Numerical analysis on the reinforcement design of a granular strongly weathered rock slope based on in-situ direct shear test

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Abstract. It is difficult in the intact sampling of the granular strongly weathered rock of a slope by bench excavation, which will in turn influence the strength test results. In order to provide more accurate design parameters for the slope, its rock shear strength is analyzed by in-situ direct shear test, then the slope reinforced with different anchor frame beams are simulated by finite element method based on the strength parameters obtained from the in-situ direct shear test. The results show that the strength parameters of the granular strongly weathered rock are \( c=75.69 \) kPa and \( \phi=35.23^\circ \). Reinforced with 1 ~ 4 layers of anchor frame beams, the maximum lateral displacement of the slope can be reduced by 30%, 47.6%, 53.5% and 53.5% compared with that of the unreinforced slope, respectively, which means that the deformation of the slope decreases with the increase of anchor frame beams. However, the fourth-layer anchor frame beam is not efficiency in the reinforcement. The maximum lateral displacement locates near the second excavation bench, which needs to be specially reinforced in the design.

Keywords: In-situ direct shear test, Granular strongly weathered rock, Finite element analysis, Reinforcement effect.

1. Introduction
The key to slope deformation and stability lies in the strength of geomaterial, which directly determines whether the slope deformation is within the allowable range and whether the slope stability meets the requirements of relevant regulations. Expert experience estimation method, parameter inversion analysis method, engineering geological analogy method, laboratory and field tests [1] are all commonly used methods to obtain the strength parameters of geomaterial. Among them, the engineering geological analogy method is to analyze, design, evaluate and select the parameters of the
current engineering case based on existing engineering experience. However, it is widely recognized that its accuracy is still open to question.

In order to improve the conclusion of parameter inversion analysis, inversion analysis combined with engineering geological analogy method is generally adopted to evaluate the strength parameter value of geomaterial comprehensively [2, 3]. At present, there are many literatures and experiences of using parameter inversion analysis method to study the parameters of geomaterial, and it has been properly applied in some engineering cases, which reflects the applicability of this method to a certain extent.

In terms of experimental research, due to the widespread problems of boundary effect and soil sample disturbance, laboratory tests are usually difficult to reflect the precise strength parameter of geomaterial [4]. Therefore, in-situ tests are widely used in obtaining the strength parameters of geomaterial, such as cross plate shear test [1], in-situ borehole shear test, torsional wing shear test, and some indirect means such as standard penetration and static penetration tests [5]. However, the in-situ borehole shear test requires high quality about borehole, moderate borehole size and even smoothness are essential, otherwise the test results will be affected. The cross plate shear test is only applicable to saturated soft clay, and standard penetration and static penetration tests can only be used as empirical auxiliary methods.

In-situ direct shear test is also a commonly used field test method for measuring soil strength parameters, and many scholars have studied geomaterial parameters through this method [7-13]. In-situ direct shear test loads and shears the in-situ geomaterial directly, from which the strength parameter values of geomaterial are obtained. This method has fewer disturbances and can obtain the properties of geomaterial more accurately.

Hu et al. [7] developed a large in-situ direct shear test equipment and then applied it in the landslide site of Xiangjiaba reservoir area. Tang et al. [8] studied the shear strength index of gravel soil by in-situ direct shear test. Liu et al. [4], Yang et al. [10], Xing Haofeng et al. [11], Lu et al. [12], Xu et al. [13] conducted in-situ direct shear test on rockfill material, landslide accumulation, strongly weathered hornstone, sandstone splint, and strongly weathered granite, respectively, which demonstrates the wide applicability of this method. In addition, many other scholars have studied its improvement [14, 15]. These previous research experiences provide valuable references for the application of in-situ direct shear test in the study of geomaterial parameters.

Therefore, through the in-situ direct shear test, the strength of the granular strongly weathered rock of an excavated slope was analyzed, and then the rock strength parameters obtained from the test were used to carry out the finite element simulation analysis of the slope reinforcement effect, which hopes to provide some guidance for the slope design.

2. Overview of slope engineering
The slope locates in a real estate project in Sanming, Fujian Province. The total slope length is about 500 m, with a slope direction of NE40° and a trend of NW310°. The excavated slope ratio is 1:0.25 ~ 1:0.5, and the slope height is about 28 ~ 79 m. The survey results show that the surface layer of the site is 3.5-11.5 m thick gravel cohesive soil, under which quartz sandstone weathered layers are distributed, mixed with granular-fragmentary strongly weathered quartzite. The stability calculation results are shown in Figure 1.

