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Research Paper

Numerical modelling of the effect of curing time on the creep behaviour of a chemically stabilised soft soil

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ABSTRACT

This work studies the effect of the curing time on the creep behaviour of a stabilised soft soil, using volumetric and deviatoric creep laws associated with constitutive models. Results of unconfined compressive strength tests for several curing times are used to define the time evolution of the mechanical and creep properties. The models/creep laws are validated by oedometer and triaxial creep tests, for 28 and 90 days of curing. The long-term behaviour of an embankment built on a soft soil reinforced with deep mixing columns shows that the effect of curing time decreases the settlement and increases the improvement factor.

1. Introduction

The reinforcement of soft soils with deep mixing columns (DMCs) is widely used in several countries to allow the construction of embankments on such soils, mitigating their poor geotechnical properties (low strength, low permeability and high deformability) [1–3]. Numerical analyses of the behaviour of embankments (and shallow foundations) built on soft soil reinforced with DMCs have been performed in several works, most of them with commercial software (Plaxis, Flac, Ansys, etc) and modelling the behaviour of the DMCs with elastic-perfectly plastic laws using Mohr–Coulomb failure criterion [4–13]. Recently, structured models have been used to improve the numerical predictions of the behaviour of stabilised soils [14–18]. Moreover, the creep analysis of the behaviour of DMCs was performed with the Modified Cam Clay model associated with two creep laws (volumetric and deviatoric) [19].

Some works have shown that the inclusion of DMCs (with a much higher stiffness) in the soft soil decreases the consolidation time [4,20] and promotes the transfer of stress from the soil to the DMCs, due to the arching effect, which has a positive impact on the reduction of the settlement of the embankment [4].

When the soft soils have a high organic matter (OM) content, significant deformations occur in the long term (long after the end of the primary consolidation process), due to the creep phenomenon [21,22]. Recent research studies have shown that the detrimental effect of the OM content, in terms of creep deformations, is still observed in soils chemically stabilised with binders [23]; in fact, creep deformations also depend on the binder quantity and composition, stress level and curing conditions [23,24].

Contrary to what is usually admitted by the geotechnical community, non-negligible creep strains can occur in embankments on soft soils reinforced with DMCs [19], fundamentally induced by the creep strain rate of the stabilised material and potentiated by the arching effect which increases the stresses on the DMCs and consequently the creep strains [19,24]. In fact, field data concerning some of the embankments studied have confirmed the existence of creep strains, since they show a constant settlement rate over time [25–27], which may be partially due to creep phenomena, since a significant reduction of the consolidation time is obtained when DMCs are used [4,20]. In another case, much higher settlement (about 100%) than that predicted numerically was observed, without any indication of the embankment's instability [28], which may be explained by the creep of the DMCs, potentiated by the relatively low level of mechanical improvement of the DMCs.

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Nomenclature

$\overline{D}$	shear stress level (q/q_{ult})	p'	average (volumetric) effective stress (Pa)
$\dot{\varepsilon}_{ax}$	axial strain rate (%/min)	PI	plasticity index (%)
$\overline{\alpha}$	Singh-Mitchell's (creep deviatoric) parameter	q_u	maximum unconfined compressive strength (Pa)
A	Singh-Mitchell's (creep deviatoric) parameter	SCR	stress concentration ratio
c'	cohesion (Mohr-Coulomb parameter) (Pa)	t_{di}	deviatoric reference time
CIU	isotropically consolidated undrained triaxial test	t_{vi}	volumetric reference time
CSL	critical state line	UCS	unconfined compressive strength (Pa)
c_u	undrained shear strength (Pa)	VCL	virgin consolidation line
$C_{\alpha e}$	secondary consolidation index ($\Delta e/\Delta \log t$)	w_L	Atterberg liquid limit (%)
DMC	deep mixing column	wP	Atterberg plastic limit (%)
E'	Young's modulus (Pa)	w_0	initial moisture content (%)
e_o	initial void ratio	WT	water table
E_u	Secant effective Young's modulus for 50% of peak strength (Pa)	ε_{ax}	axial strain (%)
		$\varepsilon_{ax\text{-}creep}$	creep axial strain (%)
$e_{\lambda o}$	void ratio for $p' = 1$	φ'	angle of shear stress (Mohr-Coulomb parameter) (°)
FEM	finite element method	γ	unit weigh (kN/m^3)
IF	improvement factor	κ	swell-recompression index (ln scale)
K_0	coefficient of earth pressure at rest	λ	virgin compression index (ln scale)
k_h	horizontal permeability coefficient (m/s)	ν'	Poisson ratio
k_v	vertical permeability coefficient (m/s)	σ'_{creep}	vertical effective stress applied during the creep phase (Pa)
M	slope of critical state line on $q–p'$ plane		
m	Singh-Mitchell (creep deviatoric) parameter	$\sigma'_{v\text{-}DMC}$	vertical effective stress on DMC (Pa)
OCR	overconsolidation ratio	$\sigma'_{v\text{-}soil}$	vertical effective stress on soil (Pa)
OM	organic matter (%)	σ'_y	vertical effective yield stress on DMC (Pa)

