The mechanical behaviour of a natural clay: Experimental results and constitutive modelling

Le comportament mecanique d'une argile: résultats expérimentaux et modélisation du comportement constitutif

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ABSTRACT: Recent experimental results have demonstrated the influence of the initial soil structure and of the structural degradation that develops with straining on the mechanical behaviour of natural clays.
The first part of this paper briefly examines the mechanical behaviour of an Italian natural stiff clay, the Pappadai clay, in order to outline the main effects of the natural soil structure and of its changes with straining on the clay behaviour. This is followed by the description of the simplified version of a recently developed constitutive model for natural clays, which can simulate the effects of the degradation of the initial structure on clay behaviour. The model is then used to simulate some of the experimental test results for natural Pappadai clay. The calibration procedure used to derive the values of the model parameters for the clay is presented and the numerical results are compared with the experimental data.

RÉSUMÉ: Les récents résultats de la recherche ont démontré l'influence sur le comportement mécanique des argiles naturelles de la part de la structure initiale du terrain ainsi que de la dégradation qui se développe avec la déformation.
Dans la première partie de cet article le comportement mécanique d'une argile dure, l'argile italienne de Pappadai, a été examiné pour décrire les principaux effets de la structure du terrain naturel et ses changements suite aux phénomènes de déformation. Il s'ensuit la description de la version simplifiée d'un modèle du comportement constitutif des argiles naturelles qui simule les effets de la structure naturelle. Le modèle est utilisé pour simuler les résultats de laboratoire sur les argiles de Pappadai. La procédure de calibrage utilisée pour obtenir les valeurs des paramètres du modèle est aussi décrite et ces valeurs sont comparées avec les résultats expérimentaux.

1 INTRODUCTION

Results of soil mechanics research developed in recent years have demonstrated that the mechanical behaviour of clays depends on their structure, that is the combination of fabric (the arrangement of the soil particles) and bonding (inter-particle forces not of a purely frictional nature), and on the structural modifications which develop with straining. Amorosi & Kavvadas, (1999) propose a geotechnical interpretation of the soil structure, referring to it as the effect of any process causing a deviation from the 'intrinsic properties' (Burland 1990), thus as the element defining the difference in behaviour between the natural and the reconstituted soil.

Cotecchia & Chandler (2000) have shown that the differences in behaviour between natural clays of different structure can be related to differences in stress sensitivity S_σ between the soils, where S_σ is the ratio of the gross yield stress in one-dimensional compression, σ_{vy}', to the equivalent pressure, σ_e^*, taken on the normal compression line of the reconstituted clay for the specific volume of the natural clay at the oedometric gross yield. Therefore S_σ is a parameter representing structure; it is higher than 1 for sensitive clays and reduces with the structure degradation taking place in these clays with straining.

Constitutive models used to describe the deformation and strength of natural clays should account for the influence of structure and for its degradation with straining, whereas the soil models stemming from classical Critical State Soil Mechanics (CSSM) do not, since they refer solely to the behaviour of reconstituted soils (S_σ =1). This paper briefly reviews the geotechnical characteristics and mechanical behaviour of a sensitive natural clay, Pappadai clay, which has been investigated in the laboratory, and discusses the application to this clay of an elasto-plastic constitutive model for structured soils (MSS; Kavvadas & Amorosi 2000). The model accounts for structure degradation, relating it to both volumetric and deviatoric straining, and is used to predict the response of Pappadai clay at medium to high pressures.

2 EXPERIMENTAL RESULTS

Laboratory testing has been carried out on Pappadai clay, a Pleistocene high plasticity marine clay, block sampled from 25 m depth at a site to the east of Taranto (Southern Italy; Cotecchia & Chandler 1997). In its geological history the clay has developed an overconsolidation ratio (OCR) of 3 due to unloading consequent to erosion. It has also been subjected to diagenesis, which has given rise to a carbonate bonding and to a consequent increase in the gross yield stresses (Cotecchia & Chandler 1997). The term 'gross yield' is here referred to the state of the soil immediately before a significant decay in stiffness caused by the onset of appreciable structure degradation. Due to diagenesis, the yield stress ratio (YSR) of the clay, defined by Burland (1990) as the ratio of the gross yield stress in one-dimensional compression, σ_{vy}', to the current vertical effective stress, σ_{v0}', is higher than the OCR (YSR=6). The specific volume, v, of the clay block samples, measured as 1.88, and the corresponding suction, equal to 700 kPa on average, define the state of the clay before testing.