Due to that the granular strongly weathered quartz sandstone in the site is very thick, highly fractured and loose, the sampling of the original rock is difficult, leading to the inaccuracy of the laboratory test. In another aspect, it is too conservative to simply use empirical parameters to design the reinforcement scheme, which will greatly increase the project cost. Therefore, after a series of conventional laboratory tests, the in-situ direct shear test was used to study the strength parameters of the granular strongly weathered quartz sandstone so as to obtain more accurate results. It aims to provide a more rigorous design guidance for the subsequent slope reinforcement.
3. In-situ direct shear test

3.1. General Situation of Test

Four specimens were taken as a group, and a total of 12 tests were carried out in 3 groups. Based on the site conditions, the vertical consolidation stress applied to the samples was 150-600 kPa. The test procedure is shown in Figure 2. First, the tested sample was cut in situ into a block with a size of 0.5m × 0.5m × 0.25m, then a shear box was installed, horizontal and vertical jacks were placed for applying load. After that, vertical pressure was applied to the test block and keeps steady, and horizontal shear force was applied step by step until the sample was destroyed. Subsequently, the shear strength was obtained according to the stress-displacement curve, and the shear strength parameters were calculated by Mohr-Coulomb principle.

Figure 1 Slope stability result

Figure 2 Steps of in-situ direct shear test
3.2. Description of test results

The test results are shown in Table 1. The strength parameters obtained from the three groups of in-situ direct shear tests are \( c = 75.18 \text{kPa}, \varphi = 34.45^\circ \), \( c = 82.96 \text{kPa}, \varphi = 35.03^\circ \) and \( c = 68.92 \text{kPa}, \varphi = 36.21^\circ \), respectively. The average values are \( c = 75.69 \text{kPa}, \varphi = 35.23^\circ \). According to relevant engineering experience and regional experience, the reduced shear strength parameters \( c = 40 \text{kPa} \) and \( \varphi = 30^\circ \) are adopted as the slope design parameters.

| Number | Vertical stress (kPa) | Shear stress (kPa) | Cohesion (kPa) | Internal friction angle (°) |
|--------|-----------------------|-------------------|---------------|---------------------------|
| 1      | 150.51                | 182.69            | 75.18         | 34.45                     |
|        | 294.41                | 281.40            | 68.92         | 36.21                     |
|        | 448.92                | 352.50            | 82.96         | 35.03                     |
|        | 589.34                | 493.68            | 35.16         | 36.33                     |
| 2      | 148.97                | 182.88            | 75.69         | 35.23                     |
|        | 292.58                | 259.67            | 82.96         | 35.03                     |
|        | 437.42                | 457.21            | 68.92         | 36.21                     |
|        | 584.63                | 457.60            | 35.03         | 36.21                     |
| 3      | 151.82                | 178.28            | 68.92         | 36.21                     |
|        | 297.27                | 284.53            | 82.96         | 35.03                     |
|        | 445.41                | 406.28            | 75.18         | 34.45                     |
|        | 594.00                | 498.97            | 68.92         | 36.21                     |

Figures 3 ~ 5 show the shear plane properties of Test Group 1 ~ 3, respectively. Generally, the shear planes are relatively flat, filled with manganese iron qualitative and granular quartz grains and earthy feldspar. The sample appears to be pulverized after been sheared, which illustrates again that it is difficult in the intact sampling of the granular strongly weathered rock. As a result, it is inconvenient to reflect the strength characteristics accurately through laboratory tests. Thus, using in-situ direct shear test is a better solution.

4. Finite element analysis of reinforcement scheme

4.1. Suggestions of reinforcement scheme and establishment of finite element model

It is proposed to adopt anchor frame beam to support the slope by bench excavation. The height of each bench is about 8 ~ 10 m. The anchor with a length of 10 m, a horizontal spacing of 4 m and the vertical spacing of 2 m is applied, with a dip angle of 15°. The finite element model is consistent with the actual engineering, as shown in Figure 6.

In order to fully study the effect of different reinforcement conditions, 5 different working conditions are applied, as shown in Table 2. The diameter of the anchor discretized by beam elements...
is 100 mm, with a yield strength of 1860 MPa. The geomaterial is discretized by solid elements. The frame beams are discretized by shell elements with a thickness of 0.3m.

The cross-section with a width of 4m is selected for analysis. The model length is 50 m and the height is 60 m. The geomaterial layers of the model from top to bottom (color from light to deep) (see Figure 6(a)) are ① gravel cohesive soil, ② granular strongly weathered quartzite, ③ fragmental strongly weathered quartzite and ④ moderately weathered quartzite.

