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SOME REMARKS ON THE STRENGTH AND DILATANCY OF A STIFF AND OVERCONSOLIDATED CLAY

OBSERVATIONS SUR LA RESISTANCE ET LA DILATANCE D'UNE ARGILE RAIDE ET SURCONSOLIDEE

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SYNOPSIS: The shear strength of a natural overconsolidated clay has been compared with that of the reconstituted material. The different past histories of the intact and reconstituted samples, in terms of stress history and time effects, produce different micro-structures (interparticle bonding and particle arrangement). Void ratio and rate of dilatancy, together, can be thought of as a measure of structure. An attempt to interpret the influence of both of them on the observed differences in the shear strength properties is presented in this work. The stress-dilatancy relationships from triaxial compression tests have been examined for Vallericca clay, and a dilatancy component of the peak strength has been isolated by means of two different procedures. The failure envelopes, normalised by the equivalent pressure relevant to the reconstituted clay, have been compared before and after correction for dilatancy. In the investigated stress range they resulted to be linear and parallel irrespectively of the dilatancy correction, which only modifies slope and intercept of the two envelopes. While for reconstituted Vallericca clay the component of effective cohesion was found to mainly be an effect of dilatancy, this was not the case for the natural clay.

INTRODUCTION

The strength and dilatancy of soils received a great deal of attention in the late 1950s and in the 1960s. At that time it came to be understood that volume changes in soils are at least as important as changes in effective stresses when trying to build a general picture of soil behaviour. The Hvorslev (1960) analysis of peak strengths of clay, the stress-dilatancy theory of Rowe (1962) and the analysis of the effects of dilatancy on the strength of overconsolidated clays (Rowe et al. 1963) provide good illustrations of the need to examine friction and dilatancy as interplaying concepts and to consider volumetric quantities as well as effective stress variables when trying to assemble strength data.

It is worth noting that the concept is applicable with equal force to both clays and sands. However, research on cohesive and cohesionless soils to some extent developed separately and, for instance, the application of Rowe's stress-dilatancy theory to clays remained essentially open until the very recent past.

With reference to sands, Bolton (1986) examined the matter in relation to the selection of strength parameters for design, and produced some expressions which link the peak and the critical state angles of friction, ϕ'_p and ϕ'_{cs}, through the introduction of a relative dilatancy index. The empirical correlations were proposed as a best fit to a wide range of data from triaxial and biaxial compression tests. They allow a prediction of the peak strength (ϕ'_p) of any element of the sand with known density and stress, on the basis of the estimate of ϕ'_{cs} from the shearing strength of samples loose enough to fail in a critical state, with zero dilation.

More recently, Scarpelli (1991) followed a similar approach in studying the strength and dilatancy of two stiff and overconsolidated clays on the basis of the results of triaxial compression tests. He presented data showing that the difference between the peak angle of shearing of the intact soil and the angle ϕ'_{cs} (from tests on reconstituted normally consolidated samples) depends on the amount of dilatancy experienced by the soil at failure. A relation linking ϕ'_p and ϕ'_{cs} was proposed, on the basis of Rowe's stress-dilatancy theory. The hypothesis was then suggested that the critical state angle of shearing ϕ'_{cs} of reconstituted normally consolidated samples is the single fundamental parameter which the shear strength of the intact clay also relies upon.

When comparing the strength of a natural overconsolidated clay with that from tests on reconstituted samples of the same material, a great deal of prudence should be used in extracting any information concerning the *structure* of the natural clay. Referring to peak data from triaxial compression tests on intact and reconstituted samples of Vallericca clay, a simple way has been explored in this work of interpreting the influence of structure on the observed strengths. Since void ratio and rate of dilatancy are *together* a measure of structure, a normalisation procedure of the peak data taking into account both of these makes understandable a great portion of the enhanced strength of the natural clay.

SOIL TESTED AND TEST PROGRAMME

Stiff overconsolidated clay deposits of Plio-Pleistocene age, of marine or lacustrine origin, are frequent in the central region of the Italian peninsula. Vallericca clay, selected for testing, was deposited in a shallow marine environment; the clay deposit is several hundred meters thick. Where the clay is overlain by the products of the neighbouring volcanic activity, an erosion surface is recognisable at the contact.

Block samples were extracted from vertical cuts in a brick pit at Vallericca, only a few kilometers North of Rome. Table I lists the basic index properties of the soil, together with its estimated in situ state. Vallericca clay is a medium plasticity and activity clay, with a calcium carbonate content of about 30%. The vertical yield stress from oedometer tests is denoted by σ'_{vy}, while p'_k is the initial mean effective stress, after sampling. An approximate estimate of the effective overburden pressure σ'_{vo} allowed for the evaluation of a yield stress ratio $\sigma'_{vy}/\sigma'_{vo}$ of ~ 7.

