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Research Paper

Comparison of model predictions of the anisotropic plasticity of Lower Cromer Till

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ABSTRACT

This paper compares predictions, made using selected soil constitutive models, of the anisotropic plastic response of a sandy silty-clay, viz., Lower Cromer Till (LCT). The performance of four elastoplastic models, designated as MCC (Roscoe and Burland, 1968), S-CLAY1 (Wheeler et al., 2003), SANICLAY14 (Dafalias and Taiebat, 2014) and YANG2015 (Yang et al., 2015), are systematically evaluated based on a series of drained triaxial stress path tests, including virgin constant-stress-ratio (CSR) compression tests, probing stress path tests on initially K_0 consolidated samples, and also various transitional CSR tests. Comparison of the various predictions shows that the isotropic MCC model cannot properly describe the mechanical behaviour of LCT due to its neglect of fabric anisotropy. The other three anisotropic models differ in their definition of the rotational hardening laws, particularly in the description of the equilibrium state of fabric anisotropy achieved under CSR loading. While significant improvements in model predictions can be observed from the three anisotropic models, for LCT S-CLAY1 generally tends to underestimate the volumetric deformation and both S-CLAY1 and SANICLAY14 are likely to overestimate the ratio of the deviatoric and volumetric strains for more anisotropic stress states. YANG2015 exhibits the most consistent performance in reproducing the mechanical behaviour of LCT among the four models under comparison. The importance of the virgin CSR tests to properly understanding the plastic anisotropy of soil fabric is highlighted.

1. Introduction

The importance of considering anisotropic plasticity of soils in order to obtain accurate predictions of their mechanical behaviour has long been recognised (e.g., [10,4,28,13,36,1,3,15,11,34,19]). Various propositions have been made for incorporating the concept of rotational hardening into the isotropic Critical State constitutive models, particularly the Modified Cam Clay (MCC) model [24]. Some of the representative works can be found in Newson and Davies [20], Pestana and Whittle [21], Wheeler et al. [30], Dafalias and Taiebat [8] and Yang et al. [33], among others. Some common assumptions can be summarised from those previous works: (1) the fabric anisotropy can be described by the inclination of the yield and plastic potential surfaces in the traditional triaxial stress space; (2) a change of fabric anisotropy is only induced by plastic straining; and (3) an equilibrium state of fabric anisotropy can be established, either explicitly or implicitly, by virgin consolidation at constant stress ratio (CSR).

Key differences between existing models can be identified. For instance, some involve an associated plastic flow rule, often for simplicity or otherwise to avoid the difficulty of accurately determining the plastic potential surface in experiments, e.g., Dafalias [5], Wheeler et al. [30], Sun et al. [28], and Yang et al. [32]; whereas others have included a non-associated flow rule, e.g., Newson and Davies [20], Pestana and Whittle [21], Dafalias and Taiebat [8] and Yang et al. [33]. Some attribute the variation of fabric anisotropy merely to the volumetric component of plastic straining, e.g., Dafalias [5], some consider the different contributions from both the volumetric and deviatoric plastic strain components, e.g., Pestana and Whittle [21] and Wheeler et al. [30], while others use the total plastic strain to quantify the change of fabric anisotropy, e.g., Dafalias and Taiebat [8] and Yang et al. [32,33].

Another difference between the various models lies in their description of the equilibrium state of fabric anisotropy. Newson and Davies [20] and Pestana and Whittle [21] assumed that at the equilibrium state of soil fabric the yield surface is aligned with the imposed CSR loading path. Dafalias [5] considered that the degree of inclination of the yield surface is a fixed fraction of the deviation of the CSR loading path away from the hydrostatic state.

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This concept has also been adopted by Newson and Davies [20] and Dafalias et al. [6] to describe the orientation of the plastic potential surface. Later, Wheeler et al. [30] and Dafalias and Taiebat [8] found that a non-linear relationship better describes the variation of the inclination of the yield surface at the equilibrium state with the imposed virgin CSR. Yang et al. [32,33] defined the equilibrium state of fabric anisotropy in terms of the inclination of both the yield and plastic potential surfaces, based on the available experimental evidence. Evolutionary improvements in the description of fabric anisotropy for clays can therefore be traced from the works of Dafalias [5], Newson and Davies [20], Pestana and Whittle [21], Wheeler et al. [30], Dafalias et al. [6], Dafalias and Taiebat [8] and Yang et al. [33].

Conventional drained and undrained triaxial tests have been commonly adopted to evaluate the performance of the proposed anisotropic models [20,22,35,8]. The stress path imposed in those conventional triaxial tests for normally consolidated samples covers a continuous variation of stress ratios ($\eta = q/p'$), which causes simultaneous changes in the plastic anisotropy of the clay fabric. Note that in the current treatment p' is the mean effective stress and q is the deviatoric stress. These conventional triaxial tests may be useful to generally validate any proposed constitutive model, but they cannot provide definitive tracking of the change of fabric anisotropy along the imposed stress paths, and thus may be inefficient and of limited value when used to validate the proposed rotational hardening rules. Therefore, laboratory tests that can provide explicit information on fabric anisotropy are preferred. For instance, a series of CSR tests would be appropriate due to the fact that a unique fabric anisotropy can be achieved in each CSR test [32,33]. Simple examples include the K_0 consolidation experienced by naturally deposited soils and the isotropic consolidation widely investigated in laboratory tests. By shifting the value of the constant stress ratio applied in these CSR tests, the validity of the proposed rotational hardening laws can be unambiguously examined, as indicated by Wheeler et al. [30], Karstunen and Koskinen [14], Belokas and Kavvadas [2] and Yang et al. [32,33].

