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Frost-heaving pressure in geotechnical engineering materials during freezing process

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ABSTRACT

Energy and resources including coal, oil, and gas are in demand all over the world. Because these resources near the earth's surface have been exploited for many years, the extraction depth has increased. As mining shafts in the coal extraction process become deeper, especially in western China, an artificial freezing method is used and is concentrated in the fractured rock mass. The frost-heaving pressure (FHP) is directly related to the degree of damage of the fractured rock mass. This paper is focused on FHP during the freezing process, with emphasis on the frost-heaving phenomenon in engineering materials. A review of the frost phenomenon in the geotechnical engineering literature indicates that: (1) During the soil freezing process, the ice content that is influenced by unfrozen water and the freezing rate are the determining factors of FHP; (2) During the freezing process of rock and other porous media, the resulting cracks should be considered because the FHP may damage the crack structure; (3) The FHP in a joint rock mass is analyzed by the joint deformation in field and experimental tests and can be simulated by the equivalent expansion method including water migration and joint deformation.

1. Introduction

Frost heaving of a rock-soil mass is a problem that exists in many geotechnical engineering applications, such as tunnel and slope engineering in cold regions, underground storage of liquefied natural gas and petroleum gas, and deep mining shaft construction using an artificial freezing method. Engineers and researchers have observed the extensive effects of frost-heaving pressure (FHP) in geotechnical engineering. Much research has been conducted on frozen soil, such as the physical and mechanical properties of frozen soil, the frost heave theory of frozen soil, and the interaction of frozen soil and structures [1–3]. However, research is lacking on details of frozen rock especially with regard to the effects of freezing on joint rock. Because the physical and mechanical properties of soil are mainly influenced by water or ice in the soil, the rock's properties are also mainly controlled by water or ice.

The joints in the rock mass represent important geological structures that determine the stability of the rock, especially in a fractured rock mass. Since the rock's strength is usually determined by the strength of the discontinuity, the properties of the joint rock are mainly influenced by ice in the joints during freezing temperatures. When the water in the joint rock freezes, the volumetric expansion of the joint fillings will be constrained by the surrounding rock mass and the frost heaving pressure will increase due to the phase change. If the pressure exceeds the strength of the rock mass, the joint rock will break. If so, the tunnel, shaft, storage cave, or other construction will be in danger [4,5]. Furthermore, low temperatures, especially temperatures below the freezing point, significantly affect the stability of the surrounding rock in many rock engineering projects. When the rock is exposed to low temperatures and freezing conditions for a long time, the deformation and intensity properties of the fractured rock mass change greatly.

The effective calculation of the frost heaving pressure is useful for the design theory to the above the geotechnical engineering. With regard to shaft construction using the freezing method, Zhou and Zhou established a model describing the growth processes of the active ice lens in soils and thereby improved the method for determining frost-heaving pressure [6]. Based on the interaction between a frozen wall and the surrounding rock, the elastic-plastic design theory was developed for the sinking of mine shafts using a freezing process [7]. The same authors provided details for the frost-heaving pressure occurring between the different engineering walls. In a study of a cold region rock tunnel, the occur-

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rence and expansion of the frost-heaving pressure were calculated and analyzed by using a finite element method to prevent and reduce frost damage [8].

2. Frost-heaving pressure in soil

The frost-heaving phenomenon in soil describes the volume expansion caused by the phase change of water in the soil into ice. The observable results of this phenomenon are the amount of frost heaving and the frost heaving pressure. Both are influenced by the water content and the properties of the soil. Temperature and pressure in the environment have critical effects on the frost heave. The frost-heaving pressure is also controlled by the confining boundaries that may exist around the soil.

The secondary frost heave theory of frozen soil is widely accepted [9]. Several assumptions about the ice pressure are given. If the cold side plane of the warmest lens, which consists of pure ice, must bear the overburden, the ice pressure equals the overburden. According to the similarities between freezing and drying, the total pore stress or "neutral" stress σ_n is $\sigma_{\rm n} = \chi u_w + (1 - \chi)u_i$, where χ is a weighting factor that is evaluated and can be affected by the unfrozen water content and the porosity of the soil, and u_w and u_i are the water pressure and ice pressure, respectively. In the ice segregation model, the lowest lens position is approximately considered as a constant. O'Neill reviewed the physics of mathematical frost heave models in frozen soil at length. The pressure in the ice where frost heaving occurs was obtained using several different methods. The main factors influencing the ice pressure are the temperature and the unfrozen water content.

Because frost heaving caused by freezing of water in situ is very small, it can be ignored from the perspective of engineering because frost heaving of soil is mainly caused by water migration [10].

