Implementation of an unsaturated anisotropic clay model (JMC-Clay) in the coupled hydro-mechanical framework of CODE_BRIGHT

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1 Introduction

Soft clays deposited under K_0 conditions often develop a pronounced cross-anisotropic fabric that governs their stiffness, strength and yielding characteristics [1]. Capturing this anisotropy is essential for reliable predictions of deformation and stability in geotechnical problems on soft ground. In many practical situations, soft clays are also subjected to suction changes due to seasonal fluctuations or construction-induced drainage. Addressing the coupled effects of anisotropy and partial saturation within a single constitutive framework is therefore of considerable interest.

The JMC-Clay model [2], recently developed for soft organic clays, extends the SANICLAY framework [3] by introducing greater flexibility in the yield surface shape through the McDowell and Hau [4] expression and enhancing the rotational hardening rule with a Lode-angle dependence. The model has been validated over a comprehensive set of triaxial stress paths in both compression and extension [2]. However, its application has so far been limited to saturated conditions.

Since the foundational framework of Alonso et al. [5] for unsaturated soils, various approaches have been proposed to extend saturated clay models to partially saturated conditions. In this work, the JMC-Clay model is extended to unsaturated states following the approach of Romero and Jommi [6], where the skeleton stress is adopted as constitutive stress variable and the water retention curve (WRC) provides coupling between the mechanical and hydraulic behaviour. The extended model has been implemented in CODE_BRIGHT [7], a finite element platform for coupled thermo-hydro-mechanical analysis in geological media. This extended abstract presents the formulation, numerical integration strategy, and validation under both saturated and unsaturated loading paths, the latter benchmarked against the experimental observations on compacted Boom clay reported in [6].

2 Model formulation

For the sake of brevity, the model is presented with reference to the triaxial space (q – p'). The saturated JMC-Clay model [2] adopts a non-associated formulation. The yield surface, based on the expression of McDowell and Hau [4] extended to account for anisotropy, reads:

$$f = 0 = (q - p'\alpha_f)^2 + \frac{({M_f}^2 - {\alpha_f}^2)}{k_f - 1} p'^2 - \frac{({M_f}^2 - {\alpha_f}^2)}{k_f - 1} {p'_c}^2 \left(\frac{p'}{p'_c}\right)^{\frac{2}{k_f}} \quad (1)$$

where α_f defines the yield surface inclination, p'_c is the preconsolidation pressure, and the shape coefficients k_f and M_f allow enough flexibility in the shape, the standard anisotropic MCC ellipse can be recovered with $k_f = 2$. The plastic potential follows the Dafalias [8] expression with a separate anisotropy variable α_g, enabling the non-associated flow rule confirmed by the experimental evidence in [2].

The rotational hardening law drives α towards bounding values α_{gb} that depend on the stress ratio normalised by the Lode-angle-dependent critical stress ratio M(θ), where θ is the Lode angle. Different de-amplification factors z_c and z_e are adopted in compression and extension, enhancing previous models such as S-CLAY1 [9] and SANICLAY [3]. The size of the yield surface is controlled solely by volumetric plastic strains [2].

For unsaturated conditions, the skeleton stress [6] is adopted: $\hat{p} = (p - u_a) + S_r \cdot s$, where S_r is the degree of saturation and s is suction. The yield surface and hardening laws are rewritten in the skeleton stress space. The preconsolidation pressure in unsaturated conditions, $\hat{p}_0$, follows the expression by Gallipoli et al. [10], incorporating the effect of S_r on the size of the elastic domain. A hysteretic water retention curve, following the approach proposed by Romero and Vaunat [11], provides the hydraulic closure, coupling the mechanical and hydraulic responses.

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3 Numerical implementation

CODE_BRIGHT [7] solves the coupled mass balance and momentum equilibrium equations using implicit time stepping and a full Newton–Raphson scheme. The unsaturated JMC-Clay model has been coded as a new mechanical constitutive law subroutine (ICL index). The stress integration employs an explicit adaptive Runge-Kutta-Fehlberg (RKF23) integration scheme with automatic error control and yield surface drift correction, which updates the stress, the preconsolidation pressure, and the rotational hardening variable α simultaneously. The tangent operator is supplied to the global solver.

Special care was taken to ensure the coupled evolution of the preconsolidation pressure and rotational hardening during wetting-induced collapse: when suction reduction triggers yielding, both $\hat{p}_0$ and α must update simultaneously within each integration sub-step, avoiding operator-splitting errors. All model parameters are accessible through the GiD pre-processor.

