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Research Paper

Numerical prediction of the creep behaviour of an unstabilised and a chemically stabilised soft soil

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ABSTRACT

This paper examines the ability of volumetric and deviatoric creep laws associated with constitutive models to simulate the creep behaviour of a soft soil in its natural state or chemically stabilised state. Initially, the models/laws are validated by oedometer and triaxial creep tests, for the stabilised and unstabilised soils. Finally, the long-term behaviour of an embankment built on a soft soil reinforced with deep mixing columns is predicted based on the properties for a curing time of 28 days. The results show that the creep phenomenon should be considered in a long-term analysis of deep mixing columns.

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1. Introduction

Over the last few years, more and more embankments have been built on soft soils, which in the past were considered less suitable for construction purposes. In general, these types of soils show high compressibility, low undrained shear strength and reduced permeability, properties that extend the consolidation time with impact on deformation development in the long term.

When the soft soils contain a high organic matter (OM) content, the soil's properties are considerably affected [1–3], and consequently significant creep deformations are expected [3] to occur in the long term after the end of the consolidation phenomenon. In these cases, two approaches are usually used to mitigate the creep deformations: (i) the use of a preloading technique to anticipate the creep deformations [4]; (ii) or installing rigid vertical inclusions with better characteristics in the soil foundation, such as: concrete piles, stone columns and deep soil mixing columns (DMC).

Some studies have shown that the creep behaviour of a chemically stabilised soft soil with binders depends on: the OM content [3,5,6], binder quantity [5], binder composition [7], stress level [7] and curing conditions [3]. Moreover, the transference of stresses from the soft soil to the DMCs, induced by the arching effect [8], potentiates the occurrence of creep settlements of embankments built on soft soils reinforced with DMCs [9,10], since there is a higher stress level on the DMCs. When the allowable deformations are very low (such as for high-speed train embankments and crane foundations), the consequences of these creep deformations may be significant. Furthermore, accurate predictions of the creep deformations are essential to reduce the work that will have to be carried out during the service life of the work constructed.

Although some constitutive models have been developed to predict the creep behaviour of clays [11–21], the numerical prediction of creep deformations of stabilised soils with binders has been practically ignored by the scientific community, since it is usually considered that stabilised soil experience negligible creep deformations. Indeed, field data from some case histories of embankments over soft soils improved with DMCs show, for even more than one year after the completion of the embankment, a continuous increase of the settlement [22–24] which may be partially related to creep phenomenon, considering that the consolidation is very fast when DMCs are used [8,25]. Additionally, in another case history the measured settlements were higher (about 100%) than the predicted settlements [26], this behaviour was explained by the yielding/softening of the DMCs (without indication of instability of the embankment [26]) and/or by the creep of the DMCs,

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Nomenclature

The following symbols are used in this paper (basic SI units are given in parentheses)

$\overline{D}$	shear stress level (q/q_{ult})
$\dot{\varepsilon}_{ax}$	axial strain rate (%/min)
$\bar{\alpha}$	Singh-Mitchell's (creep deviatoric) parameter
A	Singh-Mitchell's (creep deviatoric) parameter
c'	cohesion (Mohr-Coulomb parameter) (Pa)
C_c	compression index; post-yield compression index
CIU	isotropically consolidated undrained triaxial test
C_r	swelling index; pre-yield swelling index
CSL	critical state line
c_u	undrained shear strength (Pa)
$C_{\alpha e}$	secondary consolidation index ($\Delta e/\Delta \log t$)
DMC	deep mixing column
E'	Young's modulus (Pa)
e_o	initial void ratio
$e_{\lambda o}$	void ratio for $p' = 1$
K_0	coefficient of earth pressure at rest
k_h	horizontal permeability coefficient (m/s)
k_v	vertical permeability coefficient (m/s)
M	slope of critical state line on q-p′ plane
m	Singh-Mitchell (creep deviatoric) parameter
OCR	overconsolidation ratio
OM	organic matter (%)
p'	average (volumetric) effective stress (Pa)
q_u	maximum unconfined compressive strength (Pa)
t_{di}	deviatoric reference time
t_{vi}	volumetric reference time
VCL	virgin consolidation line
w_L	Atterberg liquid limit (%)
w_P	Atterberg plastic limit (%)
WT	water table
ε_{ax}	axial strain (%)
$\varepsilon_{ax\text{-}creep}$	creep axial strain (%)
ϕ'	angle of shear stress (Mohr-Coulomb parameter) (°)
γ	unit weigh (kN/m^3)
κ	swell-recompression index (ln scale)
λ	virgin compression index (ln scale)
ν'	Poisson ratio
$\sigma'_{v\text{-}DMC}$	vertical effective stress on DMC (Pa)
$\sigma'_{v\text{-}soil}$	vertical effective stress on soil (Pa)

which is expected to be significant considering the low level of improvement of the DMCs used in this case [26].