### Table 2 Working conditions

| Working conditions | Object of study               |
|--------------------|-------------------------------|
| 1                  | Unreinforced                  |
| 2                  | Single anchor frame beam      |
| 3                  | Double anchor frame beam      |
| 4                  | Three-layer anchor frame beam |
| 5                  | Four-layer anchor frame beam (fully covered) |

![Figure 6 Side view of the slope before and after reinforcement](image)

#### 4.2 Geomaterial parameters

The Geologic Cap Model [16] in LS-DYNA is used to simulate the geomaterial, and its strength parameters are calculated through the transformation of cohesion and internal friction angle. Based on the results of regional experience, engineering experience, laboratory tests and in-situ direct shear tests, the material parameters of the Geologic Cap Model required for numerical calculation are obtained, as shown in Table 3.

The anchor frame beam is linear elastic material. The elastic modulus of the frame beam is 25 GPa, the Poisson's ratio is 0.2, and the density is 2500 kg/m³. The elastic modulus of the anchor is 200 GPa, the Poisson's ratio is 0.3, and the density is 7800 kg/m³.

### Table 3 Parameters of Geologic Cap Model for geomaterial

| Parameters                             | Layer Number | ①   | ②   | ③   | ④   |
|----------------------------------------|--------------|------|------|------|------|
| Density $\rho$ (kg/m³)                 | 1850          | 2050 | 2150 | 2400 |
| Geological cap $X_0$ (kPa)             | 400           | 1000 | 1000 | 1000 |
| Shear modulus $G$ (MPa)                | 22            | 32   | 40   | 80   |
| Bulk modulus (MPa)                     | 48            | 80   | 100  | 200  |
| Cohesion parameter $\alpha$ (kPa)      | 38.5          | 48   | 117  | 213.7|
| Internal friction angle parameter $\theta$ (radian) | 0.114       | 0.231| 0.273| 0.356|
| Envelope parameter $\beta$ (MPa⁻¹)     | 0             | 0    | 0    | 0    |
| Envelope parameter $\gamma$ (MPa)      | 0             | 0    | 0    | 0    |
| Plastic parameter $W$                  | 1             | 1    | 1    | 1    |
| Plastic volumetric strain rate $D$ (MPa⁻¹) | 0.0725      | 0.0725| 0.0725| 0.0725|
| Cap shape factor $R$                   | 4             | 4    | 4    | 4    |
| Tension $T$ (kPa)                      | 0             | 0    | 0    | 0    |
4.3. Result analysis

4.3.1. Lateral displacement. Figure 7 is the comparison of lateral displacement of each condition, and Table 4 is the comparison of the maximum lateral displacement values. Figure 7 shows that:

1. Working condition 1 (Figure 7(a)): The maximum lateral displacement of the slope before reinforcement is 66.41 cm, which locates on the second bench. The deformation is huge. Therefore, reinforcement treatment is urgently needed.

2. Working condition 2 (Figure 7(b)): The maximum lateral displacement is reduced to 46.48 cm after the anchor frame beam is adopted in the first bench of the excavated slope, which is about 30% less than that before reinforcement. The area with large deformation is reduced, which proves the reinforcement effect of the anchor frame beam.

3. Working condition 3 (Figure 7(c)): After the first and second benches of the excavated slope are reinforced by anchor frame beams, the maximum lateral displacement decreases to 34.77 cm, with a significant reduction of 47.6% compared with that before reinforcement.

4. Working condition 4 (Figure 7(d)): The maximum lateral displacement is reduced to 30.86 cm by adopting the anchor frame beam in the first three benches of the excavated slope, which is 53.5% lower than that before the reinforcement. However, compared with working condition 3, the decreasing rate of the displacement is slowed down, indicating that the effect of the third-layer anchor frame beam has been weakened.

5. Working condition 5 (Figure 7(e)), with the anchor frame beam fully covered on the excavated slope, the maximum lateral displacement is the same as working condition 4, which indicates that the top bench of the slope is relatively stable and the reinforcement of the fourth-layer anchor frame beam has little effect and is not necessary.

According to the displacement nephogram, it can be found that the maximum lateral displacement of the slope is almost located at the second excavation bench. It indicates that this is the key point of the slope reinforcement. The deformation of the top bench itself is relatively small and can be treated as a secondary reinforcement part. Hence, the numerical simulation can provide some guidance for the rational design of reinforcement scheme in advance.

