | 3.03, 4.54, 6.05, 7.57 | 12                 |
| 9     | 6.0        | 4.0        | 2.0      | 3.03, 4.54, 6.05, 7.57 | 12                 |
| 10    | 7.0        | 3.0        | 2.0      | 3.03, 4.54, 6.05, 7.57 | 12                 |
| 11    | 8.0        | 2.0        | 2.0      | 3.03, 4.54, 6.05, 7.57 | 12                 |

2.4.3. Shear test of specimens with a single-rectangular step joint

Figure 5 displays a shear test diagram for specimens with a single-rectangular step joint.

In the figure, $l_3$ and $l_4$ respectively indicate distances from the left lower corner of the single-rectangular step joint to the left side of the specimen and from the right lower corner of the single-rectangular step joint to the right side of the specimen. Additionally, $l_5$ indicates the length of the top of the single-rectangular step joint, and $h$ indicates the step-joint height.

Three cases were considered for this test: (1) at fixed values of $l_3 = l_4 = 4.0$ cm and $l_5 = 2.0$ cm, $h = 1.0, 1.5, 2.0, 2.5,$ and $3.0$ cm; (2) at fixed values of $l_3 = l_4$ and $h = 2.0$ cm, $l_5 = 2.0, 4.0, 6.0,$ and $8.0$ cm; (3) at fixed values of $l_5 = 2.0$ cm and $h = 2.0$ cm, $l_3$ and $l_4$ were variable. The test groups are shown in Table 2.
Table 2
Shear test groups of artificial jointed rock mass specimens with a single-rectangular step joint.

| Study | $l_3$/ cm | $l_4$/ cm | $l_5$/ cm | h/cm | Normal stress / MPa | Amount of specimens |
|-------|--------|--------|----------|-----|--------------------|---------------------|
| 1     | 4.0    | 4.0    | 2.0      | 1.0 | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 2     | 4.0    | 4.0    | 2.0      | 1.5 | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 3     | 4.0    | 4.0    | 2.0      | 2.0 | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 4     | 4.0    | 4.0    | 2.0      | 2.5 | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 5     | 4.0    | 4.0    | 2.0      | 3.0 | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 6     | 1.0    | 1.0    | 8.0      | 2.0 | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 7     | 2.0    | 2.0    | 6.0      | 2.0 | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 8     | 3.0    | 3.0    | 4.0      | 2.0 | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 9     | 2.0    | 6.0    | 2.0      | 2.0 | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 10    | 3.0    | 5.0    | 2.0      | 2.0 | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 11    | 5.0    | 3.0    | 2.0      | 2.0 | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 12    | 6.0    | 2.0    | 2.0      | 2.0 | 3.03, 4.54, 6.05, 7.57 | 12                  |

2.4.4. Shear test of specimens with a double-rectangular step joint

Figure 6 shows a shear diagram for specimens with a double-rectangular step joint.

In the figure, $l_6$ and $l_7$ indicate the respective lengths of the bottom and top of the step joint, and $h$ is its height.

In the test, the value of $l_6 = l_7 = 2.0$ cm was fixed, and $h = 1.0, 1.5, 2.0, 2.5$, and 3.0 cm. The test groups are shown in Table 3.
Table 3
Shear test groups of artificial jointed rock mass specimens with a double-rectangular step joint.

| Study | \( l_6 / \text{cm} \) | \( l_7 / \text{cm} \) | \( h / \text{cm} \) | Normal stress / MPa | Amount of specimens |
|-------|-----------------------|-----------------------|-------------------|---------------------|---------------------|
| 1     | 2.0                   | 2.0                   | 1.0               | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 2     | 2.0                   | 2.0                   | 1.5               | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 3     | 2.0                   | 2.0                   | 2.0               | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 4     | 2.0                   | 2.0                   | 2.5               | 3.03, 4.54, 6.05, 7.57 | 12                  |
| 5     | 2.0                   | 2.0                   | 3.0               | 3.03, 4.54, 6.05, 7.57 | 12                  |

3. Shear Test Results For Intact Specimens

Figure 7 and Table 4 display the shear-stress–shear-displacement curves and shear strengths, respectively, of intact specimens.

