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# A spherical template indenter for a frozen soil long-term shear strength test

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ABSTRACT

Certain mechanical apparatus have long been considered indispensible to practical engineering design. In particular, the spherical template indenter (STI) has been widely used for permafrost soil testing in the former USSR and Russia. Over the last 60 years, experimental engineering theories and methods have been greatly improved. But the STI has gone largely unchanged, the long-term strength and total deformation modulus analyzed by the impression of STI on soil, simple as it is to use, and effective as it is at quickly measuring the properties and forecasting the long-term strength of frozen soil. This paper makes a brief introduction to the STI apparatus. The capabilities of the STI are shown through a series of test results. It is evaluated under the pretext of being a promising tool for the investigation of frozen soil strength property. Three different methods were used to yield results predicting the long-term strength of frozen loess.



## 1. Introduction

As more infrastructures continue to be constructed in permafrost regions, it's of great importance that builders understand the mechanical properties and long-term shear strength of frozen soil. To determine the capacity of a frozen soil structure, one must first determine the soil's long-term shear strength. Many researchers have conducted tests on the shear strength properties of frozen soil using wedge shear equipment, a direct shear device, or a triaxial apparatus (Zhu, 1988).

There are limitations when using the direct shear test to measure the mechanical properties of frozen soil. For instance, the high strength of the frozen soil makes it difficult to shear. In addition, it's cost prohibitive to control the temperatures of testing sites in the field. Because of these difficulties, a triaxial apparatus is often used to study mechanical property of frozen soil. However, because this device requires a long testing period, and can be expensive to use, it has not been widely adopted in the practical applications (Zhang et al., 2012).

Many researchers have undertaken studies on long-term shear strength by using the triaxial creep test (Zhu et al.,1998; Chen, 1995; Ma et al., 1994, 1997; Mi et al., 1993; Qu et al., 2011; Sheng et al., 1996; Wang et al., 1996; Wu et al., 1997; Yang, 1996; Zhang et al., 1995; Arenson and Springman, 2005; Zhang and Fu, 2011; Yin et al., 2013). These studies are primarily concerned with the changing law of deformation with regard to time, and the myriad factors that influence creep indexes (Lai et al., 2013). The triaxial creep test of frozen soil's long-term and shear strength requires a lengthy process to maintain the uniformity of the samples. Due to the large errors inherent to the sample preparation, the experimental results are often incomparable. In an effort to find a solution to these testing issues, this paper introduces the spherical template indenter (STI) — an instrument that can be used to quickly test and predict frozen soil's long-term strength.

In 1947, Tsytovich was the first to use the instrument to study cohesive force of different soils, such as silt, coarse soils, loess, frozen and other kinds of soils (Tsytovich, 1947). In 1952, Dinnik (1952) adopted the impression of a sphere in a visco-elastic half-space as a basis question in this study, and Chertolyas (1977) used STI to determine compression modulus in thawed clayey soils, then Roman (1987) validated the possibility of determining deformation characteristics for permafrost from data on the impression of STI. In Russia, this method has long been used in the study of frozen soil mechanics long-term shear strength. In the fields of science and construction engineering it has also been highly regarded, and even written into Russia's standard testing procedures for frozen soil testing.

Others have confirmed the notion that this apparatus is well-suited for testing frozen soil (Chamberlain et al., 1972; Ma, 1983; Ourvy, 1985; Zhu, 1988; Zhang et al., 2012). Due to the need of economical constructions, engineering construction in frozen soil regions rises in China, which mainly includes the Qinghai–Tibet Highway, the Xining–Yushu Highway, the Qinghai–Tibet Railway, the Qinghai–Tibet power transmission lines, the Golmud–Lhasa Oil pipe, China–Russia Oil pipe and the West Route of South-to-North Water Diversion (Lai et al., 2013). The STI apparatus has seen increased use in applied research. In fact, a series of test programs were carried out to demonstrate the effectiveness of this device.

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## 2. Apparatus description and theoretical basis

As shown in Fig. 1, the device has three primary parts: the pressure system, support member, and displacement meter. The pressure system is used for loading the samples and includes spherical indenter (4), samples with fresh-keeping film (5), screw cap (6) and horizontal scaffold (7). The support member binds the instrument together and includes bearing plate (3), weight (8) and guide bar (10). The displacement meter (1, 2) measures the depth pressed into a sample by the spherical indenter (4).

The experimental principle of the STI is similar to the Brinnel hardness meter (Tsytovich, 2010). This principle, first proposed by Ishlinskiy, was based on the plasticity theory of ideal viscosity and non-strengthening body (Ishlinskiy, 1945). Tsytovich and Vyalov used the apparatus to determine soil mechanics, and established a theory on frozen soil strength, experimentation, calculation and prediction methods. More recently, Roman expanded upon the application of the apparatus, building a method for calculating the modulus and improving the process for predicting long-term strength.