4 Validation

The implementation is first verified under saturated conditions. The single-element driver used for verification employs the same explicit adaptive RKF23 integration scheme with automatic error control and yield-surface drift correction, ensuring consistency between the reference solution and the CODE_BRIGHT subroutine. The results from the driver are compared with a fully coupled CODE_BRIGHT boundary value problem simulation of a triaxial test (400 quadrilateral elements, with prescribed boundary conditions reproducing the physical test setup, as shown in Figure 1) under two paths: (a) isotropic consolidation, undrained triaxial compression (TxCU) and undrained triaxial extension (TxEU); (b) undrained shearing from K0-consolidated states (CK0CU). The simulation results of the shearing stage, together with the evolution of anisotropy α during K0 consolidation, are presented in Figure 2. The two sets of results are virtually identical, confirming the correctness of the implementation. The relevant model parameters adopted in the simulations are listed in Table 1 to Table 3 (the definition of each parameter, not reported here for the sake of brevity, can be found in [2], [6] and the CODE_BRIGHT user's manual).

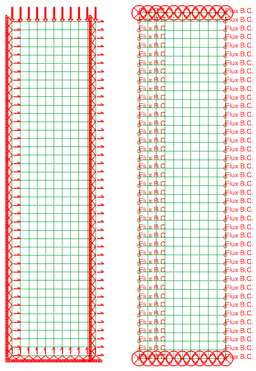

Figure 1. Model in CODE_BRIGHT simulation of a triaxial test.

Table 1. Relevant model parameters for simulations corresponding to TxCU and TxEU paths.

$M_{g,c}$	$M_{g,e}/M_{g,c}$	λ	κ	ν	c	$M_{f,c}$	k_f
1.75	0.74	3	0.4	0.3	0	1.75	2

Table 2. Relevant model parameters for simulations corresponding to CK0U path.

$M_{g,c}$	$M_{g,e}/M_{g,c}$	ν	c	z_c	z_e	s	y	$M_{f,c}$	k_f
1.75	0.74	0.3	50	1.6	1.2	2.2	2	1.5	1.5

Table 3. Relevant model parameters for simulations corresponding to wetting-drying-wetting path (path EFGH in [6]).

$M_{g,c}$	$M_{g,e}/M_{g,c}$	ν	λ (JMC)*	κ	c	z_c	z_e	s	y
0.87	0.99	0.2	0.125	0.014	136	1.6	1.2	2.2	2
$M_{f,c}$	k_f	b_1	b_1	P_0 (MPa)	λ (WRC)*	$S_{r,l}$	$S_{r,s}$		
0.87	2	0.11	8.2	0.048	0.183	0	1		

*JMC – JMC-Clay, WRC – Water retention curve

The unsaturated validation is benchmarked against the experimental data of Romero and Jommi [6] on statically compacted Boom clay (w = 15%, ρ_d = 1.40 Mg/m^3, s_0 = 1.9 MPa). A specimen was subjected to wetting under constant isotropic net stress p'' = 0.6 MPa with suction reduced in stages via the axis-translation technique. The test was simulated in CODE_BRIGHT as a fully coupled hydro-mechanical boundary value problem, reproducing the axis-translation boundary conditions and the liquid flow process. In [6], the experimental data were simulated with a rotated modified Cam-Clay model in skeleton stress, using a hysteretic WRC and the Dafalias [8] rotational hardening rule.

Figure 3 presents the CODE_BRIGHT simulation of the complete wetting-drying-wetting path (path EFGH in [6]) under constant isotropic net stress. The predicted response qualitatively reproduces the key features reported by Romero and Jommi [6]: (i) an initial anisotropic collapse during the first wetting, with radial strain exceeding axial strain at high suction; (ii) progressive anisotropy evolution as deviatoric strains accumulate; and (iii) irreversible shrinkage upon subsequent drying. Quantitative differences with the results in [6] are attributed to the different rotational hardening rule adopted in JMC-Clay, with its Lode-angle-dependent bounding values, compared to the Dafalias [8] form in [6]. Figure 4 illustrates the corresponding evolution of the yield locus in the skeleton stress space. The progressive rotation from the initial K_0-inclined configuration towards the isotropic axis during the first wetting, and the subsequent expansion without further rotation during the drying-wetting cycle, are clearly visible.

