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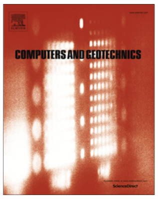

Research Paper

Modelling creep behaviour of anisotropic soft soils

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ABSTRACT

This paper presents a three dimensional constitutive model that describes the creep behaviour of natural clays with anisotropic stress–strain response, focussing on robust model implementation. Creep is formulated using the concept of a constant rate of visco-plastic multiplier, resulting in a formulation with easily determined creep parameters. A key assumption in the model formulation is that there is no purely elastic domain. Of the 10 input parameters that can be defined based on standard laboratory testing, five are similar to those used in the Modified Cam-Clay model. The performance of the model at element level and boundary value level is demonstrated, for the latter by comparing the simulations with the measured response of Murro test embankment in Finland. For comparison, the simulations are also done using the previously published anisotropic creep model and an equivalent rate-independent model. This enables studying the role of evolution anisotropy and creep at boundary value level by systematic comparisons.

1. Introduction

In recent years, various constitutive models have been proposed to describe fundamental features of natural soil behaviour, such as anisotropy, structure and rate-dependence (e.g. [1–5]). Different approaches have been used to capture the various rate-dependent phenomena, such as strain-rate effects, creep, relaxation and accumulated effects. These constitutive models include empirical models, rheological models and general stress–strain–time models that are based on theories of visco-plasticity. Visco-plastic models are easily adaptable to numerical implementation in a general purpose finite element framework, as they are often formulated in incremental form.

Most of the rate-dependent models were developed based on the Perzyna's [6,7] overstress theory (e.g. [1,2,4,8]). This approach has become a preferred basis for the further development of viscoplastic models. However, determination of model input parameters for overstress models is difficult (see e.g. [4]), and strictly speaking not feasible in practical context due to the very low loading rates required in the laboratory tests. As a consequence, the input values require calibration via parametric studies, which limits their practical adaptation, and furthermore, the values for the input parameters are not necessarily unique. The latter can lead to unrealistic predictions in some stress paths when applied in 3D stress space. As discussed by Yin et al. [5], the major assumption in the classic overstress models – that viscoplastic strain will not occur inside the static yield surface (i.e. there is a purely elastic region) – is in conflict with the experimental observations. It is commonly thought that a consequence of the overstress theory is that it lacks the capability to model tertiary creep, i.e. the acceleration of the creep process [9], but as shown by Yin et al. [5] this problem can be overcome by introducing some damage or destructuration law in the formulation. However, it is only possible to model stress relaxation if the stress state lies outside the current static yield surface.

As an alternative, the concept of Nonstationary Flow Surface (NSFS) theory has been used to model visco-plastic behaviour of soils in general stress space (e.g. [10,11]). According to Liingaard et al. [12] this approach has the following limitations:

(1) NSFS theory cannot describe the relaxation process when it is initiated from a stress state inside the yield surface (flow surface).
(2) The creep process initiated from a stress state inside the yield surface cannot be predicted satisfactorily.

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Notation

α_0	initial value of anisotropy
α	scalar value of anisotropy
$\boldsymbol{\alpha}_d$	deviatoric fabric tensor
β	creep exponent
$\boldsymbol{\delta}_{ij}$	Kronecker's delta
ε_a	axial strain
ε_r	radial strain
ε_v	volumetric strain
ε_q	deviatoric strain
$\dot{\varepsilon}$	strain rate
$\dot{\varepsilon}^e$	elastic strain rate
$\dot{\varepsilon}^c$	creep strain rate
$\dot{\varepsilon}^e_v$	volumetric elastic strain rate
$\dot{\varepsilon}^e_q$	deviatoric elastic strain rate
$d\boldsymbol{\varepsilon}_d$	incremental deviatoric strain tensor
$\dot{\boldsymbol{\varepsilon}}^c_{ij}$	creep strain rate tensor
σ'_a	effective axial strain
σ'_r	effective radial strain
$\boldsymbol{\sigma}'_d$	deviatoric stress tensor
κ^*	modified swelling index
λ^*	modified compression index
λ	slope of normal compression line
η	stress ratio
η_0	stress ratio corresponding K_0 state
μ^*	modified creep index
υ'	Poisson's ratio
τ	reference time
θ_α	lode angle
ω	rate of rotation
ω_d	rate of rotation due to deviator stress
C_α	creep index
CSS	current stress surface
$\boldsymbol{D}_{ijhk}$	stiffness matrix
e_0	initial void ratio
G	shear modulus
$\boldsymbol{I}$	identity matrix
$(J_2)_\alpha$	modified second invariant to α-line
$(J_3)_\alpha$	modified third invariant to α-line
K	elastic bulk modulus
K_0^{nc}	lateral earth pressure at rest for normally consolidated state
$M(\theta)$	stress ratio at critical state
M_c	stress ratio at critical state in triaxial compression
M_e	stress ratio at critical state in triaxial extension
NCS	normal consolidation surface
OCR	over-consolidation ratio
p'	mean effective stress
p'_p	effective preconsolidation pressure
p'_{p0}	initial effective preconsolidation pressure
p'_{eq}	effective equivalent mean stress
POP	pre-overburden pressure
q	deviatoric stress
Δt	time increment

