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Abstract

In this paper a finite deformation version of an isotropic hardening elastoplastic constitutive model for bonded soils is used to reproduce the behaviour of a saturated soft structured clay during the penetration of a piezocone in standard CPTu tests. The formulation of the model is based on the multiplicative split of the deformation gradient and on the existence of a free energy function for the elastic behaviour. The model is equipped with two bonding–related internal variables which provide a macroscopic description of the effects of clay structure. The mechanical effects of structure degradation associated to the plastic deformations are quantified by suitable evolution equations. In order to deal with strain localization, typically observed in bonded geomaterials upon yielding, the model has been equipped with a non–local version of the hardening laws for the internal variables, which has proven to be capable of regularizing the pathological mesh dependence of classical finite element solutions in the post–localization regime. The results of the numerical simulations, conducted for different soil permeabilities and bond strengths, show that the model is capable of capturing: a) the development of plastic deformations induced by the advancement of the cone tip; b) the destructuration of the clay associated with such plastic deformations; c) the space and time evolution of pore water pressure as the cone tip advances. The possibility of modelling the CPTu tests in a rational and computationally efficient way opens a promising new perspective for their interpretation in geotechnical site investigations.

Key words: *PFEM; finite deformations; CPTu; structured clays; geotechnical site investigations*

1 Introduction

The Cone Penetration Test with measurements of pore water pressure (CPTu) is a widely used investigation tool for the characterization of both coarse– and fine–grained soils, for its simplicity, reliability and its relatively low cost. The conventional interpretation of CPTu tests is typically based on empirical and semi–empirical correlations, the last based on very crude descriptions of soil behavior, such as the adoption of a total stress approach to circumvent the difficulties associated to the evaluation of the excess pore water pressures induced by the total stress changes around the cone tip. The aim of this work is to show that a more rational interpretation of the coupled deformation and flow processes occurring in the soil during a CPTu test is possible by resorting to the numerical solution of the relevant governing equations coupled with a realistic constitutive model for the soil.

In early attempts to simulate the CPT test with the FE method, adopting an ALE formulation, the extreme deformations imposed to the soil by the penetration of the piezocone probe have represented a substantial difficulty, due to strong mesh distortions which resulted in significant loss of accuracy or loss of convergence at relatively small penetration depths, see, *e.g.*, [10].

An effective alternative to the FEM which has proven to be quite efficient in dealing with the large displacements and deformations induced by the cone penetration process is the Particle Finite Element Method (PFEM) [8]. The PFEM shares many similarities with the updated Lagrangian approach of non–linear FEM, but it is capable of handling the problem of severe mesh distortion by a frequent mesh re–triangulation and h–adaptive refinement using very efficient algorithms based on extended Delaunay tesselation. The nodes of the spatial discretization – performed with low–order linear triangles or tetrahedra – are treated as material particles, the motion of which is tracked during the numerical simulation. Applications of PFEM to the modeling of CPTu tests have been reported, *e.g.*, in [4, 3, 5].

In all the aforementioned works dealing with CPTu tests in clays have been carried out modeling the soil with the classical MCC model. Although this critical state model is capable of capturing the essential features of soft, lightly overconsolidated clays, it fails to reproduce the behavior of natural structured clays, characterized by the presence of intergranular bonds of various origin. To investigate the effects of bonding on the soil response to the piezocone advancement, in this work the isotropic hardening elastoplastic model with bonding–related internal variables proposed by Nova and co–workers [9, 6] has been extended to finite deformations adopting a multiplicative decomposition of the deformation gradient into elastic and plastic parts, see, *e.g.*, refs. [2, 1]. The resulting model, referred to as FD_Milan model in the following, has been implemented in a geomechanics–oriented PFEM code (G–PFEM [4]) and used to simulate some CPTu tests in a relatively soft, structured natural clay.

An overview of the constitutive model for structured soils is briefly recalled in Sect. 2, while the details of the CPTu simulations program are given in Sect. 3. A selection of the results obtained in the PFEM simulations is presented in Sect. 4, along with the main concluding remarks.

2 Overview of the FD_Milan model

The FD_Milan model is a three–invariants isotropic hardening model employing independent yield function f and plastic potential g. A representation of the yield surface in the Kirchhoff stress invariants space P:Q, for the set of constants of Tab. 1, is given in Fig. 1.

