Experimental Research on Mechanical Properties of Frozen Sands under Isotropic Compression Conditions

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Abstract: The K-G model has better practicability and superiority than the E-μ model. Conventional triaxial tests of frozen sand samples were carried out at -10 C under confining pressures of 0.5 MPa, 1.0 MPa, 2.0 MPa, 4.0 MPa and 6.0 MPa. During the consolidation process, the samples behave an isobaric state. While the confining pressure σ3 is unchanged, axial pressure σ1 is gradually increased during the shearing process. The test results show that the volumetric strain increases nonlinearly with the increase of the volumetric stress in the isobaric state, showing a power function trend. An improved K-G model is proposed to describe strain softening of frozen sand during shear. The verification results show that the model has good applicability.

1. Introduction

Frozen soils, a kind of special composite material, are composed of soil skeleton, unfrozen water, gas and ice. The mechanical properties of frozen soils are not only affected by the physical properties of each component, but also significantly changed by temperature and pressure. In recent years, with the continuous construction of industry and agriculture in cold area, as well as the sustained development of underground mining projects, the importance of frozen soils research has become more and more obvious. Frozen soils as the foundation of building has been reasonably verified, however, with the increase of building height, the excavation depth will also be deeper, and new challenges will be encountered in geotechnical engineering. Therefore, the theoretical study of the constitutive relationship is a breakthrough to solve these problems. At present, these are few studies on the constitutive relationship of frozen soil, which are mainly based on the assumption of continuous medium, and the constitutive model is established or modified by analyzing the stress-strain curve through test data[1].

The nonlinear model of soil can be roughly divided into the E-μ model and the K-G model[2]. The predicted results calculated by the E-μ model is large[3], and the K-G model not only approximately reflects the stress path factors[4], but also its parameters can be directly determined by tests[5]. Therefore, based on the conventional triaxial tests, this paper studies the volume stress-strain relationship curve of frozen sand, and proposes a K-G model which can reflect the strain softening of frozen sand. The model calculated curve agrees well with the test results, which have verified its rationality.
2. Test conditions
The test sample is sand along the Qinghai-Tibet Railway with a dry density of 1.75 g/cm³. The particle size gradation curve is shown in Figure 1. A series of triaxial tests on frozen sand were carried out by MTS-Landmark 370.10 frozen soil dynamic and static triaxial test system. The test temperature condition is -10°C, and the confining pressure conditions is 0.5 MPa, 1.0 MPa, 2.0 MPa, 4.0 MPa, and 6.0 MPa. During the consolidation process, the sample is in an isobaric state, the confining pressure $\sigma_3$ is unchanged and axial pressure $\sigma_1$ is gradually increased until failure.

3. Test result
The volume stress-strain curve in consolidation stage is shown in Figure 2. From Figure 2, it can be seen that the volume strain of specimen increases nonlinearly with the increase of volume stress, and finally tends to a stable value. The relationship is as follows:

$$\varepsilon_v = a + bp^c$$

(1)

Where $\varepsilon_v$ is the volume strain in the consolidation stage, $p$ is the volume stress, and $a$, $b$, and $c$ are test parameters.

4. K-G model
In the three-dimensional stress state, the stress is often decomposed into spherical stress and deviatoric stress, and the volume modulus $K_v$ and the shear modulus $G_t$ reflect respectively the elastic properties

Figure 1. The particle distribution curve of soil

Figure 2. The volume stress-strain curve

T = -10°C
of the soil under the action of spherical stress and deviatoric stress. The volume modulus is defined as 
\[ K_t = \frac{dp}{d \varepsilon} \], and the shear modulus is 
\[ G_t = \frac{dq}{(3d\varepsilon)} \].

4.1. Volume modulus \( K_t \)

The consolidation process of the conventional triaxial test is equivalent to the isotropic test. According to the definition of the volume modulus, the test results of the consolidation phase are plotted in the \( p/p_c-e/v/e_{vc} \) coordinate system. The stress-strain relationship is shown in Figure 3. The following formula is fitted:

\[
\frac{p}{p_c} = \frac{\varepsilon}{\varepsilon_{vc}} \left[ \beta + \gamma \left( \frac{\varepsilon}{\varepsilon_{vc}} \right)^{m-1} \right]
\]

(2)

Where \( \beta, \gamma \) and \( m \) denotes test parameters.