Table I - Index properties and in situ state

G_s	≤2μm %	w_L %	I_p %	w_o %	I_L	σ'_{vy} MPa	p'_k kPa
2.78	42	59.2	31.6	28.6	0.03	1.9	430

Tests were carried out on two separate sets of triaxial samples, 38 mm in diameter. In the first set, specimens of intact clay were carefully cut from blocks taken from the toe of vertical faces about 30 m high. The samples were then sheared after isotropic consolidation to values of p' of 0.05 to 1.2 MPa. The second group of samples was reconstituted in the laboratory. Portions of the block samples were oven-dried, pulverised to pass a 0.25 mm sieve, and then mixed with distilled water at a water content of about 1.5 w_L. First the slurry was consolidated in a large oedometer where a vertical effective stress of 200 kPa was applied to avoid significant cross-area reductions under the subsequent stage of isotropic consolidation. Then triaxial samples were extruded and placed in the triaxial cell, where an isotropic consolidation brought three samples to the desired mean effective stress (0.3, 0.6 and 1.2 MPa) in a normally consolidated condition. The remaining samples were consolidated to p'= 2.0 MPa and then unloaded to give values of the isotropic overconsolidation ratio R of 5 to 40. Thereafter, both the natural and reconstituted samples were sheared in standard triaxial undrained or drained compression, or drained constant p' compression. The rate of axial strain was constant at 0.24 to 0.48 %/hr in the undrained tests and at 0.02 to 0.06 %/hr in the drained tests. Some of the tests on natural samples were carried out at Imperial College of London as part of a joint research project with the University of Rome (Viggiani et al. 1993).

DISCUSSION OF TEST RESULTS

The following discussion will be in terms of stress parameters $q = (\sigma'_a - \sigma'_r)$ and $p' = (\sigma'_a + 2\sigma'_r)/3$, and of strain parameters $\varepsilon_s = 2(\varepsilon_a - \varepsilon_r)/3$ and $\varepsilon_v = (\varepsilon_a + 2\varepsilon_r)$, where the subscripts *a* and *r* refer to axial and radial directions in the cylindrical samples. Superscripts *p* and *e* will be used, referring to plastic and elastic components of strain. Finally, following Burland (1990), the properties of the reconstituted soil will be referred to as *intrinsic* and denoted by an asterisk.

Stress-Dilatancy Relationships

For all the tests the relationship was examined between the stress ratio $\eta = q/p'$ and the plastic strain increment ratio. The latter is expressed in terms of the angle β between the strain increment vector and the $\delta\varepsilon_v{}^p$ axis so that $\tan\beta = \delta\varepsilon_s{}^p/\delta\varepsilon_v{}^p$. In the present work, elastic volumetric strains, but not elastic axial strains, have been taken into account. The increments of plastic volumetric and shear strains were calculated by assuming:

$$\delta\varepsilon_v^p = \delta\varepsilon_v - \delta\varepsilon_v^e = \delta\varepsilon_v - \frac{C_s}{2.303}\frac{\delta p'}{p'}\frac{1}{1+e} \qquad (1)$$

$$\delta\varepsilon_s^p = \delta\varepsilon_a^p - \delta\varepsilon_v^p/3 = \delta\varepsilon_a - \delta\varepsilon_v^p/3 \qquad (2)$$

where C_s is the swelling index from oedometer tests (C_s= 0.061; C_s^*= 0.085). The first relation simplifies for the undrained tests, in which $\delta\varepsilon_v$=0 and the void ratio e is a constant, and for the drained constant p' tests, in which $\delta p'$=0.

In Fig. 1 the stress-dilatancy relationship observed for normally consolidated samples of the reconstituted clay is compared with the Rowe's relationship and the flow rules of Cam clay and modified Cam clay. None of the theoretical curves satisfactorily match the experimental data, although it can be noted that the modified Cam clay shows the worst agreement with them. While other data exist confirming this last finding for isotropically compressed spestone kaolin (Wood 1990), the present results in themselves do not seem to allow any conclusions to be drawn. A more direct experimental study of flow rules for Vallericca clay is beyond the scope of the present work.

Fig. 2 shows the typical stress-dilatancy relationships observed in triaxial compression of overconsolidated samples of Vallericca clay. Data from drained (a, b) and undrained (c, d) tests are shown in the figure. It is worth noting that according to modified Cam clay, the reference size p'_o of the yield locus corresponding to the estimated yield effective vertical stress is about 1.8 MPa. Thus, not only the mean effective stress is the same, but also in a broad sense, the state of overconsolidation is comparable for tests (a) and (b) or (c) and (d).