Some natural clays, like those Scandinavian clays studied by Toivanen [29], Koskinen et al. [16], Karstunen and Koskinen [14] and others, may be significantly heterogeneous in terms of their mineral composition and may also exhibit a time-dependent response to loading. They can also be sensitive to disturbance. The coupling or co-existence of fabric anisotropy, soil structure and also time-dependency makes it difficult for a clear-cut evaluation of the single aspect of anisotropic plasticity in proposed models. Therefore, the most appropriate soils, that will allow this aspect of soil behaviour to be revealed, would be those with a relatively homogeneous mineral composition, which are time-independent and display no discernible effect of structure. Of the data available in the literature, the series of tests on reconstituted Lower Cromer Till (LCT) conducted by Gens [9] is one of the best candidates to investigate the anisotropic plasticity inherent in soil. This systematic testing program on LCT provides a relatively complete data set for the validation of a typical critical state elastoplastic constitutive model. The various CSR and stress path probing tests can be used to provide a clearer understanding of the mechanical effect of fabric anisotropy, as suggested by Yang et al. [33].

In the following, the performance of four constitutive models, namely the Modified Cam Clay (MCC) model [24], the S-CLAY1 model [30], the recently modified SANICLAY model [8], and another model proposed by Yang et al. [33] will be compared though their numerical predictions of various virgin and transitional CSR tests on Lower Cromer Till. This work will be presented with first a concise description of these four models, then a systematic comparison of the model predictions, and finally some discussion and conclusions.

2. Model descriptions

The four models listed above will be briefly introduced in this section. For convenience, the model suggested by Dafalias and Taiebat [8] is denoted as SANICLAY14, whereas the model proposed by Yang et al. [33] is denoted here as YANG2015.

2.1. Plastic potential surface and yield surface

S-CLAY1, SANICLAY2014 and YANG2015 all employ a rotated and distorted ellipse to describe the plastic potential surface (PPS), which in the traditional $p' - q$ stress plane is given as

$$g = (q - \alpha_g p')^2 - \left(M_g^2 - \alpha_g^2\right)p'(p'_{m,g} - p') \quad (1)$$

where M_g is the critical state stress ratio; and $p'_{m,g}$ and α_g are the internal hardening parameters controlling the size and the inclination of the PPS. Note that M_g can be Lode-angle dependent and will acquire different values for the compression and extension states of stress, i.e., $M_{g,c}$ and $M_{g,e}$ [26], where the subscripts, c and e, denote the compression and extension stress state, respectively.

The corresponding yield surface (YS) can be expressed in a similar elliptical function as

$$f = (q - \alpha_f p')^2 - \left(M_f^2 - \alpha_f^2\right)p'(p'_{m,f} - p') \quad (2)$$

where $p'_{m,f}$ and α_f, similar to $p'_{m,g}$ and α_g, are the internal hardening parameters for the YS; whereas M_f is effectively the shape factor of the YS.

Eqs. (1) and (2) meet the various requirements for all four models, the specific configurations of which can be found in Table 1. For LCT samples subjected to K_0 (=0.5) consolidation to p' = 233.3 kPa, both the PPS and YS predicted by Eqs. (1) and (2) for all four models are depicted in Fig. 1. It can be seen that S-CLAY1 has a single inclined surface (Fig. 1b), whereas SANICLAY14 and YANG2015 employed two different inclined surfaces (Fig. 1c and d). As indicated in Table 1, SANICALY14 assumes the same size and inclination for both the YS and PPS ($p'_{m,f} = p'_{m,g}$ and $\alpha_f = \alpha_g$) but different shape parameters ($M_f \neq M_g$), which was suggested by Jiang and Ling [12]. This configuration leads to the plastic potential surface in SANICLAY14 not crossing the current stress state on the yield surface (Point A in Fig. 1c). Dafalias and Taiebat [8] then referred to the outward normal to the PPS at a conjugate point A' along the same stress ratio to specify the dilatancy at the current stress point A on the YS (see Fig. 1c). Once anisotropy is absent the surfaces for S-CLAY1, SANICLAY14 and YANG2015 automatically degenerate to that of MCC, whose principal direction is constant and aligned with the hydrostatic axis (Fig. 1a).

2.2. Flow rule

The plastic strain rate vector $\dot{\boldsymbol{\varepsilon}}^p = (\dot{\varepsilon}_p^p, \dot{\varepsilon}_q^p)$ can be expressed by the flow rule as a function of the stress rate vector $\dot{\boldsymbol{\sigma}} = (\dot{p}, \dot{q})$, i.e.,

$$\dot{\boldsymbol{\varepsilon}}^p = \boldsymbol{n}_g \frac{\boldsymbol{n}_f^T \dot{\boldsymbol{\sigma}}}{H_M} \quad (3)$$

where H_M is the plastic modulus, and $\boldsymbol{n}_f$ and $\boldsymbol{n}_g$ are the unit vectors on the yield and the plastic potential surfaces, respectively. The

Table 1
Configuration of YS and PPS via Eqs. (1) and (2) for the four models.

Models	f vs. g	α_f vs. α_g	$p'_{m,f}$ vs. $p'_{m,g}$	M_f vs. M_g
MCC	$f = g$	$\alpha_f = \alpha_g$	$p'_{m,f} = p'_{m,g}$	$M_f = M_g$
S-CLAY1	$f = g$	$\alpha_f = \alpha_g$	$p'_{m,f} = p'_{m,g}$	$M_f = M_g$
SANICLAY14	$f \neq g$	$\alpha_f = \alpha_g$	$p'_{m,f} = p'_{m,g}$	$M_f \neq M_g$
YANG2015	$f \neq g$	$\alpha_f \neq \alpha_g$	$p'_{m,f} \neq p'_{m,g}$	$M_f = M_g$