Experimental Study on Strength Characteristics of Frozen Sands

Li Li¹, Qiong Shen¹*, Yaodan Liu¹, Yingjun Wang¹ and Qianru Dai¹

¹College of Architecture and Urban-Rural Planning, Sichuan Agricultural University, Dujiangyan Sichuan, 611830, China

*Corresponding author’s e-mail: swydong@sicau.edu.cn

Abstract. The MTS-Landmark 370.10 dynamic and static triaxial test system is used to carry out low temperature conventional triaxial tests at a temperature of -10 °C and the confining pressures of 0.5MPa, 1MPa, 2MPa, 6MPa, and 8MPa to study the strength characteristics of frozen sands. The test results show that under different confining pressures, the stress-strain curves of frozen sand are strain soften. With the increasing confining pressures, the degree decreases gradually, and the strength has a non-linear characteristic. Based on the envelope theorem, a non-linear strength criterion is proposed in this paper. Compared with the test results, the strength criterion can well describe the non-linear relationship between the strength of frozen sand and confining pressure.

1. Introduction

The strength of frozen soil refers to the ability to resist damage under load, which is of great significance for evaluating the bearing capacity of foundation, foundation pit and slope stability of natural soil slope. As early as 1937, Tsytovich and Sumgin [1] through uniaxial compression tests found that the strength of frozen silt and clay at -12 °C increased with the increase of ice content, and when increased to the maximum, with the further increase in the amount of ice will decrease. Wu et al. [2] found that with the increase of confining pressure or temperature, the plasticity and strain hardening properties of frozen sand were obviously enhanced. Li et al. [3] found that the shear strength of frozen soil could be described by Mohr-Coulomb strength theory. The variable angle shear tester is one of the effective methods for determining the shear strength of frozen soil. Lai et al. [4] studied the influence of supersaturated moisture content and temperature on the strength of frozen sand through triaxial tests. Sun et al. [5] studied the influence of water content and salt content on the strength of artificial frozen sand. He proposed that there was a peak value of the strength of artificially frozen soil with the change of water content at the same temperature. The corresponding peak value of water content was defined as "the best water content of frozen soil", and its mechanism was revealed. Shi et al. [6] found that the freezing strength of frozen soil and structural interface showed brittle failure and strain softening, and the residual strength showed typical characteristics such as periodic fluctuation and decay. The freezing strength of frozen soil and structural contact surface was affected by contact surface temperature and The roughness has a significant effect and is linear and logarithmic as a function of the test temperature range.

In this paper, the strength characteristics of frozen sands are studied by conventional triaxial test. Based on the envelope theorem, a non-linear strength criterion is established.
2. Test conditions
A series of three axis tests for frozen sand were carried out by the MTS-Landmark 370.10 test system. Samples with a diameter of 61.8mm and a height of 125.0mm were prepared. Test samples were frozen for 48 hours after air extraction and saturated. The test temperature was -10 °C, the confining pressures were 0.5MPa, 1MPa, 2MPa, 6MPa, 8MPa, respectively, and the moisture content was set as 20%. Shear of samples began after consolidation for 2 hours. In this paper, the axial load was applied at a strain rate of 1.25 mm/min, and the test was terminated when the axial strain reached 20%.

3. Test result
A series of tests were carried out on frozen sands with a temperature of -10 °C. The test results are shown in Fig.1. As can be seen from Fig.1, the stress-strain curves are divided into two stages. In the first stage, it is the linear elastic phase, when the strain is less than 1%, the stress increases approximately linearly with the strain development. This is due to the existence of ice in the soil, which makes the frozen soil maintain good initial stiffness in this stage. In the second stage, it is the elastoplastic stage, when ε1>1%, the stress increases slowly with the increase of strain. When the stress reaches the stress peak, it gradually decreases with the increase of strain until the sample is destroyed. This is due to the plastic deformation inside the frozen soil, which causes the ability of the frozen soil to resist deformation.

![Figure 1: Stress-strain curves of frozen sands at -10 °C](image)

4. Nonlinear strength criterion
The relationship between the first principal stress and the third principal stress is shown in Fig. 2. It can be seen from the figure that the relationship between the confining pressure σ3 and the axial stress σ1 is nonlinear when shearing damage occurs in the frozen sand, and σ1 increases with the increase of σ3. The relationship between them can be described by formula (1).

\[
\frac{\sigma_1}{p_a} = a_0 + b_0 \left( \frac{\sigma_3}{p_a} \right)^{c_0}
\]

where \(a_0, b_0 \) and \(c_0\) are the material fitting parameters, \(p_a\) is the standard atmospheric pressure. Among \(a_0=43.409, b_0=7.419, c_0=0.610\).
Figure 2. Relationship between $\sigma_1$ and confining pressure $\sigma_3$

The equation of the molar stress circle expressed by the maximum principal stress $\sigma_1$ and the minimum principal stress $\sigma_3$ is:

$$f(\sigma, \tau, \sigma_1, \sigma_3) = \left(\sigma - \frac{\sigma_1 + \sigma_3}{2}\right)^2 + \tau^2 - \left(\frac{\sigma_1 - \sigma_3}{2}\right)^2 = 0$$  \hspace{1cm} (2)

where $\sigma$ and $\tau$ are the normal stress and shear stress on the failure surface of the soil element, respectively.