The volumetric strain of frozen soil induced by freezing migrating water and original water was described by Yang et al. [11]. The volumetric strain increment $d\varepsilon^h$ is described by the following two equations:

$$d\varepsilon^h = 0.09d(W_0 - W_u) + 1.09dW_l \quad (1)$$

where W_0 is the initial volume fraction of water; $W_{\rm u}$ is the volume fraction of unfrozen water, which is the difference between the volume fraction of water (including original water and water migration) and the volume fraction of frozen water; $d(W_0 - W_{\rm u})$ is the increment of ice volume fraction of the original water; and $dW_{\rm l}$ is the increment of pore water volume fraction or the water migration quantity, where the migration water is generally completely frozen, and can be described as follows:

$$\begin{cases} dW_1 = \frac{dq}{V} = q_2 - q_1 \\ q = m\sqrt{T_t} + n \end{cases} \quad (2)$$

where q_1 and q_2 are the total inflow q per volume at time t_1 and t_2, respectively; m and n are constants depending on the condition of the water supply and the soil properties; and T_t is the freezing time.

By applying the analysis model, which couples temperature, water, and stress fields, to a tunnel corridor excavation, Yang et al. found that the design parameters affecting the frost heave were the thickness of the overlaying soil and frozen wall, the excavation radius, and the cooling brine temperature [11]. All of the design parameters had almost no effect on the position of the maximum horizontal displacement. An increase in the thickness of the frozen wall increase the maximum frost heave at the ground surface.

Zhang et al. explored the water migration and other frost heave mechanisms using soil samples with three levels of soil saturation: 34.78%, 61.40%, and 100.00% [12]. The water migration volume, heaving or settlement, pore water pressure, and permeability explained the degree of frost heave in coarse sandy soil. The tests indicated that the phase change of water occurred when the rate of temperature and temperature gradient changed.

Ma et al. conducted experiments with regard to pore water pressure during soil freezing, as shown in Fig. 1, where T_0 is the freezing point, $T_{\rm s}$ is the segregation temperature, and $T_{\rm l}$ is the critical temperature when the phase change of water into ice almost complete [13]. During soil freezing, the pore water pressure undergoes three phases. In the first phase, the temperature is higher than T_0 and the pore water pressure reaches the maximum pressure. In the second phase, as the phase change occurs in the frozen fringe, the pore water pressure drops as the temperature decreases. The pressure reaches a minimum when the phase change of water into ice is complete. In the third phase, the pore water pressure increases slightly and is controlled by the mechanical equilibrium.

A simulation model is given by Wu et al. to calculate the total water content in the soil during the freezing process [14]. The total volumetric water content θ_{tw} is expressed as $\theta_{tw} = \rho_i\theta_i/\rho_w + \theta_w$, where ρ_i and ρ_w are the density of ice and water respectively, θ_i and θ_w are the volume content of ice and water respectively, $\theta_{\rm i} + \theta_{\rm w} = n$, and n is the porosity of the test sample. During the freezing process, the volumetric strain ε_v can be calculated as $\varepsilon_v = \theta_i + \theta_w - n_0$, where n_0 is the initial porosity. The total frost heave can be described as follows (Fig. 2):

$$H = \frac{\int_\Theta \varepsilon_v d\Theta}{\int_\psi d\psi} \quad (3)$$

where H is the frost heave amount; and Θ and ψ are the volume and the cross-sectional area of the soil sample, respectively.

A new non-destructive method can be used to measure the amount of unfrozen liquid water by using a multifunctional instrument that includes a time-domain reflectometry sensor and thermal pulse technology [15]. This method was applied to monitor soils during the freeze-thaw cycle and the results showed that the new sensor functioned properly. The variation in the degree of freezing as related to temperature is shown in Fig. 3.

In the macroscopic view, the frost heave pressure in the soil induces the deformation of the soil. Under low temperatures, especially temperatures below the freezing point of water, the soil will expand with the phase change of water into ice. When the soil deformation is constrained by a surrounding boundary, the frost heave pressure will occur around the frozen soil body. Since the actual change in volume of the soil particles is very small, the soil volume change is caused for the most part by the water in the soil. Usually, there are two sources of water in the soil, one is the initial water content, and the other is the water migrating from outside sources. These two water sources will decide the amount of frost heave. In addition, after the freezing process, some water in the soil will remain in the liquid state. The unfrozen water content and the migration water content are the key factors that influence the FHP and are decided for the most part by the soil properties and can be obtained using experimental data and empirical equations.

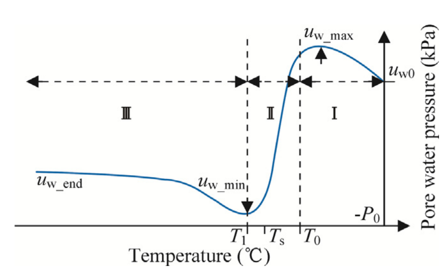

Fig. 1. Changes in pore water pressure during freezing (modified from [13]).

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