In oedometer compression the clay exhibits a gross yield state and post-gross yield compression curve (i.e. virgin compression curve) that lie to the right of the ICL up to very high pressures. This is indicative of the higher strength of the natural clay structure by comparison with that of the same clay reconstituted. This difference in structural strength is reflected into a value of stress sensitivity S_σ of 3.5 for the natural clay.

The mean effective stress of the clay at gross yield in isotropic compression, p_y', is equal to 2000 kPa. The values of the compressibility characteristics are N = 3.77, λ = 0.254 and κ = 0.02.

Drained and undrained shear tests have been carried out on clay specimens consolidated isotropically to values of mean effective stress, p_0', varying in a large range: 250 – 3800 kPa. All the tests corresponding to $p_0' < p_y'$ exhibit a significant decay in stiffness at gross yield in shear. A possible initial gross yield surface is indicated in Figure 1. The figure also shows the stress

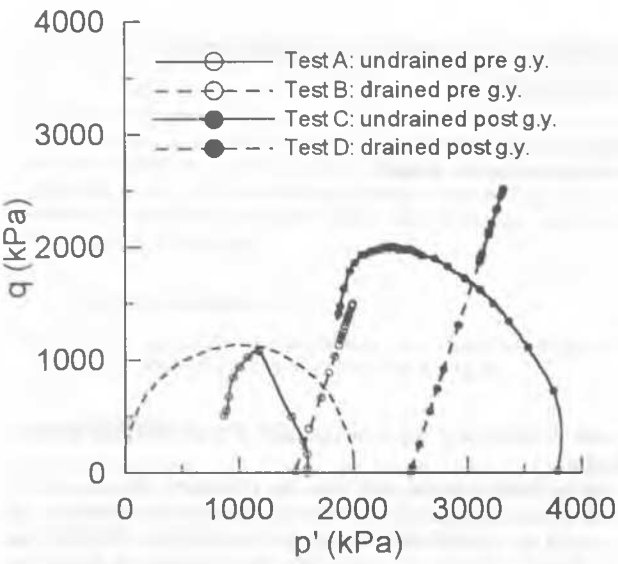

Figure 1. Tests A, B, C and D: effective stress paths

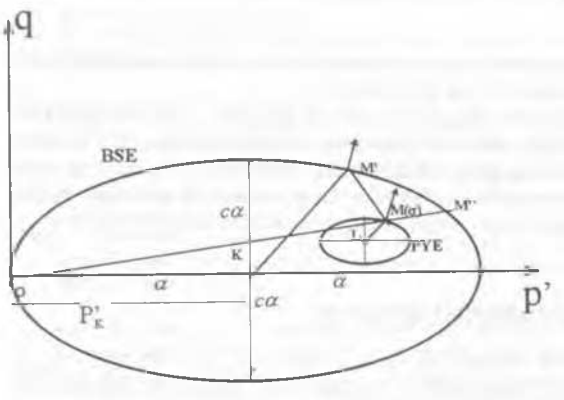

Figure 2. Characteristic surfaces of the MSS model

paths of an undrained test, A, and a drained test, B, consolidated pre-gross yield, and those of the undrained test, C, and the drained one, D, both consolidated post-gross yield.

In the following it is assumed that the mechanical behaviour of structured soils, like Pappadai clay, is characterised by a hardening regime controlled by both the degradation of structure and the 'intrinsic' (i.e. Cam-Clay like) behaviour of the material. Consistently with this hypothesis, the high pressure consolidation stages of tests C and D determine a lower enlargement of the gross-yield surface than what CSSM would predict. This is due to the structure degradation phenomena, occurring during consolidation, which would cause by itself a reduction of the dimension of the same surface. Thus, the comparison between tests results obtained consolidating the soil to p_0' below or above p_y' points out the effects of different degrees of structural degradation prior to shear on the behaviour of the soil. The comparison between tests characterised by the same amount of structure degradation induced prior to shear (A and B, C and D) points out the differences in the structure degradation process occurring during drained and undrained shearing. In fact, as Amorosi & Rampello (1998) showed with reference to an other natural stiff clay, the degradation process induced during drained shearing can be larger than that observed in undrained conditions due to the different amount of volumetric plastic strains occurring during the tests.

