Cold Regions Science and Technology 132 (2016) 44–59

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Time-scales for the redistribution of stress in the course of pressuremeter creep tests in permafrost

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ARTICLE INFO

Article history:
Received 6 November 2015
Received in revised form 12 August 2016
Accepted 3 September 2016
Available online 7 September 2016

Keywords:
Nonlinear creep
Stress redistribution
Large strain
Non-stationary
Finite element
Time scale

ABSTRACT

This study deals with nonlinear creep and the time taken for completion of the stress redistribution process within a borehole scenario. Specifically, the pressuremeter test, with emphasis on a step loading of long duration, in ice saturated frozen soils is analyzed. A closed form stationary creep solution based on the model of a thick cylinder under plane strain condition, that considers large strains, is first developed. Subsequently non-stationary creep finite element analyses were carried out via this model and an assumption-relaxed model that considers the actual geometry of a typical pressuremeter test (where the net cavity pressure is applied only on a portion of the borehole cavity). Finally estimates of the extent to which stress redistribution occurs is numerically considered by revisiting classical theories and proposing a time scale by introducing a redistribution index, RI.

1. Introduction

The determination of constitutive equations for the analysis of foundations in permafrost areas necessitates a suitable tool for in situ evaluation of the rheological properties of frozen soils. In situ investigations are advantageous when compared to laboratory measurements not only for reasons related to the scale of the tests, but because soil properties are obtained with minimal physical and thermal disturbance of the frozen ground.

As demonstrated in this theoretical study, the pressuremeter could fulfill this role provided one accounts for the stress redistribution phenomenon triggered by nonlinear creep of the frozen soil. In order to correctly interpret the creep field test results, a proper evaluation of a time scale is necessary.

The borehole pressuremeter in frozen soils is best described in the pioneer works of Ladanyi and Johnston (1973) and Ladanyi and St-Pierre (1978). These studies were among the first in the area of frozen ground engineering to address the issues of stress redistribution in the early phase of a borehole creep test. Specifically they indicated that reliable results are obtained only if sufficient time is allowed for the stress to redistribute. As a consequence, various authors have recommended correction factors in order to time shift the resulting experimental curves (Murat et al., 1989, Ladanyi and Huneault, 1987, Ladanyi and Eckart, 1983). This task is extremely complicated because stress redistribution is a nonlinear process that depends not only on the level of the applied stress, but on the initial stress as well. For this reason, Ladanyi and Huneault (1987) propose a correction factor which linearizes a revisited but modified form of the Calladine (1969) theory.

This paper examines the pressuremeter test with a special emphasis on the phenomenon of stress redistribution in an ice saturated frozen soil. The frozen soil is modeled as a nonlinear viscoelastic medium Ladanyi (1972). This constitutive model is generally adopted for ice saturated soils where experimental evidence suggests the absence of a threshold stress upon which initiation of the creep process rests (Foriero et al., 2005). A frozen ice saturated soil is regarded as a single phase material where soil particles are more or less embedded in an ice matrix whose macroscopic behaviour is different than that of its constituent components.

Generally, two quantitative parameters are used to describe the ground ice conditions that leads to this macroscopic behaviour (Khublaryan, 2009). The first is based on the ice content (the ratio of the weight of the ice to that of the dry soil in percentage). Ice rich soils have ice contents that normally range between 50 and 100%. The second is based on the amount of excess ice. Excess ice refers to the amount of supernatant water present (the volume of supernatant water expressed as a percentage of the total volume of soil and water) if a vertical column of frozen soil were thawed. A frozen soil that contains excess ice is considered as an ice rich soil.

Particular attention to two different physical models of the pressuremeter test is also addressed in this paper. The pressuremeter test entails the drilling of a borehole into which an expandable probe (Fig. 1) is introduced, thus producing axisymmetric loading and geometry. Researchers generally interpret the problem as that of a thick walled cylinder under a plane strain condition (Foriero and Ciza, 2016,

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http://dx.doi.org/10.1016/j.coldregions.2016.09.006

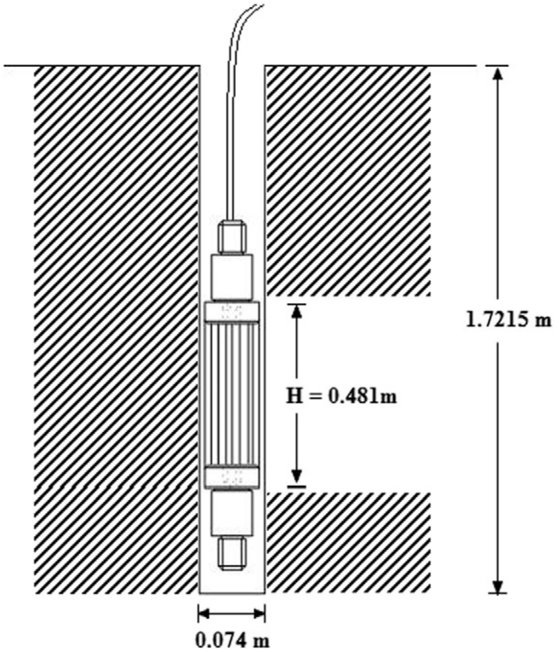

Fig. 1. A typical pressuremeter-probe geometry for insi-tu testing.

Ladanyi and Foriero, 1998). This approach will be examined both analytically and numerically within the context of stress redistribution. The other physical model scrutinized in this work is to relax the plane strain condition and model the pressuremeter test as closely as possible to the conditions on site. In this case a numerical treatment with respect to stress redistribution is also carried out. The primary goal of this study is to determine realistic redistribution times in the context of pressuremeter testing in frozen ice saturated soils. For this reason, the implication of using a particular model over another is discussed.