Table 4
Shear strengths of intact specimens.

| Normal stress / MPa | No. of specimen | Shear strength / MPa | Average value of shear strength / MPa |
|---------------------|-----------------|----------------------|---------------------------------------|
| 3.03 (0.2\( \sigma_c \)) | # F0.2-W-S-1   | 6.953                | 7.217                                 |
|                     | # F0.2-W-S-2   | 6.839                |                                       |
|                     | # F0.2-W-S-3   | 7.858                |                                       |
| 4.54 (0.3\( \sigma_c \)) | # F0.3-W-S-1   | 8.243                | 8.196                                 |
|                     | # F0.3-W-S-2   | 8.148                |                                       |
|                     | # F0.3-W-S-3   | 5.668                |                                       |
| 6.05 (0.4\( \sigma_c \)) | # F0.4-W-S-1   | 9.388                | 9.388                                 |
|                     | # F0.4-W-S-2   | 11.818               |                                       |
|                     | # F0.4-W-S-3   | 7.48                 |                                       |
| 7.57 (0.5\( \sigma_c \)) | # F0.5-W-S-1   | 9.973                | 9.622                                 |
|                     | # F0.5-W-S-2   | 8.404                |                                       |
|                     | # F0.5-W-S-3   | 10.49                |                                       |
Accordingly, the specimen shear strength increased gradually with normal stress from $0.2\sigma_c$ (3.03 MPa) to $0.5\sigma_c$ (7.57 MPa). More particularly, such an increase in shear strength was visible from $0.2\sigma_c$ (3.03 MPa) to $0.4\sigma_c$ (6.05 MPa) and less noticeable from $0.4\sigma_c$ (6.05 MPa) to $0.5\sigma_c$ (7.57 MPa).

### 4. Shear Test Results Of Specimens With A Single-ladder Step Joint

#### 4.1. Analysis of shear strength

Figure 8 displays the shear strengths of specimens with a single-ladder step joint when $l_1 = l_2 = 5.0$ cm and $h = 1.0, 1.5, 2.0, 2.5$, and $3.0$ cm.

In this figure, the shear strength tended to increase and then decrease, reaching a maximum value at $h = 2.5$ cm.

Figure 9 shows the shear strengths of specimens with a single-ladder step joint, given a fixed value of $h = 2$ cm and a variable $l_1 = 2.0, 3.0, 4.0, 5.0, 6.0, 7.0$, and $8.0$ cm.

Obviously, the specimen shear strength decreased gradually with further increases in $l_1$.

#### 4.2. Analysis of shear strength parameters

To obtain the values of cohesive force $c$ and internal friction angle $\varphi$, the Mohr–Coulomb strength criterion, defined in Eq. (1) below, was used for analysis of the shear test results of specimens with a single step joint:

$$
\tau = c + \sigma \tan \varphi.
$$

Here, the symbols $\tau$ and $\sigma$ represent shear strength and normal stress, respectively.

Figure 10 illustrates the variation of $c$ and $\varphi$ with $h$ in specimens at $l_1 = l_2 = 5.0$ cm.

Apparently, as $h$ increased from 1.0 to 3.0 cm, $c$ decreased initially, increased, and then eventually decreased, reaching a maximum value at $h = 2.0$ cm. There was no noticeable change in the value of $\varphi$.

Figure 11 shows the variation of $c$ and $\varphi$ with $l_1$ in specimens, assuming a fixed value of $h = 2.0$ cm.

Here, $c$ decreased gradually. For $\varphi$, as with Fig. 10, the change was not obvious.

Figure 12 displays a diagram of the rock bridge in specimens with a single-ladder step joint. Here when $l_1$ increases gradually, the length of the rock bridge in the direct shear direction of the specimen should also decrease gradually.

According to the figure, with longer $l_1$, the length of the rock bridge decreased gradually, resulting in a similar gradual reduction in shear strength of the specimen. Moreover, as the length of the rock bridge
changed, the dominant role of $c$ and $\varphi$ in the specimen shear strength would likewise change. Assuming a small $l_1$ and a longer rock bridge, $c$ would play a major role in the shear strength; alternatively, assuming a large $l_1$ and a shorter rock bridge, $\varphi$ would play a major role in the shear strength.

