Applicability of single sample method to test strength parameters of sandstone

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Abstract: The single sample method allows the mechanical parameters of rocks to be obtained with very few rock samples; however, the method has not been widely used. This is mainly because the yield point of the single sample method is more difficult to control than the conventional triaxial compressive test and the effect of the different control methods on the measured data is not well understood. The single sample method obtains the strength parameters of the rock by loading a single rock sample with multiple stages of confining pressure. Multistage loading tests are divided into peak strength control and long-term strength control according to yield point control. In this study, multistage loading tests of sandstone were carried out to obtain strength parameters using long-term strength control. The results show that sandstones undergo seriously brittle damage in conventional triaxial compressive tests. Although the sandstones have been rigorously selected, they still vary considerably, and long-term strength points are more difficult to control. The error of strength parameters of sandstone obtained using the single sample method may exceed 20% compared to those obtained by conventional triaxial compressive tests. So this method must be used with caution for sandstones.

1. Introduction
China is rich in deep mineral resources, and many of the key issues facing their development are closely related to rock mechanics [1]. The rock strength criterion is the basic theory used to judge whether the failure occurs in a rock under a certain stress state. Experiments of conventional rock mechanics require multiple failure tests at different confining pressures and a large number of rock samples to obtain rock's strength parameters [2]. When there are fewer samples, the discreteness is large, and the reliability of experimental results is lost. In petroleum engineering, drilling and sampling are costly, and samples are scarce and poorly reproducible [3-4]. To solve the above problem, K. Kovari and A. Tisa (1975) proposed the triaxial compressive test for a single rock sample [5], also known as the single sample method. The single sample method is used to alternately load the perimeter pressure and axial pressure to obtain the maximum strength of the rock at different confining pressures, thus obtaining the rock's strength envelope. The single sample method is currently carried out in the following ways: (1) multistage failure test [5]; (2) unloading multistage failure test [6]; (3) modified multistage failure test [7]. The main methods for determining the yield point of the single sample method are peak strength control [1,8-10] and long-term strength control [11-14]. The control point for peak strength is the point at which the slope of the axial stress-strain curve tends towards zero, i.e. $\frac{\partial \sigma_a}{\partial e_a} = 0$. Some scholars
also use the point \( \Delta V / V = 0 \) as a control point [7]. This method can save rock samples and improve experimental efficiency [15], but it has not been widely promoted. Whether the method applies to all types of rocks deserves to be investigated. Therefore, this paper focuses on applying the long-term strength control method to determine sandstone strength parameters using the single sample method.

2. Triaxial compressive test of sandstone by the single sample method

2.1 Rock samples preparation

Rock samples were taken from the sandstone of the Xujiahe Formation at Longchang, Sichuan. The samples were screened using an ultrasonic test and processed into cylinders of approximately 5.0 cm in length and 2.5 cm in diameter. The ultrasonic test data and rock samples are shown in Figure 1. The sonic interval transit time was similar for each rock sample, indicating that the internal structure of the selected rock samples was relatively consistent.

![Sandstone samples and their ultrasonic testing data](image)

Figure 1. Sandstone samples and their ultrasonic testing data

2.2 Test procedures

The RTR-1000 static (dynamic) triaxial rock mechanics test system obtains the stress-strain curve from a single rock sample. The procedure for the single sample method is shown in Figure 2. The procedure is divided into the following steps:

1. Rock samples are wrapped in a rubber sleeve and placed in the triaxial testing machine. Check the status of each valve opening and closing and prepare to start the experiment.

2. The test is started by loading the initial confining pressure to the specified value. The axial load and the confining pressure should normally be increased simultaneously before the hydrostatic pressure reaches the initial confining pressure. The volumetric stress-strain curve is monitored in real-time by software and checked using an acoustic emission device. The position \( \partial (\Delta V / V) / \partial \sigma = 0 \) on the stress-strain curve is the control point for each level of loading, and the axial load loading is stopped when the acoustic emission device responds.

3. At this time, When the confining pressure is increased to another value, the axial load should be continuously increased at a constant strain rate \( 10^{-2} \text{ to } 10^{-5} \text{ m} \cdot \text{s}^{-1} \). The axial load is continued to a constant value, and the volumetric stress-strain curve and the response of acoustic emissions are monitored. Abort the test at the above aborting point and ensure that only plastic deformation of the rock sample occurs without failure.