Therefore, the tests A, B, C and D have been selected in this work as representative of the structure degradation processes affecting Pappadai clay during the consolidation and shearing stages. These features are explicitly described by the constitutive model described below, making meaningful the comparison of laboratory tests results with model predictions.

3 CONSTITUTIVE MODEL

The constitutive model adopted in the simulations is a simplified version of the recently developed Model for Structured Soils (MSS), based on multisurface plasticity concepts and presented by Amorosi & Kavvadas (1999) and Kavvadas & Amorosi (2000). A key feature of the MSS model is the treatment of preconsolidation as a structure-inducing process and the unified description of all such processes via a "Bond Strength Envelope" (BSE), associated with the onset of appreciable de-structuring and distinguished from the onset of plastic yielding. Other features of the model include: a damage-type mechanism to model volumetric and deviatoric structure degradation, the evolution of stress and bond-induced anisotropy using a fading memory scheme, adaptable predictive capabilities depending on the sophistication of the available test data, modularity to extend its applicability in several soil types and mathematical formulation in a general tensorial space to facilitate its incorporation in finite element codes.

In the present work the original model has been reformulated in the triaxial stress space and simplified excluding the description of the evolution of stress and bond-induced anisotropy. The constitutive model is briefly outlined in the following; for a more detailed description the reader should refer to the references quoted above.

The model is characterised by two Cam-Clay like elliptical surfaces: the internal PYE, corresponding to the yield surface, and the external bounding surface BSE, which represents the material states associated with the onset of degradation of structure at appreciable rate (Figure 2). The latter is centred on the isotropic axes and expressed by the function:

$$F \equiv \frac{1}{c^2}q^2 + (p' - p_K')^2 - \alpha^2 = 0 \qquad (1)$$

where p_K' represent the co-ordinate of the centre of the ellipse K, α is the length of the half-axes along the isotropic axes and $c\alpha$ is the length of the half-axes along the deviatoric axes. The PYE is geometrically similar to the BSE and is expressed by the function:

$$f \equiv \frac{1}{c^2}(q - q_L)^2 + (p' - p_L')^2 - (\xi\alpha)^2 = 0 \qquad (2)$$

where p_L' and q_L represent the co-ordinates of the centre of the ellipse L. The PYE is fully contained inside the BSE and is characterised by a reducing dimension factor ξ <<1.

For states inside the PYE the reversible behaviour is described by a hyperelastic formulation originally proposed by Houlsby (1985) to include the elastic stiffness dependence on effective stresses; the elastic strain energy function is the following:

$$V\left(\varepsilon_v^e;\varepsilon_q^e\right) = p_r \exp\left(\frac{\varepsilon_v^e}{\kappa^*}\right)\left\{\kappa^* + \frac{3\alpha^*}{2}\left(\varepsilon_q^e\right)^2\right\} \qquad (3)$$

where $\kappa^* = \kappa/(1+e)$ and α^* are material constant.

Once plastic behaviour occurs for states inside the BSE, the PYE moves towards a point (M'), conjugate of the current state point (M), computed by the formulas:

$$p'(M') = p_K' + (p' - p_L')/\xi \qquad (4a)$$

$$q(M') = q_K + (q - q_L)/\xi \qquad (4b)$$

The translation of the centre L is described by the formulas:

$$\dot{p}_L' = \frac{\dot{\alpha}}{\alpha} p_L' + \dot{\mu}\beta_{p'} \qquad (5a)$$

