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A viscoplastic constitutive model for unsaturated geomaterials

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ABSTRACT

In this paper a viscoplastic constitutive model for unsaturated geomaterials is presented. The constitutive laws for the description of the time-dependent mechanical behaviour of saturated and unsaturated geomaterials generalise the isotach approach proposed by Šuklje [52] to the elastoplastic strain hardening based constitutive laws for unsaturated soils. The formulation encompasses strain rate effects and allows the description of the coupled effect of strain rate and suction on the viscoplastic behaviour of geomaterials. The model has been used to simulate tests involving variable stress and/or strain rate conditions, including creep phases and soaking tests. Numerical results demonstrate its reliability in reproducing the general features of the rate-dependent behaviour together with the dependency upon suction. Further tests are currently under consideration to extend model verification to others saturated and unsaturated geomaterials.

1. Introduction

Viscous behaviour of geomaterials has been extensively documented in clays (e.g. [6,55,25,33,51]), sands (e.g. [53,15]), rockfill (e.g. [41,42]), rocks and soft rocks (e.g. [52,12,17,50]). Recent reviews of time dependent processes in soils have been proposed by Augustesen et al. [5], Liingaard et al. [34] and Laloui et al. [28].

Although often identified exclusively with creep phenomena (secondary consolidation), it is now well accepted that viscous behaviour of soils is more generally the result of strain rate dependency of the material. In fact, time effects influence soils behaviour both in compression and shear by modifying material strength [55,21,32,51]. Under this circumstance, in order to describe these behavioural features, the basic effective stress–strain constitutive relationship used to describe the mechanical behaviour of soils has to be extended. Following early works by Šuklje [52], Leroueil et al. [31] have demonstrated experimentally for clays subjected to one-dimensional compression that a natural extension of the effective stress–strain constitutive relationship can be achieved incorporating the strain rate as an additional state variable. In other words, the state of a given soil is fully described by a unique relationship among vertical stress–vertical strain–vertical strain rate ($\sigma'_V : \varepsilon_V : \dot{\varepsilon}_V$). This rheological law is also known as isotach behaviour [52].

Various approaches have been proposed for the constitutive modelling of time-dependent behaviour of geomaterials. A rather large variety of models are based on Perzyna's theory of elasto-viscoplasticity [35,47]. These models are often qualified as "overstress models". Examples of overstress models for soils and soft rocks are available in Adachi and Oka [1], Fodil et al. [18], Datcheva et al. [11], Collin et al. [8], De Gennaro et al. [12], Alonso et al. [3], Yin et al. [59]. A major shortcoming of overstress models is the weak physical meaning that viscous parameters have and the way these parameters are determined. A trial and error problem solving procedure is often adopted.

Various models have been formulated adopting Bjerrum's notion of equivalent (or reference) time (e.g. [6,7,26,58,57,59,23]). In these models, viscoplastic strains evolve along log-linear and parallel lines (time-lines) characterised by a given time of sustained loading (creep). Since time appears explicitly in the constitutive equations, these models might suffer from some drawbacks for complicated loading time histories if the origin of time is not conveniently defined.

Finally, other models used the concept of the Non-Stationary Flow Surface (NSFS) theory or extended elastoplasticity (e.g. [16,39,30,34]). Also in this case time is often considered explicitly as an internal state variable.

While quite a large number of contributions have been devoted to the description of the mechanical time-dependent behaviour of saturated geomaterials, few contributions have tackled the problem of the time-dependent behaviour of unsaturated geomaterials. Actually, unsaturated states are quite common situations encountered in current practice since geomaterials are recurrently submitted to natural or man-induced saturation-desaturation cycles.

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A few examples may be cited. In conventional geotechnical engineering, such situations are encountered for earth structures subjected to interactions with the atmosphere. In the case of mining engineering, excavation of galleries to exploit chalk for instance induces the desaturation of the rock close to the rooms and pillars. In the case of radioactive waste disposals, engineered barriers made of unsaturated compacted clay material are considered. Geological storage of carbon dioxide (CO_2) in deep reservoirs also involves partially saturated geomaterials [48,56]. When this occurs, the coupled effect of strain rate and suction needs to be considered. This issue has been investigated recently by Oldecop and Alonso [41,42] in rockfill material, by Pasachalk 2 [43], Priol [49], Priol et al. [50] and De Gennaro et al. [13] in chalk, by Herbstová and Herle [22] in clay fill material and by Muñoz-Castelblanco et al. [37] in natural loess. The main results of these studies have shown that suction changes modify the creep rate and the strain rate-dependent yield stress of rockfill and chalk. However, no available viscous models are capable to capture the coupled effect of strain rate and suction.

De Gennaro et al. [14] and Pereira and Gennaro [46] have proposed a viscous model for chalks, called RASTRA, that includes rate effects by means of an extended strain rate-dependent hardening law. The formulation has been restricted to the isotropic loading condition. The aim of this paper is:

- to show how the isotach approach can be encompassed in the theoretical framework of elastoplasticity;
- to extend the isotach approach to unsaturated states to account for suction effects;
- to extend the formulation of RASTRA model to deviatoric loading conditions;
- to validate the proposed constitutive approach against available experimental data.