Two independent scalar internal variables account for the hardening/softening effects due to volumetric and deviatoric plastic strains (*preconsolidation pressure* P_s) and for the effects of intergranular bonds (*bond strength* P_t). A positive value of P_t results in an expansion of the elastic domain in stress space, an increase of the isotropic yield stress in compression by a quantity $P_m = kP_t$, with k a material constant, and in the presence of a true cohesion and a non–negligible tensile strength. As a consequence of the microstructural rearrangement of the soil fabric – accompanied by macroscopic plastic deformations – the intergranular bonds are progressively destroyed and P_t reduces accordingly. When $P_t \to 0$, the bond–permitted space reduces to zero and the yield surface coincides with the yield surface of the corresponding unbonded soil. The hardening laws for P_s and P_t are given by:

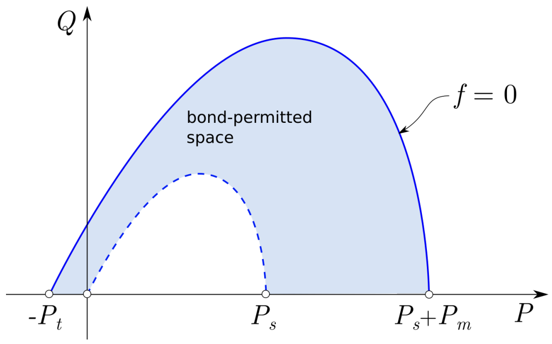

Figure 1: Yield surface of the FD_Milan model.

$$\dot{P}_s = \dot{\gamma}\,\rho_s P_s \left(\hat{V} + \xi_s \hat{D}\right) \qquad\qquad \dot{P}_t = -\dot{\gamma}\,\rho_t P_t \left(|\hat{V}| + \xi_m \hat{D}\right) \tag{1}$$

where: $\hat{V} = \mathrm{tr}(\partial g/\partial \boldsymbol{\tau})$; $\hat{D} = \sqrt{2/3}\,\|\mathrm{dev}(\partial g/\partial \boldsymbol{\tau})\|$; $\dot{\gamma}$ is the plastic multiplier; $\boldsymbol{\tau}$ is the Kirchhoff stress, and ρ_s, ρ_t, ξ_s and ξ_t are material constants. For $\xi_s = 0$, eq. $(1)_1$ reduces to the classical volumetric hardening law of critical state soil mechanics. Plastic volumetric compaction produces an increase of P_s while plastic dilation is accompanied by a reduction of P_s. As the RHS of eq. $(1)_2$ is always negative, any plastic process gives rise to a monotonic decrease of P_t (bond destructuration). In order to provide a characteristic length scale to the constitutive equation, to regularize the numerical solution in presence of strain localization phenomena, an integral non–local approach has been adopted, in which the internal variables P_s and P_t are treated as non–local, spatially averaged quantities over a neighborhood Ω of the material point. The size of this neighborhood is controlled by a material constant ℓ_c, called *characteristic length*. The details of the FD_Milan model formulation can be found in ref. [7].

3 Simulation program

In the PFEM simulation of CPTu tests, a standard piezocone, with radius R = 1.78 cm and a cone tip angle of 60° is inserted in a calibration chamber with radius B = 0.45 m and height H = 1.05 m, filled with a fully saturated clay. The problem has been assumed as axisymmetric.