The shear strength of frozen soil is influenced by the soil skeleton, mineral composition, and structure, as well as the permafrost temperature ($\theta$), water content ($W$), and the time of loading ($t$). Just like with thawed soil, the shear strength of frozen soil is made of cohesive force and internal friction angle, while also qualifying for the Mohr-Coulomb criterion under certain conditions. The shear strength can be calculated with the following procedure (Ma, 1983):

$$\tau = C(\theta, W, t) + \sigma \tan\varphi(\theta, W, t) \tag{1}$$

Frozen clayed-soil is often an ideal viscoplastic body; its internal friction angle $\varphi$ ($\theta$, $W$, $t$) is close to zero, then the above formula (1) can be simplified as:

$$\tau = C(\theta, W, t) \tag{2}$$

In other words, the shear strength will in fact equal the cohesive force. The value of the cohesive force deduced from the theory of plasticity is expressed as (GOST, 1991; Ershov and Roman, 1995):

$$C_t = K\frac{P}{\pi d S_t} \tag{3}$$

where $C_t$ is the cohesion of the per unit area, which changes with time, kg/cm$^2$; $P$ is the vertical load on the ball presser, kg; the proportion coefficient ($K$) is 0.18; $d$ is the diameter of the pressing plate, cm; $S_t$ is the depth pressed into a sample, cm.

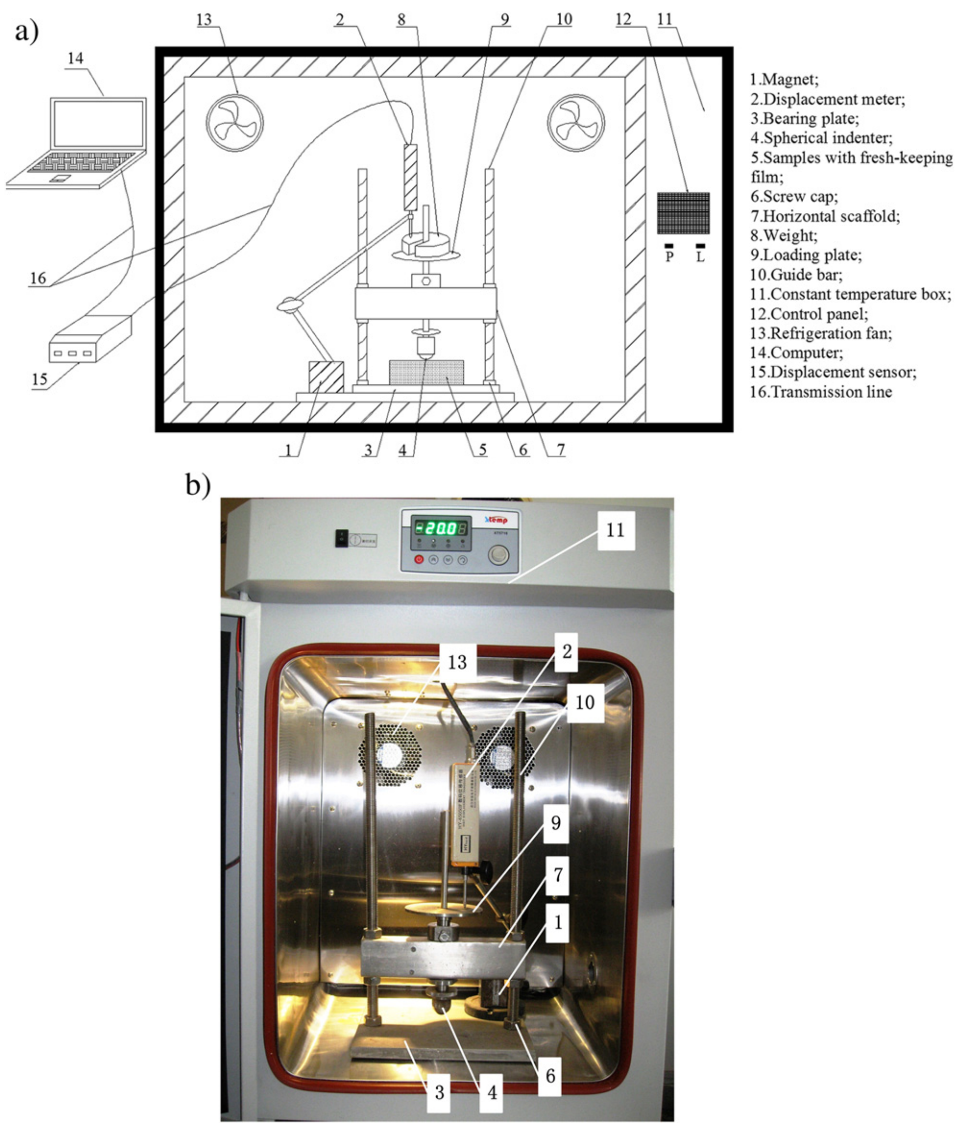


**Fig. 1.** Device of spherical template indenter.