2. Scope of the study

The main aim of this work is to study the ability of two creep laws to simulate the creep behaviour of a soft soil, whether unstabilised or chemically stabilised with binders. Firstly, the creep laws are used to simulate the creep behaviour obtained in eodometer and triaxial creep tests (validation stage). Then, the constitutive models and creep laws are used to predict the long-term behaviour of an infinite embankment built on a soft soil reinforced with DMCs, in order to study the influence of the creep phenomenon of the stabilised material.

A 2-D finite element program with several constitutive models, upgraded at the University of Coimbra [28] and capable of carrying out elastoplastic analyses with coupled consolidation and creep, is used in these analyses. The constitutive models used are either the Modified Cam Clay (MCC) alone or in combined with the Von Mises (MCC/VM) model. These two models are associated to two creep laws, composed by a volumetric and a deviatoric component.

3. Brief description of the models

3.1. Creep laws

Regarding previous studies [12–14], the creep deformation in soils can be broken down into a volumetric and a deviatoric components. Creep volumetric strains (ε_v^c) are calculated on the basis of the secondary consolidation equation proposed by Taylor [29] for oedometer tests:

$$\varepsilon_v^c = \int \frac{C_{\alpha e}}{2.3(1+e)t_v} dt \tag{1}$$

where $C_{\alpha e}$ (=$\Delta e/\Delta \log t$) is the index of secondary consolidation, e the void ratio and t_v the volumetric age of the soil in relation to the reference volumetric time (t_{vi}). Considering the work of Kavazanjian and Mitchell [12] the oedometer tests results can be used to evaluate the volumetric creep deformations, since these authors, based on a general volumetric model in void ratio-log stress-log time space, stated that the deformation at constant deviatoric stresses levels is described by a series of parallel planes. Therefore, C_{ae} is constant and independent of the shear stress level. Creep deviatoric strains (ε_{ax}^c) are calculated based on Singh-Mitchell's law [15], where the axial strain is evaluated from creep triaxial tests (drained or undrained):

$$\varepsilon_{ax}^c = \int A\, e^{\bar{\alpha}\overline{D}} \left(\frac{t_{di}}{t_d}\right)^m dt \tag{2}$$

where A, $\bar{\alpha}$ and m are soil creep parameters, $\overline{D}$ (=q/q_{ult}) is the deviatoric stress level and t_d the deviatoric age of the soil in relation to the deviatoric reference time (t_{di}). Parameter A represents the shear strain rate for $\overline{D}$ equal to zero [30], reflecting the influence of the composition, structure and stress history. Parameter $\bar{\alpha}$ reproduces the effect of the shear stress level and usually varies in the range 1.0–7.0 [31]. Parameter m controls the decrease of the creep strain rate with time, varying from 0.7 to 1.25 [15]; in general the creep failure implies values of m lower than 1.0 [31]. Eq. (2) is only valid for a steady state creep phase, i.e., for $0.3 < \overline{D} < 0.9$ [15], or $0.2 < \overline{D} < 0.9$ [14].

3.2. Constitutive models associated with the creep laws

Two constitutive models are used in this work, the MCC and MCC/VM models to simulate the behaviour of the natural soft soil and the stabilised soil, respectively.

The MCC model is an elastoplastic soil model based on isotropic conditions, described by a yield function represented by an ellipse oriented in line with the p′ axis, where the size of which depends on the isotropic preconsolidation pressure, p'_c (Fig. 1a). The yield function of the MCC model with creep can be described by:

$$F(\sigma'_{ij}, e_k, t_v) = f(\sigma'_{ij}) - h(e_k, t_v) \tag{3}$$

where f is the load function:

$$f(\sigma'_{ij}) = (\lambda - \kappa) \cdot \ln\left[p'\left(1 + \frac{\eta^2}{M^2}\right)\right] \tag{4}$$

M is the slope of a critical state line, λ and κ are, respectively, the slope of the virgin consolidation line (VCL) and the slope of the

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