### 4.3. Damage morphology

Figure 13 displays the damage morphology in specimens with a single-ladder step joint after being subjected to the shear test, assuming fixed $l_1 = l_2 = 5.0$ cm and variable $h$.

Note that when $h = 1.0$ cm and the normal stress was 3.03 MPa, there were hardly any cracks generated with the specimen breaking, eventually causing direct shear failure. With an increase in normal stress, oblique cracks appeared at the bottom and apex points of the step joints, with more likelihood of occurrence at the bottom point, mainly because of a gradual increase in bending moment caused by greater normal stress, along with the shear forces. Furthermore, when $h = 1.5$, 2.0, 2.5, and 3.0 cm and the normal stress was 3.03 MPa, oblique cracks appeared at the bottom point but were hardly generated at the apex point; nevertheless, there was more likelihood of an oblique crack appearing at the apex point than at the bottom point of the step joint, with an increase in normal stress.

Figures 14 and 15 display the post-shear-test damage morphology in specimens with a single-ladder step joint under normal stresses of 3.03 and 7.57 MPa, respectively, given fixed $h = 2$ cm and variable $l_1 = 2.0$, 3.0, 4.0, 5.0, 6.0, 7.0, and 8.0 cm.

At 3.03 MPa, when $l_1$ was small, oblique cracks occurred at the bottom and apex points of the step joint, causing the surface of the specimen to partially fall off. Similarly, when $l_1$ was large, oblique cracks were generated at the bottom and apex points; nevertheless, the number of cracks and the degree of coalescence were not as good as when $l_1$ was small.

Moreover, for specimens with a small $l_1$, the number of cracks before specimen breakage would increase with greater normal stress. Otherwise, for those with large $l_1$, the number of cracks before specimen breakage would decrease with an increase in normal stress, although such a decline might not be significant.

On the basis of Figs. 14 and 15, a smaller $l_1$ would generate more cracks before the specimen breaks, with a better coalescence degree among the cracks. Moreover, the frictional sliding force in these cracks would induce an increase in the specimen shear strength.

### 5. Shear Test Results Of Specimens With A Single-rectangular Step Joint

#### 5.1. Analysis of shear strength
Figure 16 displays the shear strengths of specimens with a single-rectangular step joint, given \( l_3 = l_4 = 4.0 \text{ cm}, l_5 = 2.0 \text{ cm}, \) and \( h = 1.0, 1.5, 2.0, 2.5, \) and \( 3.0 \text{ cm}. \)

Under different normal stresses, the shear strength of specimens with a single-rectangular step joint followed a type-W variation with \( h \), reaching a minimum at \( h = 2.5 \text{ cm}. \) Generally, the specimen shear strength increased with normal stress.

Figure 17 displays the shear strengths of the same specimens, given \( l_3 = l_4 \) and \( h = 2.0 \text{ cm}, \) and \( l_5 = 2.0, 4.0, 6.0, \) and \( 8.0 \text{ cm}. \)

Accordingly, Fig. 18 shows a diagram of the rock bridge in specimens with a single-rectangular step joint.

Apparently, a decrease in \( l_5 \) caused a corresponding gradual decrease in the length of the rock bridge and the shear strength of the specimen.

Figure 19 displays the shear strengths in specimens with a single-rectangular step joint, assuming fixed values of \( l_5 = 2.0 \text{ cm} \) and \( h = 2.0 \text{ cm}, \) and variable \( l_3 \) and \( l_4 \).

Under different normal stresses, the specimen shear strength varied with an increase in \( l_3 \), reaching its maximum value at \( l_3 = 5.0 \text{ cm}, \) under normal stresses of \( 3.03 \) and \( 4.54 \text{ MPa}. \) Likewise, at \( 6.05 \) and \( 7.57 \text{ MPa}, \) the specimen shear strength was maximum at \( l_3 = 4.0 \text{ cm} \) and \( l_3 = 2.0 \text{ cm}, \) respectively.