4. Repeat the above steps until the required confining pressure has been reached as far as possible, then keep the confining pressure constant and increase the axial load. This causes failure to the rock sample, and the axial stress falls to a residual value. The test is stopped by continuously reducing the confining pressure until the sample is completely unloaded and a full stress-strain curve is obtained.

After the test, the test equipment is restored to the initial state, the test environment is cleaned, and the test data is analyzed and processed.
3. Experimental results

3.1 The relationship between axial stress and confining pressure
When the confining pressure is constant, the axial stress is increased to the next level of the expanded volume position; then, the axial stress is kept constant, and the confining pressure is increased to the next level of the confining pressure, which is the basic process of the test. The relationship between the axial stress and the confining pressure is shown in Figure 3. Although the tests were controlled using the same servo system, the axial stress and the confining pressure behaved differently. Increasing the axial stress, the previously set confining pressure remained constant throughout. However, when the confining pressure was increased, the previously set axial stress tended to decrease. This is mainly due to the evolution of cracks within the rock as a result of damage sustained during the pre-loading of the rock. As a result, the strength of the rock does not remain constant and tends to decrease as the confining pressure is increased.
3.2 Stress-strain curve

The stress-strain curves were obtained from the test, as shown in Figure 4. It can be seen that there is still some difficulty in obtaining real-time control points during the loading process. In addition, there is a strong relationship with the experience of the test operator, and the values taken at the flattening stage of the curve can cause some errors. As can be seen from the results obtained from the conventional triaxial compressive test and the single sample method, the sandstone still exhibits significant brittleness as the confining pressure increases, with the stress-strain curve dropping instantly when the peak load is reached.

3.3 Strength comparison between single rock sample and conventional triaxial test

Table 1. Comparison of axial pressure between conventional triaxial test and single sample method

|                     | Conventional triaxial test | Single sample method |
|---------------------|----------------------------|----------------------|
| Sample No. 1        | 100                        | 90                   |
| Sample No. 2        | 100                        | 90                   |
| Sample No. 3        | 120                        | 110                  |
| Sample No. 4        | 160                        | 150                  |

Figure 3. Relationship between axial stress and confining pressure

Figure 4. Stress-strain curve of single rock sample
Comparative data on the axial pressure of the conventional triaxial compressive test and the single sample method at different confining pressures were obtained, as shown in Table 1. It can be seen from the test results that the long-term strength of the first two control points of sample No.1 is 84%~88% of the failure strength, and the long-term strength of the last control point is only 67.26% of the failure strength. The long-term strength of the first three control points of sample No.3 was above 95% of the failure strength, and the last control point had a long-term strength of 88.21% of the failure strength. The long-term strength of the four control points of sample No.2 is 74%~82% of the failure strength. The long-term strength of sample No.4 is mostly close to the failure strength, and the long-term strength of control point 1 is even higher than the peak strength value. Overall, the long-term strength and failure strength of sample No. 4 are the closest. Although the rock samples were strictly selected, the heterogeneity of the rock samples is still very large, which is an important reason for the difference in the test results.

4. Discussions
Figure 5. Comparison of the results of the conventional triaxial compressive test and the single sample method on three types of marble

Tests on marble and granite carried out by long-term strength control in the literature [15] showed that the long-term strength of a single sample of marble obtained was 80% to 95% of the failure strength. The cohesion obtained by the single sample method is between 79% and 84% of that obtained by conventional triaxial compression tests. In comparison, the angle of internal friction obtained by the conventional method is 90% to 97% of that obtained by the single sample method. The results of the single sample method for several types of marble in the literature [10] show that more accurate experimental results can be obtained for both middle and large-crystalline marble and that the errors in the long-term and failure strengths obtained by the single sample method are both within 10%, see Figure 5. The results of tests on sandstone in the paper [12] show that the long-term strength is about 80% of the failure strength. These show that the influence of lithology on the results of the single sample method is significant. Rocks with significant ductile deformation are well adapted to the single sample method. However, the results of this test show a large variability in the results obtained from different rock samples. In addition, the number of multistage loading may have had an important influence on the test results. Both samples No.1 and No.4 showed significantly lower failure strength at the third loading, and rock failure during loading may have been an important cause of this phenomenon. Table 2 shows the cohesion and internal friction angles obtained by the conventional triaxial compressive test and the single sample method. Results show that the cohesion obtained by the single sample method for samples No. 3 and No. 4 are close to 80% of that obtained by the conventional triaxial compressive test.