![Figure 3. The p/p_c-e/v/e_{vc} relationship curve](image)

The test data is divided into two parts: the consolidation data and the shear data. By fitting the test data in consolidation data, the test parameters \( \beta, \gamma \) and \( m \) can be obtained. Details are shown in Table 1.

| Initial test conditions | Fitting parameters |
|-------------------------|--------------------|
| \( p_c \) (kPa) | \( \varepsilon_{vc} \) (%) | \( \beta \) | \( \gamma \) | \( m \) |
| 500 | 6.8624 | 0.2237 | 4.3726 | 2 |

By differentiating (3)

\[
dp = \frac{p_v}{\varepsilon_{vc}} \left[ 1 + m\gamma \left( \frac{\varepsilon_v}{\varepsilon_{vc}} \right)^{m-1} \right] d\varepsilon_v
\]

(3)

According to the definition of volume modulus

\[
K_t = \frac{p_v}{\varepsilon_{vc}} \left[ 1 + m\gamma \left( \frac{\varepsilon_v}{\varepsilon_{vc}} \right)^{m-1} \right]
\]

(4)

4.2. Shear modulus \( G_t \)

Generally, to obtain the shear modulus \( G_t \), a triaxial shear tests is needed under the condition of volume stress \( p \) being constant. During the shearing process, \( dp=0 \). However, its test equipment and test technology requirements are high. Liu Zudian elaborated the method of calculating shear modulus \( G_t \) in conventional triaxial test[6]. Based on the stress-strain model modified by Lai Yuanming[7], the shear
modulus \( G_i \) is obtained in the conventional triaxial test. In the triaxial shear test,

\[
\begin{align*}
q &= \sigma_i - \sigma_3 \\
\varepsilon_s &= \varepsilon_i - \varepsilon_3 \\
\varepsilon_r &= \varepsilon_i + 2\varepsilon_3
\end{align*}
\]  

(5)

To describe the strain softening of frozen sand, it is suggested that the expression of stress-strain relationship be as follows:

\[
\sigma_i - \sigma_3 = \frac{\varepsilon_s}{a + b\varepsilon_s + c\varepsilon_s^2}
\]  

(6)

In Formula 6,

\[
\begin{align*}
a &= 1/3G_i \\
b &= 1/(\sigma_i - \sigma_3)_m - 2/(3G_i\varepsilon_{sm}) \\
c &= 1/(3G_i\varepsilon_{sm}^2)
\end{align*}
\]  

(7)

Where \((\sigma_i - \sigma_3)_m\) is the maximum deviation stress, \(\varepsilon_{sm}\) denotes the corresponding shear strain, and \(G_i\) is the initial shear modulus.

Combined with formula (6), the shear modulus can be expressed as:

\[
G_i = \frac{dq}{3d\varepsilon_s} = \frac{d(\sigma_i - \sigma_3)}{3d\varepsilon_s} = \frac{a - c\varepsilon_s^2}{3(a + b\varepsilon_s + c\varepsilon_s^2)^2}
\]  

(8)

When \(\varepsilon_s = 0\), the initial shear modulus can be expressed as:

\[
G_i = \frac{dq}{3d\varepsilon_s} = \left(\frac{a - c\varepsilon_s^2}{3(a + b\varepsilon_s + c\varepsilon_s^2)^2}\right)_{\varepsilon_s \to 0} = \frac{1}{3a}
\]  

(9)

According to the above solution method, the value of \(c\) obtained from the test data is smaller. Therefore, in order to verify the applicability of the model, \(c=0.0035\) can be assigned and the relevant parameters in shear modulus can be obtained by substitution formula (7). Details are shown in Table 2.

| \(\sigma_3\) (kPa) | \(a\)   | \(b\)   | \(G_i\) (kPa) |
|-------------------|---------|---------|---------------|
| 500               | 0.1318  | 0.1507  | 5961.62       |
| 1000              | 0.1292  | 0.1359  | 6711.73       |
| 2000              | 0.1069  | 0.1311  | 7401.88       |
| 4000              | 0.1016  | 0.1130  | 8010.05       |
| 6000              | 0.1027  | 0.1281  | 6540.33       |

5. Preliminary validation of the model

In order to verify the rationality of the model, the calculated values of the model are compared with the test results. Due to space limitation, the comparative results under confining pressure of 0.5 mPa and 4.0 mPa are presented in this paper, as shown in Figure 4. The calculated values of the model are basically consistent with the test results.
6. Conclusions

(1) In the isostatic test, the volume strain of frozen sand increases nonlinearly with the increase of volume stress, which is roughly a power function law.

(2) In conventional triaxial shear tests, the $q$-$\varepsilon_s$ curve of frozen sand has obvious strain softening characteristics, and the improved KG model can better describe the stress-strain relationship.

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