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Research Paper

Frost jacking characteristics of screw piles in seasonally frozen regions based on thermo-mechanical simulations

Tengfei Wang [a], Jiankun Liu [a,b,*], Bowen Tai [a], Chuanzhen Zang [a], Zhichun Zhang [c]

[a] School of Civil Engineering, Beijing Jiaotong University, Haidian District, Beijing, China
[b] Qinghai Research and Observation Base, Key Laboratory of Highway Construction & Maintenance Technology in Permafrost Region, Qinghai Research Institute of Transportation, Xining, Qinghai, China
[c] Shenshuo Railway Branch of China Shenhua Energy Co., Ltd, Yulin, Shanxi, China

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ABSTRACT

In this paper, a thermo-mechanical model is proposed to simulate the frost jacking behaviour of screw piles subjected to frost heave, and the results are further validated by laboratory tests. The calculated results show that large multi-helix piles yield the least frost jacking when the freezing depth reaches half the embedment depth of pile. Based on the modified cylindrical shear method and individual bearing method, the optimal geometric parameters of screw piles are determined by a series of numerical calculations. The numerical approach is expected to serve as a reference for designing effective and economical pile types in practice.

1. Introduction

Seasonally frozen soil is defined as soil or rock having a monthly mean temperature below 0 °C during cold seasons for at least one year and is characterized by a discontinuous distribution [1]. In China, the seasonally frozen region is approximately 5.13×10^6 km^2, accounting for 53.5% of the total land area, and it is mainly distributed in the northern and eastern parts. To date, many artificial structures have been built in these seasonally frozen regions, e.g., photovoltaic generation projects in Inner Mongolia. Photovoltaic frames with panels are generally installed in light-rich areas, which extensively overlap with the seasonally frozen regions. Consequently, widespread frost heave of soil occurring in winter imposes severe challenges to the normal operation of the photovoltaic panels. According to some researches on tower foundations along the Qinghai-Tibet Power Transmission Line, uneven frost jacking of the foundations with the development of the ground freezing process may lead to total failure of the superstructures [2,33,34]. As a result, systematic investigations of frost damage to the foundations of photovoltaic structures are required.

To address these problems, screw piles have been widely applied because they can be quickly installed, are reusable, removable and cost effective, produce little noise and vibration during installation, require minimal dewatering and equipment, and offer high tensile capacity, which is the most distinctive superiority in this study (mitigating frost jacking) [3–8]. Initially, the screw piles were utilized to bear tensile loads (e.g., foundations of transmission towers and pipelines), and then their applications were further extended to structures and infrastructure exposed to compressive and lateral loads [5]. In contrast to conventional piles, screw piles are commonly made of steel with helices fixed to the shaft at a certain spacing, and at most cases, the existence of a pointy toe guarantees better installation into the ground [9]. Screw piles with various helix and shaft diameters, helix spacing, embedment depths, etc., are adopted for diversified working conditions. The mechanical interlock between the helices of the screw piles and the soil greatly improves the strength of the pile-soil system, thus screw piles have unique advantages in anti-jacking projects in seasonally frozen regions.

Mohajerani et al. [10] reviewed the analysis and design methods of screw piles, which have mainly been centred on vertically loaded piles in compression and tension in both cohesive and non-cohesive soils. A series of laboratory tests were conducted to evaluate the anti-frost jacking abilities of several screw piles with various types of helices [11]. Abdrabbo and Wakil [12] studied the responses of horizontally loaded screw piles with different helix diameters, numbers, and spacing. A numerical method was presented to simulate screw displacement piles interacting with

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* Corresponding author at: School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China.
E-mail address: jkliu@bjtu.edu.cn (J. Liu).

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non-cohesive subsoil during the transfer of compression load by using the Plaxis 2D program [13]. The uplift behaviour of helical anchors in clay was investigated using finite element limit analysis, and the factors that influence the model uncertainty of the cylindrical shear method were also examined [14]. A finite element method was performed to simulate nonlinear responses of a steel pile embedded in frozen ground at a field test site in Alaska [15]. Liu et al. developed a numerical model to simulate the stress-strain relationships in the pier and in the surrounding frozen soil [36]. However, there is little information in the literature on numerical simulations regarding screw piles and frost jacking.

The main objective of this paper is to compare the frost jacking abilities of different screw piles and determine the optimal geometric parameters of screw piles subjected to frost heave. The paper is organized as follows. First, a numerical model is established for the screw piles in seasonally frozen regions on the basis of heat transfer, mechanical deformation and temperature-related properties of soil. Then, several types of screw piles adopted in laboratory tests, including one with no helix, are taken as examples to simulate the freezing process and frost jacking behaviour of piles using a numerical approach. Finally, the theoretical calculation methods for the uplift capacities of screw piles in frozen soil are modified, through which optimal designs are determined to resist frost jacking. Inherent mechanisms are explained from the perspectives of the modified cylindrical shear method and individual bearing method. This study offers a better understanding of the frost jacking process of screw piles under one-dimensional freezing conditions.