Rewrite equation (1) as:

$$g(\sigma_1, \sigma_3) = \frac{\sigma_1}{p_a} - a_0 - b_0 \left(\frac{\sigma_3}{p_a}\right)^c$$  \hspace{1cm} (3)

According to the envelope theorem:

$$\frac{\partial f}{\partial \sigma_1} \cdot \frac{\partial g}{\partial \sigma_3} - \frac{\partial f}{\partial \sigma_3} \cdot \frac{\partial g}{\partial \sigma_1} = 0$$  \hspace{1cm} (4)

Differential equations (2) and (3), thus obtaining

$$\frac{\partial f(\sigma, \tau, \sigma_1, \sigma_3)}{\partial \sigma_1} = \sigma_3 - \sigma$$  \hspace{1cm} (5)

$$\frac{\partial f(\sigma, \tau, \sigma_1, \sigma_3)}{\partial \sigma_3} = \sigma_1 - \sigma$$  \hspace{1cm} (6)

$$\frac{\partial g(\sigma_1, \sigma_3)}{\partial \sigma_1} = \frac{1}{p_a}$$  \hspace{1cm} (7)

$$\frac{\partial g(\sigma_1, \sigma_3)}{\partial \sigma_3} = -c_0 b_0 \left(\frac{\sigma_3}{p_a}\right)^{c_0-1} \cdot \frac{1}{p_a}$$  \hspace{1cm} (8)

Substitute equation (5) - (8) into equation (4), thus

$$\left(\sigma_3 - \sigma\right) \left(-c_0 b_0 \left(\frac{\sigma_3}{p_a}\right)^{c_0-1} \cdot \frac{1}{p_a}\right) - \left(\sigma_1 - \sigma\right) \cdot \frac{1}{p_a} = 0$$  \hspace{1cm} (9)

From equation (9), you can get
Substituting equation (10) into equation (2), shear stress $\tau$ can be obtained as follows:

$$
\tau = \left( \frac{\sigma_1 - \sigma_2}{2} \right)^2 - \left( \frac{\sigma_3 c_h h_0 \left( \frac{\sigma_3}{p_a} \right)^{a-1} + \sigma_1}{\sigma_3 c_h h_0 \left( \frac{\sigma_3}{p_a} \right)^{a-1} + 1} - \frac{\sigma_1 + \sigma_3}{2} \right) \left( \frac{\sigma_3 c_h h_0 \left( \frac{\sigma_3}{p_a} \right)^{a-1} + \sigma_1}{\sigma_3 c_h h_0 \left( \frac{\sigma_3}{p_a} \right)^{a-1} + 1} \right)
$$

Equations (1), (10) and (11) are mathematical expressions for the nonlinear strength criterion of frozen sand.

In order to verify the applicability of the strength criterion, the molar stress circle and intensity envelope are thus plotted, as shown in Fig.3. It can be seen from the figure that the nonlinear strength criterion established in this paper can better describe the nonlinear relationship between the shear strength of frozen sand and the confining pressure.

5. Conclusions

Through the research and analysis of the triaxial test results of freezing sand with a temperature of -10 °C and a confining pressure of 0.5MPa, 1MPa, 2MPa, 6MPa and 8MPa, the following conclusions can be drawn:

(1) The stress-strain curve of frozen sand mainly exhibits strain softening characteristics. As the confining pressure increases, the degree gradually decreases.

(2) The nonlinear Mohr strength criterion proposed in this paper has high precision and can accurately describe the law that the shear strength of frozen sand changes nonlinearly with confining pressure.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant Nos. 41701063 and 41672304) and Sichuan Science and Technology Department Project (Grant Nos.2018JY0251)

References

[1] TSYTOVICH, N. A., SUMGIN, M. I. Principles of mechanics of frozen ground [C]. U. S: SIPRE Transl., 1937, 19: 106-107.

[2] Wu, Z. W., Ma, W., Zhang C.Q., et al. Strength characteristics of frozen sand [J]. Glacier permafrost, 1994, V16(1): 15-20.
[3] Li, D.W., Wang, R.H. Shear strength characteristics and experimental study of frozen soil [J]. Journal of Anhui University of Technology (Natural Science Edition), 2004, (S1): 52-55.

[4] Lai, Y. M., Zhang, Y., Zhang, S. J., et al. Effect of supersaturated water content and temperature on strength of frozen sand [J]. Geotechnical Mechanics, 2009, 30(12): 3665-3670.

[5] Sun, L. Q., Lu, J. G., Li, H, et al. Experimental study on the influence of water content and salt content on the strength characteristics of artificial frozen soil [J]. Journal of Geotechnical Engineering, 2015, 37(zk2): 27-31.

[6] Shi, Q. B., Yang, P., Tan, J. Z., Tang, G. Y. Development and experimental study of freezing strength pile-pressing method for frozen soil-structure interface [J]. Journal of Geotechnical Engineering, 2019, 41(01): 145-153.