Moreover, a numerical study concerning the creep on the DMCs shows that, with the consideration of creep phenomena, the DMCs are less efficient, that is, the settlement over time increases, which induces a decrease in the improvement factor, as well as augmenting the stresses on the DMCs [19].

Although several studies have shown the enhancement of the mechanical properties (mainly strength and stiffness) of chemically stabilised soils over time, due to pozzolanic reactions [1,23,29], the current design of structures with stabilised soils (as usual in concrete engineering) makes use of the mechanical properties evaluated for 28 days of curing [4,19]. Considering the lack of numerical studies concerning the enhancement of the mechanical properties over longer periods of time, it is very pertinent to study this effect in a long-term analysis, mainly when associated with the consolidation and creep phenomena.

2. Objectives of the work

The novelty of this work is to joint together the effects of the creep phenomenon with the curing time (t_c) in order to improve the long-term prediction of the behaviour of geotechnical structures. While the creep phenomenon increases the settlement over time and reduces the efficacy of DMCs [19], the increase in mechanical properties with curing time tends to induce the opposite effect, attenuating the impact of creep.

Firstly, results of eodometer and triaxial creep tests for different curing times [1] are used to validate the performance of the constitutive models associated with the two creep laws used (composed by deviatoric and a volumetric components) and taking the effect of the curing time into consideration. Finally, the effect of the curing time on the long-term behaviour of an infinite embankment built on a soft soil reinforced with DMCs is analysed, considering elasto-plastic constitutive models and creep laws.

A 2-D finite element program with several constitutive models, upgraded at the University of Coimbra and capable of carrying out elastoplastic analyses with coupled consolidation and creep, is used in these analyses. The constitutive models chosen for the stabilised material is the Modified Cam Clay (MCC) combined with the Von Mises (VM) model. The constitutive model is associated with two creep laws, both of which depend on the curing time, thus inducing different mechanical and creep characteristics of the stabilised soil over time.

3. Description of the models/laws

3.1. Creep laws

The creep strains of a soil can be broken down into a volumetric and a deviatoric component [30–32]. Based on the secondary consolidation theory stated for oedometer tests [33], creep volumetric strains (ε_v^c) are calculated by Eq. (1):

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

where e is the void ratio, $C_{\alpha e}$ (=$\Delta e/\Delta \log t$) the index of secondary consolidation and t_v the volumetric age in relation to a reference time (t_{vi}). $C_{\alpha e}$ can be evaluated from oedometer creep tests, since the general volumetric model in e-$\log \sigma' - \log t$ space states that the deformation at constant deviatoric stress levels is represented by a series of parallel planes, consequently, $C_{\alpha e}$ is constant and independent of the shear stress level [30]. For unstabilised soils, t_v is usually evaluated by Eq. (2), which is based on the difference between the void ratio of the current state (e_1) and the one on the boundary surface state (e_2) [32–34]:

$$t_v = t_{vi}.e^{\left(\frac{e_2-e_1}{C_{\alpha e}/2.3}\right)} \tag{2}$$

Singh-Mitchell's law [35] is used to calculate the creep deviatoric strains $\left(\varepsilon_{ax\text{-}creep}\right)$, which are based on the evolution of the axial strain from drained or undrained creep triaxial tests: