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A study of Triaxial creep test and yield criterion of artificial frozen soil under unloading stress paths

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ABSTRACT

The triaxial shear test method with consolidation, low temperature freezing, and radial unloading was applied to simulate the mechanics process of the unloading process of deep artificial frozen clay during the excavation of a freezing mine shaft. The triaxial unloading creep test on artificial frozen clay showed that the first and second stages of the creep deformation occur only when the deviatoric stress is low and that creep deformation accounts for > 70% of the total deformation. The third stage of creep deformation occurs only when the stress level exceeds a certain critical value, and is characterized by the frozen soil undergoing a large plastic flow, with breaking for 3 to 5 h. The creep strength envelope at low confining pressure is linear, in compliance with the Mohr-Coulomb strength criterion, and the critical stress value in the third stage can be described with the improved Zienkiewicz-Pande parabolic yield criterion.

1. Preface

Artificial freezing shaft sinking in the deep topsoil involves sophisticated engineering of complex environments and stress states, including the problem of deep artificial frozen soil mechanics under the high stress unloading path. Existing mechanical models such as the artificial frozen soil yield criterion, the instantaneous stress-strain relationship and the creep deformation law are not suitable for practical deep shaft freezing engineering. Therefore, it is necessary to study the mechanical properties of artificial frozen soil, especially the coupled constitutive model of the creep damage for frozen soil.

Many previous studies have investigated on the mechanical properties of frozen soil. Arenson et al. (2011) reviewed the effects of stress and temperature on the creep characteristics of frozen soil. Yamamoto and Springman (2017) conducted three-point bending and four-point bending tests on artificial frozen soil samples at temperatures near 0 °C. Loria et al. (2016) described the mechanical behavior of artificial frozen soil by constructing a nonlinear model. Christ et al. (2009) studied the mechanical and acoustic properties of frozen soil at different temperatures and for different numbers of cycles. Li et al. (2011) studied the creep characteristics of artificial frozen soil under high confining pressure. Lai et al. (2014a, 2014b) studied the water-heat-mechanical properties of frozen soil by theoretical deduction and laboratory tests. Amiri et al. (2016) researched constitutive models of saturated frozen soil. Xu et al. (2016) studied the mechanical properties of frozen silt and considered brine concentration by applying the triaxial test. Sheng et al. (1997) researched the creep index of frozen soil under uniaxial stress. Zhang et al. (2016) analyzed and predicted the long-term strength of frozen soil by application of the time analogue method.

In this paper, the triaxial creep test for artificial frozen soil under different stress paths was carried out to simulate the mechanics of the excavation and unloading of a freezing mine shaft after deep frozen wall formation allowing deformation and strength of the frozen soil under deep high stress. This was an effective approach to further investigate the mechanical behavior and failure characteristics of field frozen soil, and our findings can provide guidance for the long-term stability analysis and behavior prediction of frozen soil structure.

2. Triaxial stress path creep test on artificial frozen soil

2.1. Test method and steps

The deep shaft artificial freezing triaxial creep test included the following seven steps, and the test was carried out in a self-developed W3Z-200 artificial frozen soil triaxial test system:

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Table 1
Arrangement of triaxial unloading creep test on frozen soil.

No.	Consolidation confining pressure (MPa)	Load value after radial unloading (MPa)	Test temperature (°C)
Group 1	4.0	3.7/3.3/3.0	− 5
		3.4/3.0/2.6	− 10
Group 2	5.0	4.7/4.3/4.0	− 5
		4.4/4.0/3.6	− 10
Group 3	6.0	5.5/5.0/4.5	− 10
		4.8/4.0/3.2	− 15
Group 4	7.0	6.5/6.0/5.2	− 10
		5.5/4.5/4.0/3.0	− 15
		5.0/4.0/3.0	− 20
	8.0	7.5/7.0/5.6	− 10
	9.0	8.5/8.0/5.8	− 10
	10.0	9.5/9.0/6.8	− 10
Group 5	8.0	7.5/7.0/6.0	− 10
		6.5/5.5/4.5	− 15
		6.0/5.0/3.0	− 20
	9.0	8.5/8.0/7.0	− 10
	10.0	9.5/9.0/8.0	− 10
	11.0	10.5/10.0/9.0	− 10

(1) The samples were processed into ϕ61.8 × 125.0 mm cylindrical shape with the flatness of the upper and lower surfaces within ± 0.03 mm and within ± 0.01 mm for the side. Six to nine samples were processed under each test temperature, and the specific conditions of the test are listed in Table 1;