$$\dot{q}_L = \frac{\dot{\alpha}}{\alpha} q_L + \dot{\mu}\beta_q \qquad (5b)$$

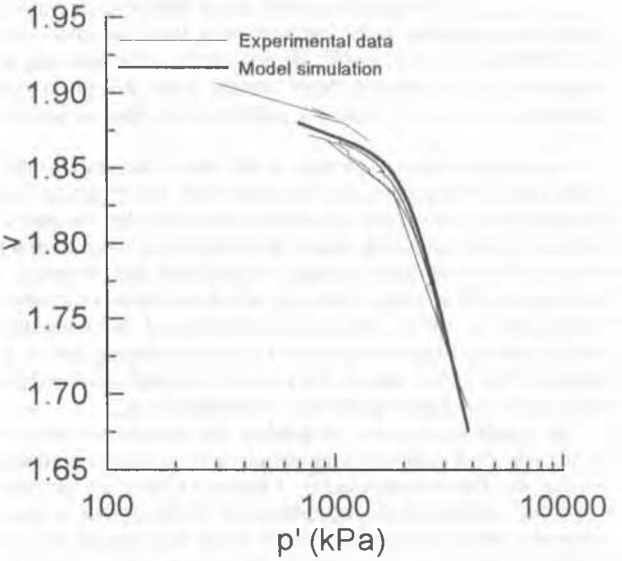

Figure 3. Isotropic compression curves: experimental and numerical data

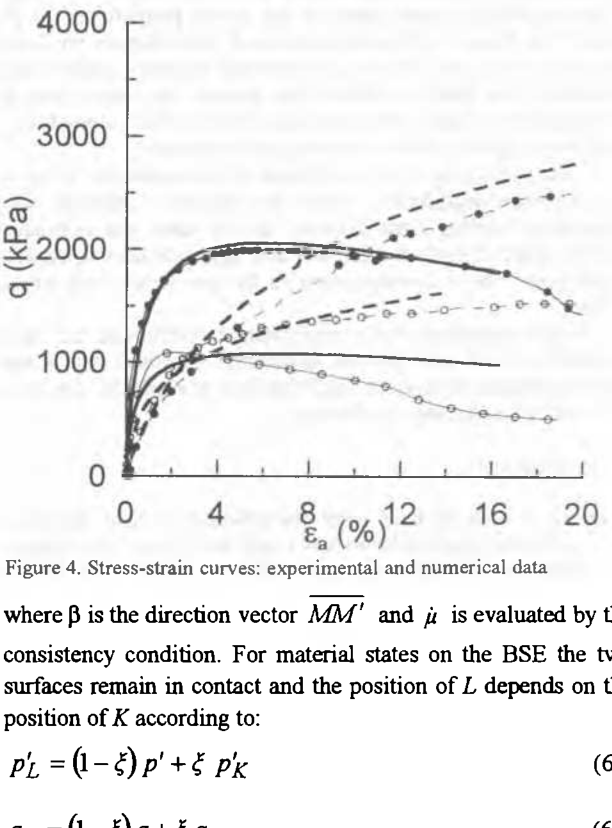

Figure 4. Stress-strain curves: experimental and numerical data

where β is the direction vector $\overline{MM'}$ and $\dot{\mu}$ is evaluated by the consistency condition. For material states on the BSE the two surfaces remain in contact and the position of L depends on the position of K according to:

$$p'_L = (1-\xi)\,p' + \xi\,p'_K \qquad (6a)$$

$$q_L = (1-\xi)\,q + \xi\,q_K \qquad (6b)$$

The flow rule of the model is associated and has the standard form:

$$\dot{\varepsilon}_v^p = \dot{\Lambda}\frac{\partial f}{\partial p'} \qquad (7a)$$

$$\dot{\varepsilon}_q^p = \dot{\Lambda}\frac{\partial f}{\partial q} \qquad (7b)$$

where:

$$\dot{\Lambda} = \frac{1}{\mathrm{H}}\left(\frac{\partial f}{\partial p'}\dot{p}' + \frac{\partial f}{\partial q}\dot{q}\right) \qquad (8)$$

with H being the plastic modulus. For material states on the BSE H is determined from the consistency condition, while for material states inside the BSE it is evaluated from the requirement for a continuous variation of its magnitude as the PYE approaches the BSE. This is expressed by the following interpolation rule:

$$\mathrm{H} = \mathrm{H}'' + |\mathrm{H}''|\left\{\left[1-(\delta/\delta_o)\right]^{-\gamma} - 1\right\} \qquad (9)$$

where H" is the value of H at point M" on the BSE (Fig.2), δ is the MM' length, δ_0 is the MM' length when plastic strains start to accumulate and γ controls the rate of decay of the plastic modulus from H = ∞ to H = H" when the stress state reach the BSE.