Yet another approach is to develop more general rate-dependent constitutive laws based on one dimensional empirical formulations, such as the model by Yin et al. [13] Yin and Graham [14], which has subsequently been extended to 3D e.g. by Yin et al. [15] and Yin et al. [16], and further modified e.g. by Bodas Freitas et al. [17]. However, these models contain concepts, which are perhaps difficult to understand, such as equivalent time or time shift, and the models mentioned ignore some key features of natural soil behaviour, such as anisotropy. One of the most used models in the category of empirical models is the isotropic Soft Soil Creep model [18,19] available in the commercial Plaxis finite element suite. Further developments of that model, based on the ideas of Bjerrum and Janbu, have been proposed by several authors (e.g. [3,20]).

Natural clays generally exhibit both elastic and plastic anisotropic behaviour as result of sedimentation and consolidation. For normally and slightly overconsolidated clays, anisotropic behaviour due to elastic strains can be neglected in most loading problems, as the magnitudes of elastic strains in natural soft clays are insignificant compared to plastic strains. This assumption makes a constitutive model simpler in terms of modelling and parameter determination. The anisotropic creep model (ACM) proposed by Leoni et al. [3] accounts for the initial anisotropy and the evolution of anisotropy in a simple manner, as an anisotropic extension of the isotropic Soft Soil Creep model. ACM uses rotated ellipses (similar to the S-CLAY1 model by Wheeler et al. [21]) as contours of volumetric creep strain rates. This approach overcomes the following limitations of the overstress theory:

1. Determination of viscous parameters is straight forward: ACM uses a modified creep index μ^* as input parameter for soil viscosity, which can be derived from the secondary compression coefficient C_α. This value can be easily obtained from laboratory tests and is internationally known, in contrast to the time-resistance concept adopted by Grimstad et al. [20].
2. The reference time τ has a clear link to the type of tests used in defining the apparent preconsolidation pressure (see [3] for details). Same value of τ can be adopted for modelling element test and a boundary value problem on the same soil as the test.
3. The model assumes that there is no purely elastic domain in contrast to the classic overstress theory, allowing for creep within the Normal Consolidation Surface.

However, as discussed by Sivasithamparam et al. [22] and Karstunen et al. [23], the consequences of adopting the concept of contours of constant volumetric creep strain rate are severe, as illustrated later on:

1. The ACM model cannot predict swelling on the 'dry' side of the critical state line, as it does not allow the stress state to cross the failure line represented by the Mohr–Coulomb criterion. Because of this, the ACM is limited to the 'wet' side of the critical state line only.
2. The ACM model cannot reach the critical state condition with shearing at constant volume and effective stresses, given the volumetric creep rates are assumed to be constant throughout the stress space. In its finite element implementation, the critical state condition is artificially imposed by switching to Mohr Coulomb failure criterion with zero dilatancy when approaching failure, resulting in a "jump" in the predicted stress–strain curve.
3. The ACM model cannot reproduce the isotach behaviour observed in natural soft clays under a stepwise change in strain-rate in undrained triaxial tests and CRS tests.