### 5.2. Analysis of shear strength parameters

To obtain values for \( c \) and \( \phi \), the shear test results of specimens with a single-rectangular step joint were analyzed using the Mohr–Coulomb strength criterion. Figure 20 shows the respective values of the two parameters given \( l_3 = l_4 = 4.0 \text{ cm}, l_5 = 2.0 \text{ cm}, \) and \( h = 1.0, 1.5, 2.0, 2.5, \) and \( 3.0 \text{ cm}. \)

Note that as \( h \) increased from \( 1.0 \) to \( 3.0 \text{ cm}, \) \( c \) decreased gradually whereas \( \phi \) increased gradually.

Figure 21 displays the values of \( c \) and \( \phi \) in specimens with \( l_3 = l_4 \) and \( h = 2.0 \text{ cm} \) and \( l_5 = 2.0, 4.0, 6.0, \) and \( 8.0 \text{ cm}. \)

Obviously, an increase in \( l_5 \) caused the length of the rock bridge to increase gradually, \( c \) to decrease gradually, and \( \phi \) to decrease initially and then increase. When both \( l_5 \) and the length of the rock bridge were large, \( c \) would mainly influence the shear strength. Alternatively, when both \( l_5 \) and the length of the rock bridge were small, \( \phi \) would mainly affect the shear strength.

Figure 22 shows the variation of \( c \) and \( \phi \) with \( l_3 \) in specimens with a single-rectangular step joint, assuming \( l_5 = 2.0 \text{ cm} \) and \( h = 2.0 \text{ cm}. \)

Apparently, an increase in \( l_3 \) did not cause any variation in the length of the rock bridge. However, the values of \( c \) and \( \phi \) of the specimens varied: \( c \) reached its minimum and \( \phi \) its maximum at \( l_3 = 4.0 \text{ cm}; \)
conversely, $c$ reached its maximum and $\varphi$ its minimum at $l_3 = 5.0$ cm.

### 5.3. Damage morphology

Figure 23 displays the post-shear-test damage morphology in specimens with a single-rectangular step joint, assuming variable $h$, $l_3 = l_4 = 4.0$ cm, and $l_5 = 2.0$ cm.

When $h = 1.0$ cm and the normal stress was 3.03 MPa, a crushing damage mainly occurred in the rectangular step joint. With an increase in normal stress, the crushing damage further developed in the rectangular step joint, but with less pronounced oblique cracks initiating in the upper-right corner of the joint. Given the same normal stress, a higher $h$ would cause the specimen to develop more oblique cracks in the upper-right and lower-left corners of the rectangular step joint. In particular, it was easier for the oblique cracks to connect the upper-left and lower-right corners. These cracks would more likely appear with greater normal stress.

Figure 24 shows the post-shear-test damage morphology in specimens with a single-rectangular step joint, given $l_3 = l_4$, $h = 2.0$ cm, and variable $l_5$.

Under the same normal stress, as $l_5$ decreased from 8.0 to 2.0 cm, less cracks were generated before the failure of the specimen, the frictional sliding force in these cracks weakened, and the shear strength of the specimen decreased gradually. With greater normal stress and a fixed value of $l_5$, the number of cracks generated before specimen breakage increased gradually, and the frictional sliding force in these cracks, along with the specimen shear strength, increased gradually.

Figure 25 displays the post-shear-test damage morphology in specimens with a single-rectangular step joint, given $l_5 = 2.0$ cm, $h = 2.0$ cm, and variable $l_3$.

Under the same normal stress, assuming $l_5 = 2.0$ cm and $h = 2.0$ cm, and $l_3 = 2.0, 3.0, 4.0, 5.0, 6.0$ cm, there was no obvious difference in crack type before specimen breakage. However, when $l_5 = 2.0$ cm, $h = 2.0$ cm, and $l_3$ was fixed, an increase in normal stress would cause the oblique cracks to generate quite easily in the upper-right corner of the rectangular step joint before specimen failure. The number of cracks, the frictional sliding force among these cracks, and the shear strength of the specimen all increased gradually.

### 6. Shear Test Results Of Specimens With A Double-rectangular Step Joint

#### 6.1. Analysis of shear strength

Figure 26 shows the shear strength in specimens with a double-rectangular step joint, given $l_6 = l_7 = 2.0$ cm and $h = 1.0, 1.5, 2.0, 2.5, 3.0$ cm.
Under different normal stresses, the specimen shear strength increased initially and then decreased with higher $h$, reaching its maximum value at $h = 2.0$ cm. Thus, with variable $h$, an increase in the normal stress of the specimens would tend to increase their shear strength as well.

