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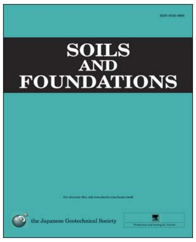

Application of practical one-dimensional frost heave estimation method in two-dimensional situation

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Abstract

Most of the presently available practical frost heave prediction methods were derived from and for one-dimensional (1D) situations. However, the real desire of engineers is a multi-dimensional frost heave analysis. It is convenient to simply accumulate numerous experimental data on original 1D practical methods and then expand them for multi-dimensional applications. However, when such equations are applied to multi-dimensional situations, the first issue encountered is how to deal with the distribution of frost heave. To solve this issue, the authors propose one simple, but effective, method for allocating the frost heave ratio in multi-dimensional spaces. Takashi's equation is taken as an example to demonstrate this proposed distribution method. The equation was originally derived from 1D indoor frost heave experiments. It can predict the frost heave ratio in the freezing direction based on the freezing rate and the constraining stress. To obtain these two factors, thermal and mechanical analyses are combined together. With respect to the heat transfer process, the latent heat produced by the phase change of water is carefully evaluated by the equivalent heat capacity method. Concerning the distribution of the frost heave ratio, anisotropic parameter β is proposed to assign the frost heave ratio in the freezing direction and its transverse direction. By adjusting the value of β, the simulation results can very closely reflect the situation in reality. In addition, the authors discuss the relationship between frost heave and anisotropic parameter β in detail. Based on this assumption, the results of indoor frost heave tests and a large-scale field experiment are illustrated to verify this method, which simultaneously provides valuable examples for a multi-dimensional frost heave evaluation.

Keywords: Frost heave; Takashi's equation; Anisotropic distribution; Coupled analysis; Finite element method (IGC: E09/E13)

1. Introduction

Nowadays, modern industrialized countries depend on huge amounts of fossil fuels for energy, most of which are provided by natural gas and oil. Therefore, it is not surprising that cold regions attract much more attention than ever before due to their large energy reserves. These fuels are mainly transported by pipelines that may stretch for thousands of kilometers over cold regions and across various types of soils. When a chilled gas pipeline passes from a non-frost-susceptible soil to a frost-susceptible soil or from a pre-frozen soil to a freezing soil, the pipeline may be subjected to different movements caused by the development of uneven frost heave at the interface of two

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soils, which can cause serious damage to the pipeline. In fact, frost heave and its related issues are the most common reason for structural damage in cold areas, and not only to the pipelines (Oswell, 2011). With this background, therefore, various methods have been developed during the last several decades in an attempt to evaluate frost heave.

From a theoretical viewpoint, the microscopic mechanism of the frost heave process has remained controversial until now. In an early study on frost heave, Taber (1930) demonstrated experimentally that benzene or nitrobenzene in a porous medium could cause frost expansion. This finding indicated that frost heave is produced by water migration, not simply by volume expansion that occurs when in-situ water freezes. For a quantitative analysis, Edlefsen and Anderson (1943) advanced the generalized Clausius-Clapeyron equation (GCCE), which is widely accepted in the frost heave field. Ma et al. (2015) discussed the applicability of GCCE and then proposed two models based on GCCE: the static model and the dynamic model. On the other hand, some researchers (Penner, 1959; Everett, 1961) suggested that the water migration process during frost heave is very similar to the capillary rise of water into a dry porous medium, driven by surface tension at the interfaces between ice and pore water. This theory is widely known as the capillary theory of frost heave. Later, a number of researchers, for example, Tutunov (1961), Tsytovich (1973), and Feldman (1988), noted that the capillaries were merely the paths of moisture migration, and therefore, not suitable for considering capillary action as the driving force of water migration during frost heave. Another distinguishing feature of frost heave is that unfrozen water plays a very critical role in the frost heave developing process. We know that in soils, such as silt, clay, and loam, only a portion of the pore water freezes at the freezing point, while some of the pore water remains at a sub-freezing temperature. This unfrozen water content depends on the specific surface of the soil (Anderson and Tice, 1973; Fukuda et al., 1997; Michalowski and Zhu, 2006). In addition, this unfrozen water content is an important property of freezing soils, which can affect the water distribution in both the frozen fringe and the frozen zone. However, although extensive studies have been conducted to explain the mechanism of frost heave and the growth of ice lenses, numerous questions remain that must be answered in order to obtain a complete and convincing understanding of the physics of frost heave (Peppin and Style, 2013). Therefore, some researchers have attempted to provide a practical evaluation method for frost heave, and several studies have been conducted over the last several decades to identify appropriate methods for estimating the frost heave ratio. Konrad and Morgenstern (1984) proposed a frost heave estimation model called the segregation potential theory. They (Konrad and Morgenstern, 1984; Konrad and Shen, 1996; Nixon, 1992) also applied this segregation potential method for predicting frost heave using a numerical simulation. This method is the most widely accepted practical model in North America. However, one critical aspect of frost heave is not included in this model, namely, the freezing rate. Instead, the segregation potential method adopts the temperature gradient to represent the thermal influence on frost heave. Furthermore, Groenevelt and Grant (2013) pointed out that the driving force in the segregation potential model should be the temperature gradient over the complete layer of the soil at sub-zero (°C) temperatures, that is, the combined frozen zone plus the frozen fringe, not just the temperature gradient in the frozen fringe. The other widely accepted frost heave estimation model was proposed by Takashi et al. (1978) in Japan, which is referred to as Takashi's model. This model has been successfully applied to the design of liquid natural gas tanks in Japan, and it considers the influence of the constraining stress and the freezing rate in the freezing direction on the frost heave ratio.

In this paper, the objective is to solve the expansion difficulties when the existing 1D practical method is applied to multi-dimensional situations. Takashi's equation, derived from 1D indoor frost heave tests, is adopted as the theory foundation of expansion. Regarding the anisotropic property of frost heave, a simple, but effective, assumption is proposed. Parameter β is introduced to allocate the frost heave ratio in the freezing direction and its transverse direction. This idea is then applied in real 1D and 2D simulations to verify the applicability of this method. The comparison between the 2D simulation and large-scale frost heave tests can provide valuable reference for further multi-dimensional frost heave studies. In addition, the relationship between the amount of frost heave and the β parameter is discussed based on specific examples.

2. Practical frost heave evaluation equation

Frost heave is mainly caused by volume expansion when water turns to ice. If water migration is not considered and the water in the soil is completely frozen, the frost heave ratio should equal the inflation ratio of ice, namely, 9%. In reality, however, the amount of frost heave is obviously larger than 9%, for example, the very common phenomenon in arctic areas, Pingo, the height of which can be up to 70 m. This phenomenon also demonstrates that water migration is the main reason for frost heave, not in-situ freezing.

Until now, no theory has been able to explain all the observed phenomena associated with the frost heave process. Therefore, a practical method to estimate the frost heave ratio is a good alternative. Practical methods do not require detailed knowledge of the situation occurring during the frost heave process. They only focus on the factors that can affect the frost heave ratio, such as temperature, stress, and the soil characteristics. The segregation potential method is one of the widely accepted practical methods; it is applied in Canada and America (Konrad, 2002, 2005; Konrad and Morgenstern, 1981, 1984; Konrad and Shen, 1996; Miller, 1978) for frost heave estimations. In Japan, Takashi et al. (1978) proposed a practical frost heave estimation equation based on numerous 1D indoor frost heave tests. Both of these methods consider stress, temperature, and the material constants. However, the segregation potential method uses the temperature gradient instead of the freezing rate to represent the thermal influence on frost heave. As is widely accepted, the freezing rate, not the

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