(2) During the creep test, the initial confining pressure was determined from three measured values for test. The middle value is calculated based on the soil weight. The three confining pressures are: (p-1) Mpa, (p) Mpa, and (p + 1) Mpa;
(3) Isotropic consolidation was carried out under a predetermined confining pressure. According to the test requirements, the test terminated when sample deformation was < 0.005 mm/h;
(4) Frozen soil samples after consolidation were placed at four different temperatures (i.e. − 5 °C, − 10 °C, − 15 °C, or − 20 °C) for freezing for at least 24 h;
(5) A series of families of creep curves were established to obtain the creep parameters. Several different stress coefficients k_i can be determined as required by the test, and here, values of 0.3, 0.5, and 0.7 were used;
(6) To freeze the samples after isotropic consolidation, the radial unloading triaxial shear creep test was used with the same radial load. The load value is determined on the basis of $k_i\sigma_s$, where σ_s represents the triaxial shear strength of the frozen soil samples at the same temperature, which is obtained from the shear strength test of frozen soil under the triaxial unloading stress path;
(7) The test ends when the specimen deformation has been stable (in the case of $d\varepsilon/dt \le 0.0005\ h^{-1}$, class I represents the stable creep stage) for > 24 h or has been destroyed (class II represents the accelerating creep stage);
(8) Gradually releasing the confining pressure and axial pressure, remove the samples, describe the damage, and measure the moisture content and density of the frozen soil samples after test;
(9) Repeat steps 1–8 for continued testing.

2.2. Results of the Triaxial creep test

The creep-time relationship curves of the artificial frozen soil samples under unloading conditions were obtained from 54 creep tests performed at different temperatures and consolidation confining pressures with 5 groups of clay, as described in Table 1 and with the results shown in Figs. 1–4.

Fig. 1 presents the triaxial unloading creep curves for the first group of samples (clay 191.0–229.1 m deep), and the results show that:

(1) Artificial frozen soil under an unloading stress path after

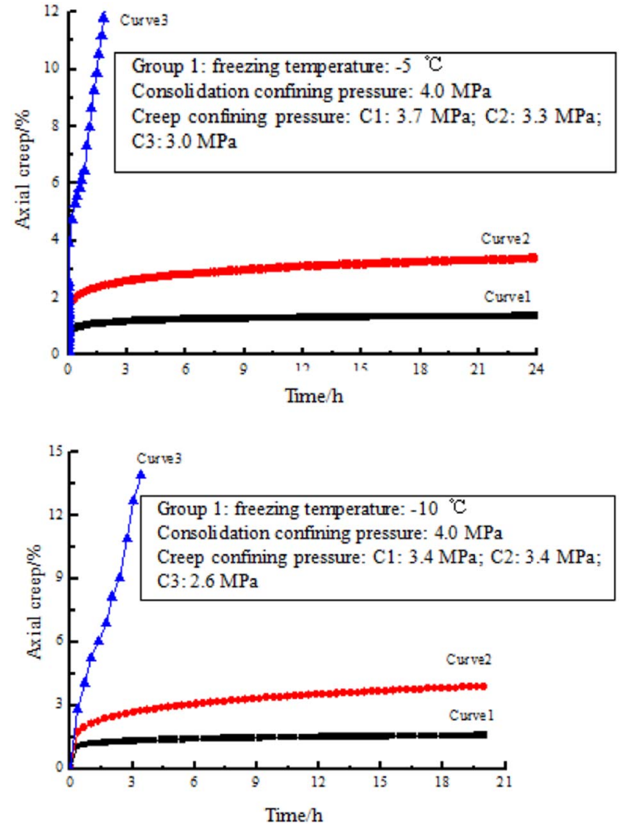

Fig. 1. Triaxial creep curves for the first group of samples.

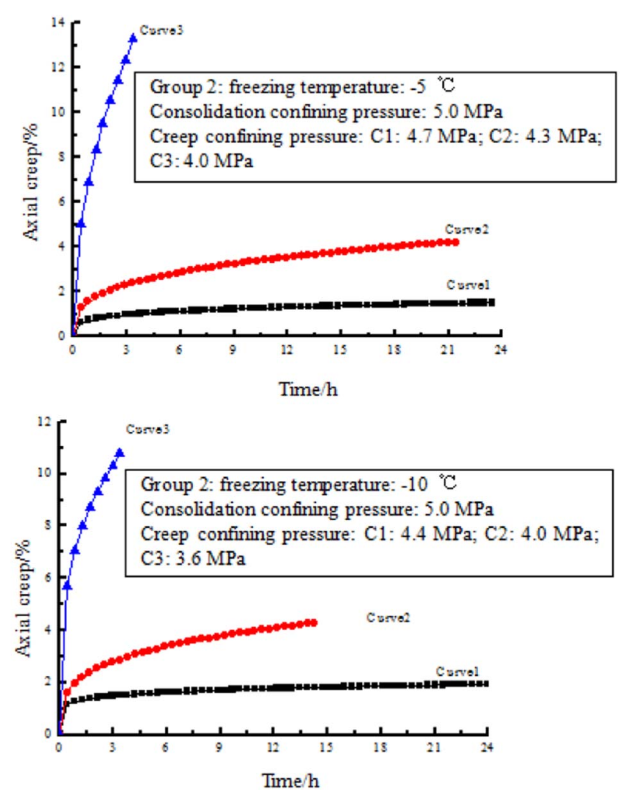

Fig. 2. Triaxial creep curves for the second group of samples.