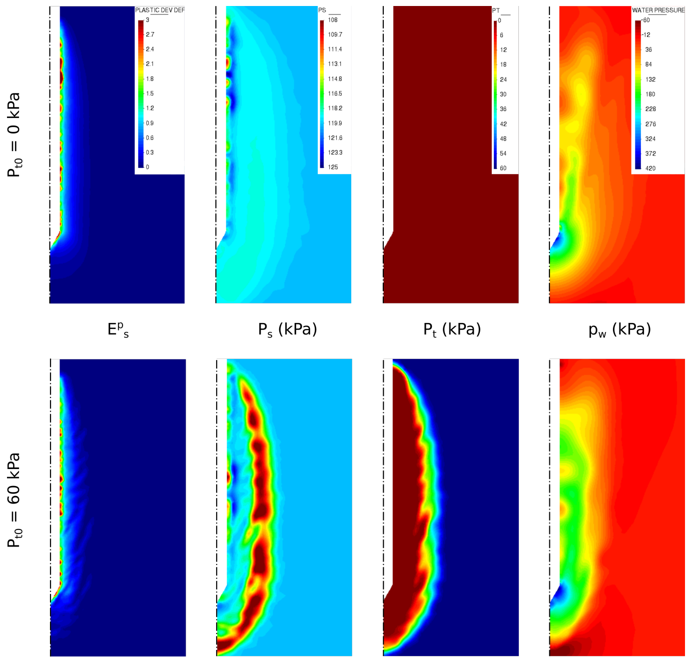

Figure 2: CPTu tests results: contour maps of E_s^p, P_s, P_t and $\Delta p_{w,1}$ at the maximum penetration depth, for P_{t0} = 0 kPa (top) and P_{t0} = 60 kPa (bottom).

The piezocone is wished–in–place at an initial depth z_0 = 0.25 m and then displaced downwards at a constant penetration speed of 2.0 cm/s, up to a depth $z = z_0 + 20R$. The piezocone tip and its lateral surface are modeled as rigid, impervious surfaces, and a smooth contact interface with the soil is employed to simulate the piezocone–soil interaction as the device penetrates the soil. Given the relatively small dimensions of the calibration chamber, the self weights of the pore water and of the soil have been ignored. The initial pore water pressure has been assumed uniform and equal to zero. The material constants adopted for the clay soil are reported in Tab. 1. The flow rule has been assumed as associative, so the plastic potential coincides with the yield function.
All the PFEM simulations have been performed as fully coupled hydromechanical problems, adopting the mixed $\boldsymbol{u}$–Θ–p_w formulation of ref. [4]. The bottom and lateral surfaces of the calibration chamber have been assumed as rigid, impervious and perfectly rough boundaries. At the top surface of the soil body a uniform normal pressure q_0 = 100 kPa and a constant pore water pressure $p_w = 0$ have been imposed. Consistently with these boundary conditions, the initial Cauchy effective stress in the soil mass has been assumed axisymmetric, with components σ_z = 100 kPa and $\sigma_r = K_0\sigma_z$ and $K_0 = 0.5$.

4 CPTu simulations results

Six different simulations have been performed considering different values of the hydraulic permeability, k_h, in the range between 1.0e-6 m/s and 1.0e-9 m/s, and initial values of the bond strength P_t in the range between 0 and 60 kPa. Fig. 2 reports some selected results from the simulations performed with k_h = 1.0e-9 and the two extreme values of the bond strength. For such a low permeability value, the penetration process occurs in almost undrained conditions.
From the contours of accumulated deviatoric plastic strains E_s^p it can be observed that in the unbonded soil (top row) the plastic zone around the piezocone extends by about $3R$ around the shaft and the cone, with contour lines following the shape of the penetrating device. In the bonded soil (bottom row), on the other hand, the observed pattern of plastic shear deformations is much more irregular and show the presence of localized shear zones which originate at about $3R$ below the cone tip and bend upwards as the cone advances. The presence of localized shear zones is a

$\hat{\kappa}$ (–)	G_0 (MPa)	α (–)	P_r (MPa)	$M_{f,c}$ (–)	α_f (–)	μ_f (–)	$M_{g,c}$ (–)
1.82	3.0	0.0	5.0	1.1	0.75	1.50	1.1
α_g (–)	μ_g (–)	ρ_s (–)	ρ_t (–)	ξ_s (–)	ξ_t (–)	k (–)	ℓ_c (mm)
0.75	1.5	8.33	15.0	0.0	3.0	5.0	5.0

Table 1: Sets of material constants adopted in the CPTu test simulations.

consequence of the softening mechanism associated to soil destructuration, clearly visible in the contour maps of P_t, bottom row. In the unbonded soil, the preconsolidation pressure P_s is only slightly affected by the penetration process. On the contrary, in the structured soil P_s experiences a significant decrease in a zone of soil located at the boundary of the plastic region, where plastic dilatancy is occurring. Peak excess pore water pressures of about 420 kPa develop at the cone mid–height in both cases, but overall, the predicted values of Δp_w around the piezocone tend to be larger for the bonded soil.

Overall, the results of this preliminary study appear consistent with the observed CPTu data in similar soils and demonstrate that the complex soil response to the penetration of the piezocone in CPTu tests can actually be modeled quantitatively in a rational and computationally efficient way. This opens a promising new perspective for a more realistic interpretation of this kind of in–situ tests for geotechnical site investigations.

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