### 6.2. Analysis of shear strength parameters

As in the previous sections, the Mohr–Coulomb strength criterion was used for analysis of the shear test results of specimens with a double-rectangular step joint, in order to determine the values of $c$ and $\varphi$.

Figure 27 shows the results for the $c$ and $\varphi$ values of the specimens, where $l_6 = l_7 = 2.0$ cm and $h = 1.0, 1.5, 2.0, 2.5,$ and $3.0$ cm.

Evidently, as $h$ increased from 1.0 to 3.0 cm, $c$ increased initially and then decreased, reaching its maximum at $h = 2.5$ cm. The results for $\varphi$ were variable; it reached its maximum value at $h = 2.0$ cm and its minimum at $h = 2.5$ cm.

### 6.3. Damage morphology

Figure 28 reflects the post-shear-test damage morphology of the same specimens at $l_6 = l_7 = 2.0$ cm and variable $h$.

Under normal stress values of 3.03, 4.54, 6.05, and 7.57 MPa, when $h = 1.0$ cm, a crushing damage mainly occurred in the rectangular step joint. As $h$ increased gradually from 1.5 cm under the same normal stress, an oblique crack appeared easily at the upper corner of the rectangular step joint, and triggered a likelihood of the occurrence of oblique cracks in the direction between the upper-left and lower-right corners of each rectangular step joint, and oblique cracks in the direction between the upper-right corner of the left-rectangular step joint and the lower-left corner of the right-rectangular step joint. These cracks were more likely to occur with higher normal stress.

### 7. Comparative Analysis Of The Shear Strength Of Specimens With Three Kinds Of Step Joint

Accordingly, the shear strengths of specimens with a single-ladder step joint, a single-rectangular step joint, and a double-rectangular step joint were compared for $h = 2$ cm. Three scenarios were considered for specimens with a single-ladder step joint: (1) $h = 2$ cm, $l_1 = 2.0$ cm; (2) $h = 2$ cm, $l_1 = 4.0$ cm; (3) $h = 2$ cm, $l_1 = 6.0$ cm. Likewise, three cases were allocated for specimens with a single-rectangular step joint: (1) $h = 2$ cm, $l_3 = 2.0$ cm; (2) $h = 2$ cm, $l_3 = 4.0$ cm; (3) $h = 2$ cm, $l_3 = 6.0$ cm. Only the case $h = 2$ cm and $l_6 = l_7 = 2.0$ cm was taken for specimens with a double-rectangular step joint. The comparison results are provided in Fig. 29.

Apparently, specimens with a single-ladder step joint demonstrated the highest shear strength, mainly because the length of the rock bridge in the straight shear direction is the highest. The shear strength of specimens with a double-rectangular step joint was higher than that of specimens with a single-
rectangular step joint. Under the same normal stress, specimens with a double-rectangular step joint had a larger number of cracks before breakage than those with a single-ladder step joint. Moreover, the rock bridge in specimens with a double-rectangular step joint in the straight shear direction was longer than that in specimens with a single-ladder step joint.

8. Conclusion

(1) On one hand, when the lengths of the top and bottom of the step joint for specimens with a single-ladder step joint are assumed to be constant, any increase in $h$ would cause a corresponding initial increase and subsequent decrease in the shear strength, a tendency for $c$ to decrease–increase–decrease, and varying values of $\varphi$. On the other hand, when $h$ is assumed to be constant, both the specimen shear strength and $c$ would decrease gradually with any increase in the length of the bottom of the step joint, along with varying $\varphi$ values. Moreover, when the length of the rock bridge is varied, the dominant influence of $c$ and $\varphi$ on the specimen shear strength would correspondingly change. For instance, assuming that the length of the bottom of the step joint is small and that for the rock bridge is large, $c$ would mainly affect the shear strength of the specimen. Conversely, when the length of the bottom of the step is large and that of the rock bridge is small, $\varphi$ would exhibit a dominant influence on the specimen shear strength.