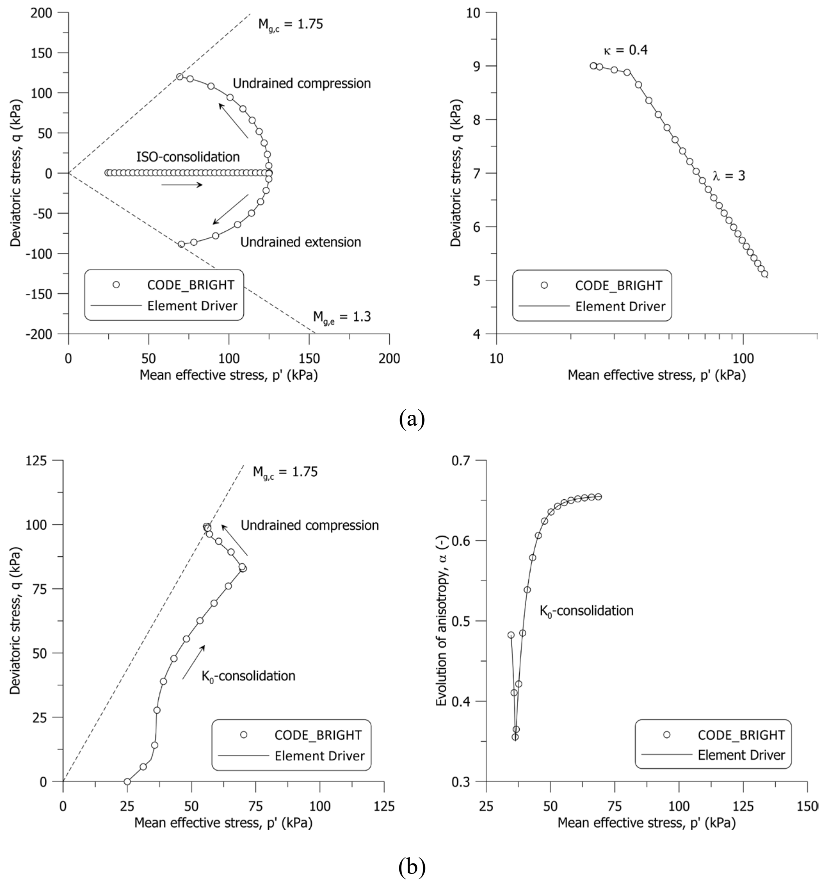

Figure 2. Element driver (lines) vs. CODE_BRIGHT (symbols): (a) TxCU and TxEU, (b) CK_0CU.

5 Conclusions

The JMC-Clay constitutive model has been extended to unsaturated conditions using skeleton stress, a suction-dependent preconsolidation pressure, and a hysteretic water retention curve, and implemented in the coupled hydro-mechanical framework of CODE_BRIGHT. Compared with existing anisotropic formulations such as S-CLAY1 [9] and SANICLAY [3], the model offers two benefits: a flexible yield surface shape through the McDowell-Hau formulation [4], which improves the fit of experimental yield points and enables accurate prediction of pre-failure response over non-monotonic stress paths; and a Lode-angle-dependent rotational hardening rule, which captures the different evolution of fabric anisotropy in compression and extension paths. The implementation was verified by comparison with an element driver under saturated stress paths. The unsaturated extension was validated against the Boom clay data of [6], simulated as a fully coupled boundary value problem, and demonstrates the model ability to reproduce the anisotropic collapse and fabric evolution over a complete wetting-drying-wetting cycle. To the authors knowledge, this represents the first implementation of an anisotropic clay model in CODE_BRIGHT, enabling the analysis of fabric anisotropy effects in fully coupled hydro-mechanical boundary value problems on soft soil. Future work will focus on applications to largerscale boundary value problems, including the simulation of climate-induced THM processes in soft soil geo-infrastructures.

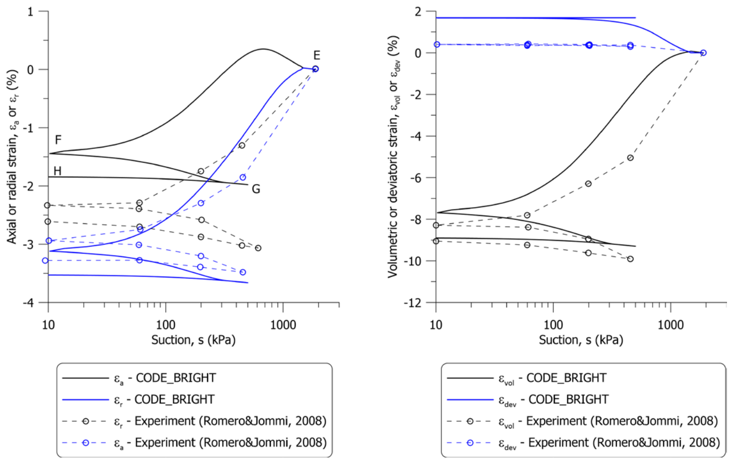

Figure 3. Axial strain, radial strain, volumetric strain, and deviatoric strain wetting-drying-wetting path EFGH.

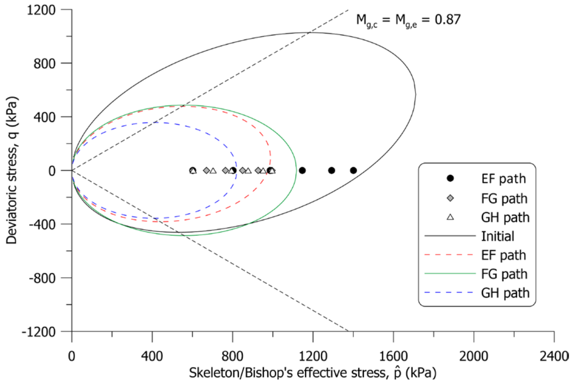

Figure 4. Evolution of the yield locus in skeleton stress space during the wetting-drying-wetting path EFGH.

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