2. Extending the isotach approach to partially saturated states

The isotach approach proposed by Šuklje [52] is schematically summarised in Fig. 1. The state of the soil sample is described by the relationship ($p' : \varepsilon_v : \dot{\varepsilon}_v$) among stress–strain–strain rate (see also [33]. Following this approach soils may experience both compression under constant strain rate (i.e. following a rate-line) or delayed compression under sustained constant load (i.e. decreasing the strain rate and crossing multiple rate-lines). The amount of delayed strain accumulated during this latter phase will depend on the elapsed time of sustained loading imposed to the soil. At the end an equilibrium void ratio is obtained. It is worth noting that each isotach (rate line) has an equivalent rate-dependent yield stress ($p_c, p_{c1}, p_{c2}, p_{c3}, \ldots$) which is larger for the higher applied strain rate. Fig. 2 shows the effects of strain rate changes on the oedometric response of Batiscan clay. It is a typical illustration of the isotach behaviour. Leroueil [33] observed that an average increase in the yield stress from 7% to 12% per log cycle of strain rate is generally obtained for inorganic clays. In the usual range of interest of the applied strain rates during one-dimensional compression tests at Constant Rate of Strain (CRS tests) (i.e. $\dot{\varepsilon}_V$ varying between 10^{-8} s^{-1} and 10^{-4} s^{-1}) the following relationship between the yield stress p'_y and the strain rate $\dot{\varepsilon}$ holds true [29]:

$$\log p'_y = A + \alpha \log \dot{\varepsilon} \tag{1}$$

where A and α are materials constants. Mesri and Godlewski [36] showed that each class of soil is characterised by typical α values (see Table 1). Note that Eq. (1) can be rewritten in differential form as follows:

$$\Delta \log p'_y = \alpha \Delta \log \dot{\varepsilon} \tag{2}$$

Along a Normal Compression Line, the following relation holds:

$$\Delta e = -C_c \log p'_y \tag{3}$$

and during secondary consolidation:

$$\Delta e = -C_{\alpha e} \log t \tag{4}$$

By virtue of the isotach approach hypothesis:

$$\Delta \log \dot{\varepsilon} = \Delta \log t \tag{5}$$

it then follows that

$$\alpha = C_{\alpha e}/C_c \tag{6}$$

where C_c and $C_{\alpha e}$ are the coefficient of compressibility and the secondary compression index, respectively. This last relation shows that a definite coupling between creep and compressibility can be established.

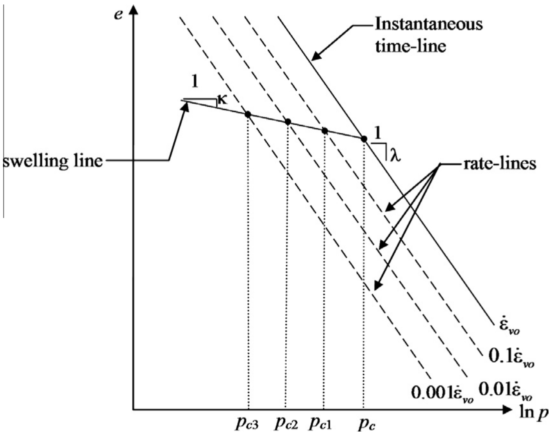

Fig. 1. The isotach model proposed by Šuklje (after [23]).

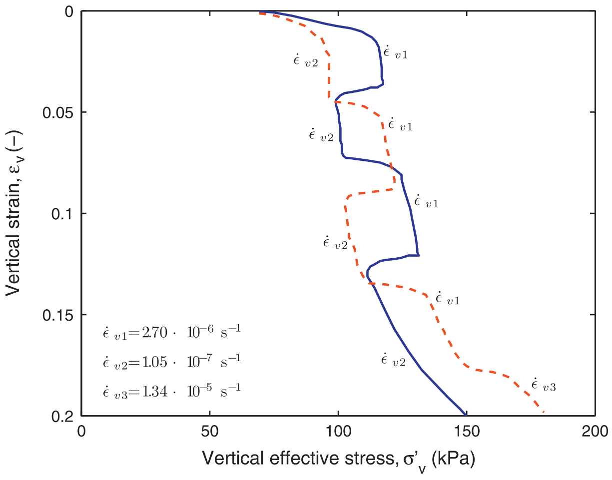

Fig. 2. Constant Rate of Strain (CRS) oedometer tests on Batiscan clay [31] illustrating isotach behaviour.

Table 1
Parameter α for various geomaterials (data from Mesri et al. [60] and [33]).

Material	$C_{\alpha e}/C_c$ equal to $\alpha = \Delta \log \sigma'_p / \Delta \log \dot{\varepsilon}$
Granular soils including rockfill	0.02 ± 0.01
Shale and mudstone	0.03 ± 0.01
Inorganic clays and silts	0.04 ± 0.01
Organic clays and silts	0.05 ± 0.01
Peat and muskeg	0.06 ± 0.01