(2) For specimens with a single-ladder step joint, a small $h$ and a relatively low normal stress would make it difficult for cracks to generate in the specimens before their breakage, resulting in direct shear failure. Moreover, with a further increase in normal stress, oblique cracks would tend to appear at the bottom and apex points of the step joint. When the specimen is subjected to low normal stress from $h = 1.5$ cm to $h = 3.0$ cm, oblique cracks would more likely occur at the bottom point of the step joint rather than at the apex point. Nevertheless, any increase in normal stress would allow oblique cracks to appear at the apex point of the step. Furthermore, under the condition of low normal stress, a constant $h$, and a small $l_1$, oblique cracks would tend to appear at the bottom and apex points of the step joint, increasing with higher normal stress values. Accordingly, assuming a large $l_1$, oblique cracks would begin generating at the bottom and apex points of the step joint, but the number of cracks and the degree of coalescence would not be as good as when $l_1$ is small.

(3) For specimens with a single-rectangular step joint under different normal stresses, any increase in $h$ would produce a type-W variation pattern with $h$ of the specimen shear strength, a tendency for $c$ to decrease gradually, and a tendency for $\varphi$ to increase gradually. At constant $h$, any decrease in $l_5$ would cause a corresponding gradual decrease in the length of the rock bridge, a gradual decrease in both the specimen shear strength and its $c$, and an initial-increase–decrease tendency for the value of $\varphi$. When both $l_5$ and the length of the rock bridge have large values, $c$ would dominantly influence the shear strength; however, when both $l_5$ and the length of the rock bridge are small, $\varphi$ would have a key influence on the specimen shear strength. When both $h$ and $l_5$ are constant, any increases in $l_5$ would not cause any
change in the length of the rock bridge, but would produce varying shear strength, $c$, and $\varphi$ in the specimens.

(4) For specimens with a single-rectangular step joint, small values of $h$ and low normal stress would allow a crushing damage to mainly occur in the step joint. Any further increases in the normal stress would allow, in addition to the crushing damage, the appearance of less pronounced oblique cracks in the upper-right corner of the step joint. Under the same normal stress, a higher $h$ would entertain the likelihood of oblique cracks appearing in the upper-right and lower-left corners of the rectangular step joint. Oblique cracks would easily form to connect the upper-left and lower-right corners of the step joint. Given a constant value of $h$ and normal stress, an increase in $l_5$ would lead to more cracks being generated in the specimen before failure, with greater frictional sliding force developing in these cracks. Moreover, if $h$, $l_5$, and normal stress are assumed to be constant, then an increase in $l_3$ would not yield any noticeable difference in the crack type during specimen failure.

(5) For specimens with a double-rectangular step joint subjected to the same normal stress, any increase in $h$ would cause an initial-increase–decrease tendency for both the shear strength and $c$, and a varying $\varphi$. For small $h$, a crushing damage would mainly occur in the rectangular step joint. Moreover, under the same normal stress, an increase in $h$ allows an oblique crack to form easily at the upper corner of the rectangular step joints. In addition, oblique cracks would more likely appear in the direction between the upper-left and lower-right corners of each rectangular step joint, and in the direction between the upper-right corner of the left-rectangular step joint and the lower-left corner of the right-rectangular step joint. (6) Furthermore, a constant $h$ would cause maximum shear strength in specimens with a single-ladder step joint, followed by specimens with a double-rectangular step joint. By contrast, the shear strength of specimens with a single-rectangular step joint would be the least.

9. Declarations

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Figures
Figure 1

Diagram of artificial jointed rock mass specimens with a double-rectangular step joint.

Figure 2

Direct shear tester.
Figure 3

Uniaxial compression stress–strain curves of intact specimens.
Figure 4

Shear test diagram for specimens with a single-ladder step joint (unit: cm).
Figure 5

Shear test diagram for specimens with a single-rectangular step joint (unit: cm).
Figure 6
Shear test diagram for specimens with a double-rectangular step joint (unit: cm).
Figure 7

Shear stress vs. shear displacement curves of intact specimens.
Figure 8

Shear strengths of specimens with a single-ladder step joint with fixed $l_1 = l_2 = 5.0$ cm and variable $h$. 

