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A novel method for estimating the elastic modulus of frozen soil

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ABSTRACT

In order to provide more reliable design parameters for geotechnical engineering, a completely analytical theory, which based on the assumption of linear elastic deformation in tension, is developed to determine the compressive elastic modulus and the tensile elastic modulus of materials simultaneously. With the Brazilian test method, the quantity-relationship between the displacement and the elastic modulus was derived. Five Brazilian splitting tests are used to check out the operability of the proposed test theory. The results show that the compressive elastic modulus is larger than the tensile elastic modulus under all loading conditions adopted in the test. The two elastic moduli in tension and compression change with the elapsed time when the samples are still in the elastic deformation stage. This is different from the previous consensus that is the elastic modulus is treated as a constant during the elastic deformation stage. This paper explores the reasons for those differences from the calculation method. The test results indicate that the proposed test method is feasible and liable, and can be treated as a convenient way to determine the elastic modulus through the Brazilian test. It was further thought that a new approach could be provided to estimate the compressive and tensile elastic moduli in Brazilian tests.

1. Introduction

The tensile strength characteristics of frozen soil have an important role in the geocryology, both in the fundamental research and the engineering application. On the one hand, tensile strength has a potential influences on ice lens initiation. According to the publicized literatures (Akagawa and Nishisato, 2009; Azmatch et al., 2011; Ming et al., 2016), a new ice lens will be formed when the water pressure, ice pressure or ice-water interface pressure exceeds the sum of overburden pressure and the tensile strength. On the other hand, numerous structures whether they are completed or being under construction in the permafrost regions, the stabilities of the structures are strongly influenced by the macro mechanical characteristics, such as the tensile and the compress behaviors of frozen soil (Christ and Park, 2010; Ma and Wang, 2015). Furthermore, the artificial freezing technique has been widely used in underground engineering (Gianpiero et al., 2015). As a very important parameter of frozen soil, the tensile strength characteristics has a remarkable influence on the stability of the underground engineering and needs farther investigation.

Generally, there are two methods to obtain the tensile strength. The first one is the direct test. The second method is the indirect test. In the earlier studies, in order to investigate the tensile strength of frozen soils, the direct tensile methods were usually carried out on dumbbell samples (Akagawa and Nishisato, 2009; Christ and Park, 2010). However, due to some limitations, such as, difficult sample preparation, poor clamping condition and eccentricity loading, the direct test method was usually not adopted. As an alternative, the indirect method was present and has several forms, such as four point bending test (Azmatch et al., 2011), the Brazilian test (Shen et al., 1994a; Zhou et al., 2015). Since the Brazilian test was invented in 1940s, it has been widely used to determine the tensile strength for rock and concrete materials. Hondros (1959) formulated a complete stress solution for the case of a radial load distributed over a finite circular arcs of the disc. Shloido (1968) through the Brazilian test, investigated the tensile strength of frozen sand, sandy loam, clay and loam. Zhou et al. (2015) studied the tensile strength for frozen soil samples under various temperatures warmer than $-2\,^{\circ}C$ through the Brazilian splitting method. However, concentrated loading will cause the stress concentration and result in the break firstly at the loading point. Latter, some relevant modifications of the traditional Brazilian test were put forward and studied (Cauwellaert and Eckmann, 1994; Yu et al., 2009). As an improved test method, two flats are induced to the Brazilian disc as loading surfaces for improving the stress states (Wang et al., 2004). Furthermore, the International Society for Rock Mechanics (ISRM)

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recommended the Brazilian test as a method for determining the tensile strength of rock materials (ISRM, 1978), the Brazilian test was also standardized by ASTM (2008).

In recent years, many researchers have paid attention to the problem that is how to determine the elastic modulus from the Brazilian test (Cauwellaert and Eckmann, 1994; Wang et al., 2004; Elghazel et al., 2015). Based on the tensile strain, a formula was given to calculate the tensile deformation modulus of rock (Liu, 1996). In order to record the tension strain, two strain gauges were pasted at the center of the disc. However, the result was affected by the length of strain gage. As an improvement, the strain gage was glued horizontally at the central point to record the strain (Ye et al., 2009). Therefore, the result of tensile elastic modulus is more reliable than that determined by Liu's method. Based on the analytical theory presented by Ye et al. (2009), Gong et al. (2010) developed a method to determine the tensile elastic modulus through monitoring displacements between two points located on the circular disc. Liu (2010) used the optical digital image correlation (DIC) technique to obtain the displacement field on the specimen surface and proposed a scheme for determining the elastic constants from the measured displacement field and the applied load. In a conclusion, many researchers have attempted to obtain more information besides the tensile strength of materials from the Brazilian test.

In the previous literatures, the test material was assumed as a homogeneous material. Due to the difference of compressive and tensile behavior of materials, the assumption, the tensile elastic modulus is considered the same with the compressive elastic modulus, is inappropriate for geomaterials. As an improvement, more attention has been paid to the tensile elastic modulus (Liu, 1996; Li and Yin, 1998). To determine the tensile elastic modulus of rock materials, two strain gauges were pasted at the center of a Brazilian disc, and the tensile elastic modulus can be calculated according to those related formula (Ye et al., 2009). A method to determine the tensile elastic modulus through the measured displacement between two points located on the circular disc was present by Gong et al. (2010) and Ye et al. (2012). In order to calculate the tensile elastic modulus through the horizontal displacement, the difference between the compressive and tensile modulus is ignored (Ye et al., 2012). Actually, this simplification is inappropriate for orthotropic materials, such as soil and rock materials.