2. Mathematical formulation

2.1. Thermo-mechanical model

In freezing soil, heat convection is negligible compared with heat conduction and the latent heat of water-ice phase changes [16,17]; hence, the energy conservation equation in soil can be written as

$$C\frac{\partial T}{\partial t} = \nabla\cdot(\lambda\nabla T) + L\rho_i\frac{\partial\theta_i}{\partial t} \tag{1}$$

where C denotes the heat capacity per unit volume, T is temperature, t represents time, $\nabla\cdot$ denotes the divergence, λ denotes thermal conductivity, θ_i represents the volumetric ice content, ρ_i denotes ice density, and L denotes the latent heat of ice-water phase change.

As no water transport equation is applied in the model, Q is introduced to replace the last term in Eq. (1), and it is defined as the heat change per unit volume of the soil due to the water-ice phase change [1],

$$Q = L\rho_d(w - w_u) \tag{2}$$

where ρ_d is the dry density of the soil, w denotes the gravimetric moisture content, and w_u represents the gravimetric content of unfrozen water. For common thermal cases, w_u of the cohesive soil can be expressed by [1]

$$w_u = K(T)\cdot w \tag{3}$$

where K denotes the correction coefficient varying with temperature.

Introducing Eq. (2) into Eq. (1), yields

$$C\frac{\partial T}{\partial t} = \nabla\cdot(\lambda\nabla T) + \frac{\partial Q}{\partial t} \tag{4}$$

The equilibrium equation is given as follows:

$$\nabla\cdot\sigma_{ij} + \rho g_i = 0 \tag{5}$$

where $\nabla\cdot$ denotes the divergence, σ_{ij} represents the total stress tensor, ρ denotes the density of the material, and g_i is the gravity vector. The stress tensor can be written as [18]

$$\sigma_{ij} = C_{ijkl}(\varepsilon_{ij} + I_{kl}\varepsilon_{inel}) \tag{6}$$

where C_{ijkl} denotes the stiffness tensor, which is associated with the material parameters such as Young's modulus E and Poisson's ratio υ, ε_{ij} is the total strain tensor, $\boldsymbol{I}_{kl}$ is the identity matrix, and ε_{inel} represents the strain induced by temperature variation, which is expressed as follows:

$$\varepsilon_{inel} = \alpha(T - T_0) \tag{7}$$

where α denotes the thermal expansion coefficient of the material, and T_0 is reference temperature. In this study, nonlinear relationship is established between ε_{inel} and temperature, which is realized by parameter α. That is to say, the thermal expansion coefficient α is treated as a linear expansion coefficient varying with negative temperature as follows:

$$\varepsilon_{inel} = \alpha(T)\cdot 1 \tag{8}$$

The volumetric strain ε_v is defined as

$$\varepsilon_v = \frac{\Delta V}{V_0} \tag{9}$$

where ΔV and V_0 represent volume change and initial volume, respectively. Then, the relationship between α and ε_v can be obtained on the basis of equivalence principle:

$$\alpha = \sqrt[3]{\varepsilon_v(T) + 1} - 1 \tag{10}$$

The volumetric strain ε_v used in this analysis is determined from a series of laboratory tests by wax coating method at a set temperature.

The frost heave ratio η is defined as

$$\eta = \frac{\Delta h}{H_f} \tag{11}$$

where Δh is confined frost heave, H_f denotes the freezing depth.

2.2. Design method and modification: tensile capacity of screw piles in cohesive soil

Fig. 1 shows the basic elements and parameters regarding the screw piles, where D = diameter of pile helix, d = diameter of pile shaft, S = helix spacing, H = embedment depth of the pile to the top helix, t = helix thickness, and φ_h = declination angle of the helix. In most cases, two possible failure mechanisms for screw piles are considered depending on the relative spacing of the helical plates (S/D). To calculate the tensile bearing strength of the screw piles, it is suggested that the cylindrical shear method (Fig. 2a) be used for close helix spacing $S/D \le 3$, whereas the individual bearing method (Fig. 2b) should be employed for $S/D > 3$.

The cylindrical shear method was introduced by Mooney et al. [19] for screw piles in silt and clay. The possible failure mode is that a cylindrical shear failure surface will develop connecting the top and bottom helices as shown in Fig. 2a. The tensile bearing strength Q_t will be a combination of shear resistance along the soil between the helices and the top helix plate bearing and the frictional resistance offered by the soil-shaft interface [10,14], given by

$$Q_t = \pi DS_f(n-1)Sc_u + A_h(N_u c_u + \gamma' H) + \pi dH_{eff}\alpha_0 c_u \tag{12}$$

where D is pile helix diameter, S_f is the spacing ratio factor, n denotes the number of helix plates, S represents the spacing between two adjacent helix plates, c_u denotes the undrained shear strength, A_h is projected area of the helix, γ' is effective unit weight of soil, H is the embedment depth of the top helix, d denotes the diameter of the pile shaft, $H_{eff} = H{-}D$, which is the effective length of the pile above the top helix due to the 'shadowing effect' of a loss