![Table 4 Comparison of maximum lateral displacement](image)

| Working Condition | 1     | 2     | 3     | 4     | 5     |
|-------------------|-------|-------|-------|-------|-------|
| Lateral displacement (cm) | 66.41 | 46.48 | 34.77 | 30.86 | 30.86 |
| Lower than before reinforcement (%) | -     | 30%   | 47.6% | 53.5% | 53.5% |

![Figure 7 Comparison of lateral displacement contour of different working conditions](image)

4.3.2. Deformation on the excavation face. The excavation face is the direct cause of slope instability and is also the position where the slope deformation is the largest. Figure 8 shows the deformation of each excavation face under different conditions. Among them, the height of each bench is normalized. Figure 8 shows that:

1. Basically, the deformation of each excavation bench decreases with the increase of anchor frame beams, indicating the anchor frame beam can provide effective reinforcement for the slope.
(2) The anchor frame beam in a certain layer not only reduce the deformation of the excavation bench right at the corresponding layer, but also reduce the deformation of other excavation benches. In detail, according to Figure 8 (a) and (b), compared with the slope before reinforcement (Condition 1), after the anchor frame beam is applied to the first excavation bench (Condition 2), the deformation of the first bench is reduced by 44.2%, while the deformation of the second, third and fourth bench is reduced by 27.7%, 28.2% and 36.8%, respectively. It indicates the anchor frame beam can restrain the deformation development of slope as a whole.

(3) The maximum deformation of each condition is basically located at the second bench, which is consistent with the results in Section 4.3.1 of this paper, that is, the second bench is the key point of slope reinforcement. In contrast, the deformation of the top excavation bench is generally the minimum, so it can be used as a secondary reinforcement part.

(4) In each Condition, the first bench basically exhibits an outward deformation mode, that is, the bottom deformation of first bench is smallest, while the top deformation is the largest, and the anchor frame beam has a weakening effect on the outward deformation.

(5) In each condition, the third and fourth benches basically present an inward deformation mode, that is, the deformation at the bottom of these benches is the largest, while the deformation on the top is the smallest.

4.3.3. Shear strain of geomaterial. The comparison of shear strain nephogram of the geomaterial under different reinforcement conditions is shown in Figure 9. A uniform scale is used to show the differences among the various conditions more clearly. Except that Condition 1 has unique shear strain characteristics and large strain amplitude, the maximum equivalent effect amplitude of other conditions is about 6%. Figure 9 shows that:

(1) The maximum shear strain of the slope before reinforcement reaches 8.3%, and the strain contour even forms a sliding arc (see Figure 9(a)), and the sliding arc gradually extends from the bottom bench at the slope foot to the top.

(2) After the reinforcement of anchor frame beams with different conditions (Figure 9(b)–(e)), the amplitude of shear strain decreases to about 6%, the sliding arc feature disappears, and the maximum shear strain locates at the slope foot.
(3) According to the comparison between Figure 9(b) and (d), the shear strain of the slope at the anchorage area decreases significantly, which indicates that the anchor can effectively reduce the shear strain of the soil, thus reducing the overall deformation of the slope.

(4) According to Figure 9(d) ~ (e), the distribution of the shear strain contour in Condition 4 and Condition 5 are generally the same. Although an additional anchor frame beam at the fourth bench are applied in Condition 5, it does not effectively reduce the shear strain of the geomaterial at this excavation bench compared with Condition 4. This again confirms that the fourth-layer anchor frame beam has little effect, which is consistent with the foregoing conclusion.

Figure 9 Comparison of shear strain contour

5. Conclusion
In this paper, the strength of granular strongly weathered rock mass of an excavated slope was studied by in-situ direct shear test. Then, based on the strength parameters, the slope reinforced with different anchor frame beams are simulated by finite element method, which hopes to provide some guidance for the slope support design. The following conclusions can be drawn:

(1) The strength parameters of the granular strongly weathered rock obtained by in-situ direct shear test are $c=75.69$ kPa and $\phi=35.23^\circ$. Based on relevant engineering experience and regional experience, the shear strength parameters $c=40$ kPa and $\phi=30^\circ$ were used for the slope design.

(2) The maximum lateral displacement of the slope with different anchor frame beams can be reduced by $30\%$ ~ $53.5\%$ compared with that before reinforcement. The displacement reduction increases with the increase of anchor frame beams, but the effect of the fourth anchor frame beam is small. The design of the first three anchor frame beams should be paid more attention to.

(3) The maximum lateral displacement of the slope is almost all at the second excavation bench, which indicates that this is the key point of the slope reinforcement.

(4) The shear deformation of the geomaterial is obviously weakened at the anchorage area, and the whole deformation of slope can be reduced by multi-layer anchor frame beams.

It should be noted that only numerical simulation is conducted in this study, but the accuracy of the simulation results should be further verified with monitoring data. In addition, the strength test results are reduced according to the authors' engineering experience and regional experience, which is more progressive than simply using laboratory test results or the empirical parameters that are too conservative, but it still needs to be further analyzed in the future research.

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