To summarize, research on the tensile strength characteristics has been focused on the following two aspects: (1) How to determine the tensile strength of soil and rock materials? (2) How can we improve the test method to obtain more accurate test information? On the basis of the primary research, a completely analytical theory is given out to determine the elastic modulus in Section 2. In this theory, the differences of tensile and compressive behaviors are adequately considered. To verify the proposed theory, five Brazilian tests are presented in Section 3. With the help of displacement sensors, both the vertical and horizontal displacements have been measured. Based on the quantitative relationship between the displacement and the elastic modulus, the calculation results of elastic modulus are presented in Section 4. To better understand the proposed theory, some relative contents are discussed in Section 5. Finally, some conclusions are drawn in Section 6.

2. Analytical algorithm to calculate the elastic module

2.1. Principles of Brazilian test

For a traditional Brazilian disc, a pair of diametrically opposite, symmetric and compressive line loads were applied to a disc (Fig. 1). For an isotropic Brazilian disc subjected to concentrated loads, the solution for the stress can be described as (Muskhelishvili, 1958),

$$\sigma_x = \frac{2P}{\pi L}\left[\frac{\sin^2\theta_1\cos\theta_1}{r_1} + \frac{\sin^2\theta_2\cos\theta_2}{r_2}\right] - \frac{2P}{\pi DL} \quad (1)$$

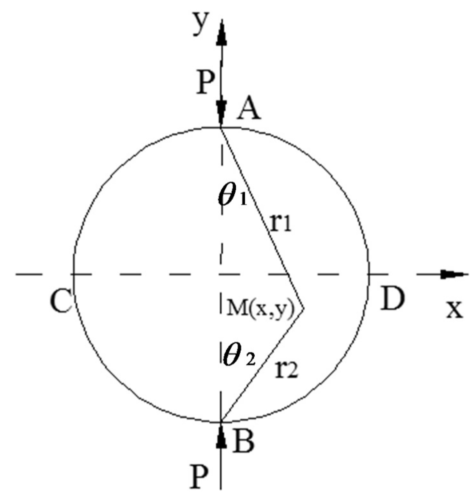

Fig. 1. Loading state of the Brazilian disc.

$$\sigma_y = \frac{2P}{\pi L}\left[\frac{\cos^3\theta_1}{r_1} + \frac{\cos^3\theta_2}{r_2}\right] - \frac{2P}{\pi DL} \quad (2)$$

where σ_x is the normal stress in x-direction; σ_y is the normal stress in y-direction; P is the applied loading; L is the length of the sample; D is the diameter of the sample; θ_1 and θ_2 are the angles; r_1 and r_2 are the distances from the point M to the loading contact points A and B (Fig. 1), respectively.

2.2. Stress field of the Brazilian test

According to the geometry relationship (Fig. 1), the following formula can be written,

$$\cos\theta_1 = \frac{0.5*D + y}{r_1} = \frac{0.5*D + y}{0.5*D + y^2 + x^{20.5}} \quad (3)$$

$$\cos\theta_2 = \frac{0.5*D - y}{r_2} = \frac{0.5*D - y}{0.5*D - y^2 + x^{20.5}} \quad (4)$$

$$\sin\theta 1 = \frac{x}{r1} = -\frac{x}{((0.5*D + y)^2 + x^2)^{0.5}} \quad (5)$$

$$\sin\theta_2 = \frac{x}{r_1} = -\frac{x}{0.5*D - y^2 + x^{20.5}} \quad (6)$$

Substituting Eqs. (3)–(6) into Eq. (1) and Eq. (2),

$$\sigma_x = \frac{2P}{\pi L}\left[\frac{0.5*D + y*x^2}{0.5*D + y^2 + x^{22}} + \frac{0.5*D - y*x^2}{0.5*D - y^2 + x^{22}} - \frac{1}{D}\right] \quad (7)$$

$$\sigma_y = \frac{2P}{\pi L}\left[\frac{0.5*D + y^3}{0.5*D + y^2 + x^{22}} + \frac{0.5*D - y^3}{0.5*D - y^2 + x^{22}} - \frac{1}{D}\right] \quad (8)$$

The stress field of the Brazilian disc based on elasticity mechanics has been known completely according to Eqs. (7) and (8). It is the theoretical foundation for measuring the elastic modulus of material through the Brazilian test.

2.3. Estimation of elastic modulus

From the view of physical and mechanical property of the geotechnical materials, the difference between compressive and tensile elastic modulus should be considered in the analytical solution of stress field in the Brazilian test. It means that the strain is influenced by both the compressive elastic modulus and the tensile elastic modulus.

When the point M on the x-axis ($y = 0$), then Eqs. (7) and (8) can be simplified as,

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