In conclusion, the rock strength parameters of the sandstone tested by the single sample method differed significantly from those of the marble. The differences in the rock samples and the higher brittleness may be important reasons for the variability. Therefore the strength parameters of the sandstone tested using this method must be treated with caution.

| Strength parameters | Conventional triaxial tests | Sample No. 1 | Sample No. 2 | Sample No. 3 | Sample No. 4 |
|---------------------|----------------------------|--------------|--------------|--------------|--------------|
| Cohesion (MPa)      | 22.15                      | 15.48        | 16.45        | 17.71        | 18.11        |
| Angle of friction (°)| 18.58                      | 23.92        | 17.60        | 27.03        | 22.20        |
5. Conclusions

(1) Use the long-term strength control method for multistage loading tests on sandstone. The selection of sandstone control points during the test is difficult and inappropriate selection may lead to large test errors.

(2) The variability of the sandstone samples has a large impact on the test results, even though the sandstone still exhibits a high degree of brittleness at high confining pressures. Multistage loading or inappropriate selection of control points may cause more severe damage to the sandstone and greatly impact the test results.

(3) The single sample method enables the strength parameters of the rock to be obtained with a minimum number of samples, but different lithologies show large variability. For example, marble shows a good adaptation, but adaptation to sandstone must be treated cautiously, resulting in errors exceeding 20%.

References

[1] Wagner, H.(2019) Deep Mining: A Rock Engineering Challenge. Rock Mechanics & Rock Engineering, 52: 1417-1446.
[2] Wittke, W. (1990) Rock mechanics: Theory and applications with case histories. Springer Verlag, Berlin.
[3] Airey, D. W. (1993) Triaxial Testing of Naturally Cemented Carbonate Soil. Journal of Geotechnical Engineering, 119: 1379-1398.
[4] Huang, J. T., Airey, D. W. (1998) Properties of Artificially Cemented Carbonated Sand. Journal of Geotechnical & Geoenvironmental Engineering, 124: 492-499.
[5] Kovari K. (1975) Multiple Failure State and Strain Controlled Triaxial Tests. Rock Mechanics and Rock Engineering, 7: 17-33.
[6] Li, H.Z., Xia, C.C., Xu, C.B., Wang, X.D., Zhang. C.S.(2008) Experimental study of rock unloading strength parameters based on multiple failure method, Chinese Journal of Rock Mechanics and Engineering. 27: 2681-2686.
[7] Adrian, M. C., David A.W. (1987) A Modified Multiple Failure State Triaxial Testing Method. In: 28th US Symposium on Rock Mechanics. Tucson, AZ.
[8] Harouaka, A., Mtawaa, B., Al-Majed, A., Abdulraheem, A., Klimentos, T.(1995) Multistage Triaxial Testing of Actual Reservoir Cores under Simulated Reservoir Conditions. In: SCA Conference, Japan. pp. 9528.
[9] Liu, B.G., Cui, S.D.(2011) Improvement of single specimen method for determination of rock strength parameters. China Civil Engineering Journal. 162-165
[10] SU, C.D., You, M.Q.(2004) Determination method of strength parameters for sandstone and marble with one specimen. Chinese journal of rock mechanics and engineering. 23: 3055-3058.
[11] Zhang, L., Wang B.X., Yang, T.(2007) Research of Rock Triaxial Compression Test with Multilevel Confining Pressure. Site investigation science and technology. 6-8.
[12] Zhang, L., Wang B.X., Yang, T.(2008) The research of rock triaxial compression with multilevel confining pressure and the data statistics. Experimental technology and management. 25: 43-47.
[13] Wang, B., Zhou, R., Zhu, J.B., Wu, A.Q. (2011) Triaxial Test on Single Specimen by MTS Rock Mechanical Test System. Journal of Yangtze River Scientific Research Institute. 28:162-166.
[14] Sharma, M. S.R., Baxter, C. D. P., Moran, K. Vaziri, H., Narayanasamy, R.(2011) Strength of Weakly Cemented Sands from Drained Multistage Triaxial Tests. Journal of Geotechnical and Geoenvironmental Engineering. 137: 1202-1210
[15] Kovári, K., Tisa, A., Einstein, H., Franklin, J. (1983) Suggested methods for determining the strength of rock materials in triaxial compression: Revised version. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 20: 285-290.