The isotropic hardening rule controlling the change in size of the BSE due to plastic strain increments is (eq. 10):

$$\dot{a} = a\left[\left\{\left(\frac{1+e}{\lambda-\kappa}\right) - \zeta_v \cdot \exp\left(-\eta_v \varepsilon_v^p\right)\right\}\dot{\varepsilon}_v^p + \left\{-\zeta_q \cdot \exp\left(-\eta_q \varepsilon_q^p\right)\right\}\dot{\varepsilon}_q^p\right]$$

where λ and κ are the intrinsic compressibility parameters, ζ_v and η_v are the volumetric structure degradation parameters and ζ_q and η_q are the deviatoric structure degradation parameters.

4 CALIBRATION OF THE MODEL AND NUMERICAL ANALYSIS

The calibration of the model parameters has been carried out with reference to the following tests: a set of high pressure isotropic compression curves and the undrained triaxial test A characterised by $p_0' < p_y'$. All the numerical tests have been performed starting from the following initial states: p' = 700 kPa, q = 0; p_L' = 700 kPa, q_L = 0; p_K' = 1100 kPa. The initial length of the horizontal axes of the BSE has been assumed to be slightly larger than the observed p_y'. In the isotropic compression tests, the pre-gross yield part has been used to calibrate the parameters κ^*, α^*, γ which influence the response within the BSE, while λ, ζ_v, η_v have been evaluated on the base of the virgin part of the compression curves. The undrained triaxial test has been used to evaluate the parameter c, the axes size ratio of the ellipses, and the deviatoric structure degradation parameters ζ_q and η_q. The ratio between the size of the PYE and the BSE has been assumed equal to 0.001. The values of all the parameters are reported in Table 1.

In both the calibration and the evaluation of the model, the numerical tests were performed reproducing the same sequence of stages as that imposed in the laboratory tests. Figure 3 shows the comparison between the isotropic compression tests and the corresponding numerical back-prediction. The values of the volumetric hardening parameters are such that a significant amount of structure degradation is still taking place at high pressures. Figures 4-5 show the comparison between the observed and predicted stress-strain behaviour of the clay in tests A, B, C and D. The $q - \varepsilon_a$ curves show that the model can reproduce the post-peak strain softening observed in the undrained tests and the monotonic strain hardening observed in the drained tests. Concerning the rates of excess pore water pressure (Δu) development in the undrained tests and of the volumetric compression ε_v in the drained tests, the observed general patterns are satisfactorily reproduced by the model, though the predictions tend to overestimate the amount of Δu and ε_v in the final part of the tests.

Table 1. Model parameters for Pappadai clay

Parameter	value
κ^*	0.013
α^*	103
λ	0.22
c	1.1
ζ_v	3.0
η_v	9.5
ζ_q	3.0
η_q	0.1
γ	3.5