2. The implications of modeling the pressuremeter test as an expanding cylindrical cavity

The general (three dimensional) partial differential equations of equilibrium in cylindrical coordinates are given in terms of the Cauchy stresses in the deformed state as

$$\begin{aligned} &\frac{1}{r}\frac{\partial}{\partial r}(r\sigma_{rr})+\frac{1}{r}\frac{\partial}{\partial\theta}(\sigma_{r\theta})+\frac{\partial}{\partial z}\sigma_{rz}-\frac{\sigma_{\theta\theta}}{r}+f_r=0\\ &\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\sigma_{\theta r})+\frac{1}{r}\frac{\partial}{\partial\theta}(\sigma_{\theta\theta})+\frac{\partial}{\partial z}\sigma_{\theta z}+f_\theta=0\\ &\frac{1}{r}\frac{\partial}{\partial r}(r\sigma_{zr})+\frac{1}{r}\sigma_{z\theta}+\frac{\partial}{\partial z}\sigma_{zz}+f_z=0 \end{aligned} \tag{1}$$

where r is the distance from the axis of revolution ($r \geq 0$ always), θ is the circumferential coordinate and z is the axial coordinate directed along the axis of revolution. In Eq. (1), the normal stresses σ_{rr}, $\sigma_{\theta\theta}$ and σ_{zz} are directed respectively in the radial, circumferential and axial directions. The indicial notation adopted for a typical shear stress σ_{ij} is that the first index represents the direction (r, θ or z) of the normal to the plane where the stress is acting while the second index represents its direction (r, θ or z). The components of the body forces per unit volume in the r, θ and z directions are respectively f_r, f_θ and f_z.

The pressuremeter test is defined as an axisymmetric problem because it consists of an inflatable probe that allows a given pressure to be applied on a segment of the wall of a borehole. The resulting volume increase of that segment of the hole is observed. Consequently, not only is the geometry of the borehole cavity axisymmetric, but the loading and the support conditions are rotationally symmetric. This means that for an isotropic nonlinear viscoelastic medium all quantities of interest are independent of the circumferential coordinate θ. Accordingly, for the pressuremeter problem, Eq. (1) reduces to

$$\begin{aligned} &\frac{1}{r}\frac{\partial}{\partial r}(r\sigma_{rr})+\frac{\partial}{\partial z}\sigma_{rz}-\frac{\sigma_{\theta\theta}}{r}=0\\ &\frac{1}{r}\frac{\partial}{\partial r}(r\sigma_{zr})+\frac{\partial}{\partial z}\sigma_{zz}+f_z=0. \end{aligned} \tag{2}$$

If one considers that a condition of plane strain exists in the central section of the pressurized length, then the system represented by Eq. (2), assuming zero body forces, reduces to the equilibrium equation

$$\frac{\partial\sigma_{rr}}{\partial r}=\frac{\sigma_{\theta\theta}-\sigma_{rr}}{r} \tag{3}$$

where the traction boundary conditions in the deformed configuration are given by

$$\begin{aligned} t_r &\equiv \sigma_{rr}n_r+\sigma_{rz}n_z=\sigma_{rr}n_r\\ t_z &\equiv \sigma_{rz}n_r+\sigma_{zz}n_z=\sigma_{zz}n_z \end{aligned} \tag{4}$$

or

$$\mathbf{t}\equiv\tilde{\boldsymbol{\sigma}}\ \mathbf{n},\quad \mathbf{n}=\begin{Bmatrix} n_r\\ n_z\end{Bmatrix},\quad \tilde{\boldsymbol{\sigma}}=\begin{bmatrix}\sigma_{rr} & 0\\ 0 & \sigma_{zz}\end{bmatrix} \tag{5}$$

with (n_r, n_z) denoting the components (or direction cosines) of the unit normal vector on the boundary.

As mentioned previously most of the theoretical developments regarding the pressuremeter use the plain strain approach (Eq. 3) because it is convenient. The reason being that a given cell pressure is assumed to be applied fully on the cavity wall which is restrained from movement in the vertical z direction. In practice this is not necessarily the case. A more realistic approach is to consider that the cell pressure is applied only on a segment of the wall of a borehole and consequently the equilibrium Eq. (2) are more appropriate. However, a theoretical analysis in this case is more complicated and consequently a numerical analysis using finite elements is usually adopted.

The implications of the previous assumptions will be examined in this paper. A theoretical as well as a finite element analysis, in the context of large strains, will provide the necessary results for the calculation of the creep redistribution times.

In the next section, the plane strain approach (Eq. 3) will be examined analytically.

3. Kinematics of large strain deviatoric creep

This section details the theoretical development of the pressuremeter problem based on large strain deviatoric creep. The assumption is that the kinematic conditions associated with this condition are based on a cylindrical cavity in a frozen soil mass which exhibits incompressibility under a plane strain condition of flow.

It is convenient (Selvadurai, 1984; Selvadurai and Spencer, 1972; Spencer, 1970) when a continuum undergoes flow, to describe the motion of generic particles in body-fixed material coordinates $X_i(x_i,t)$, $(i = 1, 2, 3)$ and, for the same particles, space-fixed coordinates $x_i(X_i,t)$, $(i = 1, 2, 3)$ of the deformed configuration. However, to describe the kinematics of circular cylinders it is practical to use cylindrical polar coordinates instead (Fig. 2). These are given in the reference (R, Θ, Z) and deformed (r, θ, z) configurations as

$$\begin{aligned} &X_1=R\cos\Theta;\quad X_2=R\sin\Theta;\quad X_3=Z\\ &x_1=r\cos\theta;\quad\ x_2=r\sin\theta;\quad\ \ x_3=z. \end{aligned} \tag{6}$$