- normal stress is 3.03 MPa
- normal stress is 4.54 MPa
- normal stress is 6.05 MPa
- normal stress is 7.57 MPa
Figure 9

Shear strengths of specimens with a single-ladder step joint with fixed $h = 2.0 \text{ cm}$ and variable $l_1$. 
Figure 10

Variation of $c$ and $\varphi$ with $h$ in specimens with a single-ladder step joint, given $l_1 = l_2 = 5.0$ cm.

Figure 11

Variation of $c$ and $\varphi$ with $l_1$ in specimens with a single-ladder step joint, given fixed $h = 2.0$ cm.
Figure 12

Diagram of the rock bridge in specimens with a single-ladder step joint.
Figure 13

Post-shear-test damage morphology in specimens with a single-ladder step joint, given fixed $l_1 = l_2 = 5.0$ cm and variable $h$. 
Figure 14

Post-shear-test damage morphology in specimens with a single-ladder step joint under a normal stress of 3.03 MPa, given $h = 2.0$ cm and variable $l_1$.

Figure 15
Post-shear-test damage morphology in specimens with a single-ladder step joint under a normal stress of 7.57 MPa, given fixed $h = 2.0$ cm and variable $l_1$.

**Figure 16**

Variation of shear strength with $h$ in specimens with a single-rectangular step joint, given $l_3 = l_4 = 4.0$ cm and $l_5 = 2.0$ cm.
Figure 17

Variation of shear strength with $l_5$ in specimens with a single-rectangular step joint, given $l_3 = l_4$ and $h = 2.0$ cm.
Figure 18

Diagram of the rock bridge in specimens with a single-rectangular step joint.
Figure 19

Variation of shear strength with $l_3$ in specimens with a single-rectangular step joint, given $l_5 = 2.0$ cm and $h = 2.0$ cm.

Figure 20

Variation of $c$ and $\varphi$ with $h$ in specimens with a single-rectangular step joint, given $l_3 = l_4 = 4.0$ cm and $l_5 = 2.0$ cm.

Figure 21

Variation of $c$ and $\varphi$ with $l_5$ in specimens with a single-rectangular step joint, given $l_3 = l_4$ and $h = 2.0$ cm.
Figure 22

Variation of $c$ and $\phi$ with $l_3$ in specimens with a single-rectangular step joint, given $l_5 = 2.0$ cm and $h = 2.0$ cm.
Figure 23

Post-shear-test damage morphology in specimens with a single-rectangular step joint, given $l_3 = l_4 = 4.0$ cm, $l_5 = 2.0$ cm, and variable $h$.  

| Figure | Normal stress is 3.03 MPa | Normal stress is 4.54 MPa | Normal stress is 6.05 MPa | Normal stress is 7.57 MPa |
|--------|---------------------------|---------------------------|---------------------------|---------------------------|
| (a) $h = 1.0$ cm | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) |
| (b) $h = 1.5$ cm | ![Image](image5.png) | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) |
| (c) $h = 2.0$ cm | ![Image](image9.png) | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| (d) $h = 2.5$ cm | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) | ![Image](image16.png) |
| (e) $h = 3.0$ cm | ![Image](image17.png) | ![Image](image18.png) | ![Image](image19.png) | ![Image](image20.png) |
Figure 24

Post-shear-test damage morphology in specimens with a single-rectangular step joint, given $l_3 = l_4$, $h = 2.0$ cm, and variable $l_5$. 
Figure 25

Post-shear-test damage morphology in specimens with a single-rectangular step joint, given \( l_5 = 2.0 \text{ cm}, \) \( h_3 = 2.0 \text{ cm}, \) and variable \( l_3. \)
Figure 26

Variation of shear strength with $h$ in specimens with a double-rectangular step joint, given $l_6 = l_7 = 2.0$ cm.

Figure 27

Variation of $c$ and $\varphi$ with $h$ in specimens with a double-rectangular step joint, given $l_6 = l_7 = 2.0$ cm.
Figure 28

Post-shear-test damage morphology in specimens with a double-rectangular step joint, given $l_6 = l_7 = 2.0$ cm and variable $h$. 
Figure 29

Comparison results of the shear strength in specimens with three kinds of step joint.