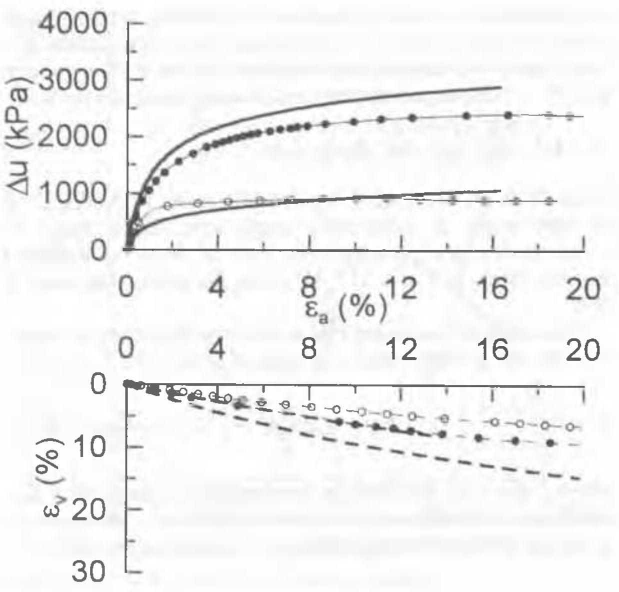

Figure 5. Excess p.w.p. and volumetric strains: experimental and numerical data

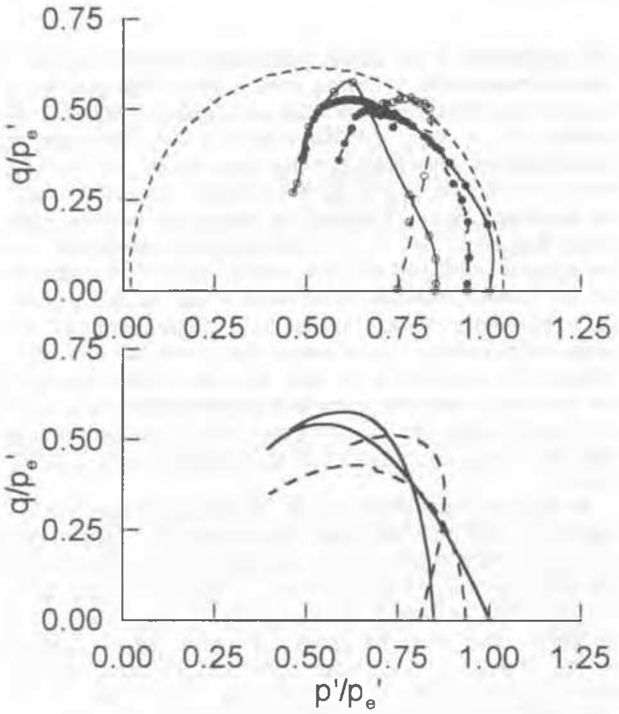

Figure 6. Normalised stress paths: experimental data (above) and numerical data (below)

5 DISCUSSION OF THE RESULTS AND CONCLUSIONS

The four tests presented in this paper refer to very different states for the soil, i.e. different values of p_0' and v. In order to properly compare the experimental results, the stress paths have been normalised with respect to the Hvorslev's equivalent pressure p_e', defined as the mean effective stress on the isotropic virgin compression curve of the natural clay for the current specific volume (Figure 6). According to CSSM, the normalised stress paths, after reaching the yield locus, follow a constant volume section of the State Boundary Surface, which represents the boundary between possible and impossible states and defines the locus of all the states of an element of soil undergoing plastic deformation. Figure 6 also reports, as a dashed line, an experimentally evaluated surface which represents the boundary between possible and impossible states for the clay when consolidated to values of p_0' below the gross yield mean effective stress. The figure shows that the stress paths starting from pre-gross yield consolidation states (A, and B) do not overlap after touching the boundary surface, whereas those starting from post-gross yield consolidation states (C and D) neither touch this surface nor overlap.

The apparent non-uniqueness of the State Boundary Surface shown in the normalised plot indicates that, for Pappadai clay, the equivalent pressure is not able to normalise the mechanical behaviour of the material, due to the progressive degradation of structure which develops during compression and shearing. In the context of hardening plasticity, which provides a theoretical background to CSSM, the non coincidence of the normalised paths shown in Figure 6 indicates that the hardening law of the material differs from that of the Cam-Clay model, implicitly assumed in the normalising process with respect to p_e'.

The constitutive model adopted in the simulations accounts for the effects of structure degradation in the isotropic hardening law (eq.10). This is composed by 3 terms: a Cam-Clay like term, a term accounting for the degradation of structure due to plastic volumetric strain and a term related to the degradation of structure due to plastic deviatoric strain. The structure degradation terms tent to reduce their effects as plastic strain accumulate. The normalised stress paths of the model predictions are also shown in Figure 6. The simulations of the pre-gross yield tests show that the degradation of structure becomes evident after touching the BSE; it affects the drained test more than the undrained one, due to the additional effects of the volumetric and deviatoric plastic strains occurring in the former.

The post-gross yield predictions are characterised by an initial structure degradation process due to plastic volumetric strain cumulated during consolidation; in this case, the normalised stress paths of both the drained and the undrained simulations plot below those corresponding to the pre-gross yield simulations.

The comparison of the experimental results and the model predictions indicates that the model can reproduce with a satisfactory degree of accuracy the behaviour of Pappadai clay as observed in a wide range of stresses.

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