The general features of the observed η : β curves are similar to those presented by Rowe et al. (1963) and Scarpelli (1991). It can be seen that they are similar for both intact and reconstituted samples, the only major difference being that in the undrained tests on the intact clay a greater amount of dilatancy develops prior to the maximum stress ratio.

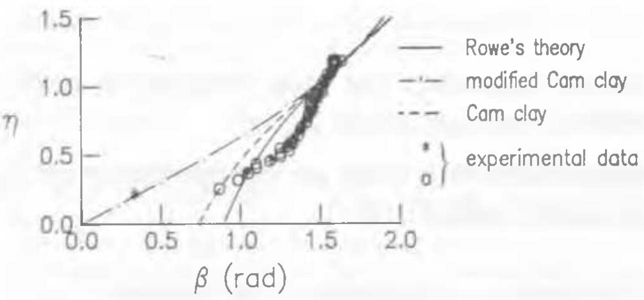

Fig. 1. Comparison between experimental data for Vallericca clay and some stress-strain relationships (drawn for M = 1.1)

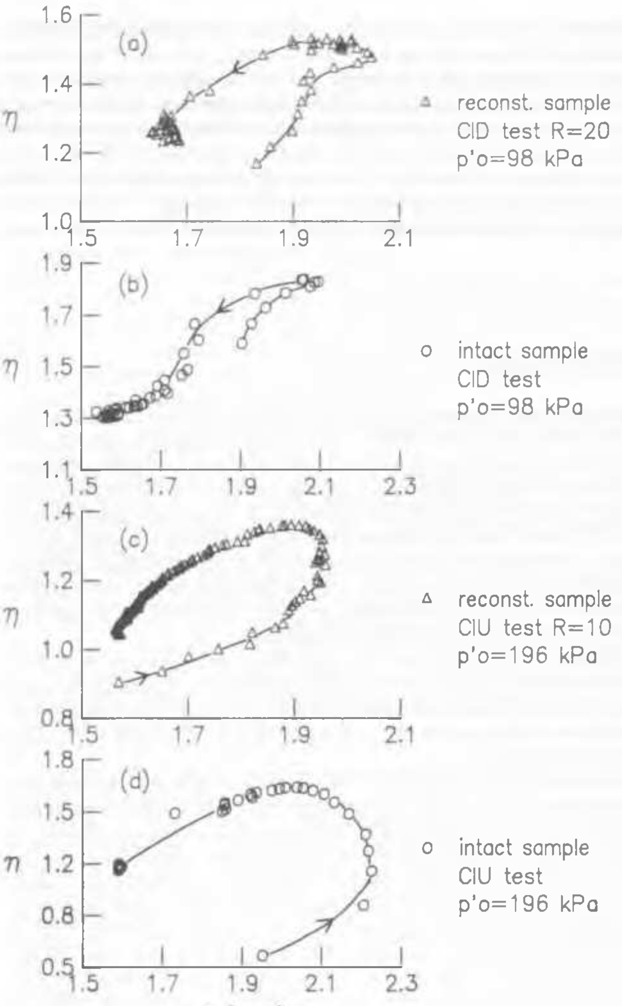

Fig. 2. Observed stress-dilatancy relationships for overconsolidated Vallericca clay.

While in all the drained tests on both reconstituted and intact samples the maximum dilatancy was observed to develop at the maximum stress ratio, this was not the case for most of the undrained tests, in which a maximum value for β was attained prior to that point. Since in these tests, depending on the effective stress path, the maximum stress ratio occurred prior to the peak of q, deviator stress and dilatancy did not reach their maximum values simultaneously. Finally, at the end of nearly all the tests a value of β = π/2 was observed, and correspondence with the critical state was attained. It is worth noting that, due to the occurrence of strain localisation phenomena, critical state should be thought of as being reached within the thin shear zone only.

Shear Strength and Dilatancy

In fig. 3 the strength envelopes for the intact and reconstituted samples of Vallericca clay have been plotted in the p': q plane. For the reconstituted material, it can be seen that a somewhat curved envelope closely fits the failure data for both the normally consolidated samples and the overconsolidated samples sheared in undrained compression. Neglecting the slight curvature, the intrinsic envelope is characterised by an angle of friction $\phi'_{cs}{}^{*}$~28°. Peak data for the intact samples for which the applied cell pressures were not sufficient to bring the clay to a state of normal consolidation plot close to the chain dotted line in the figure, lying above the envelope for the reconstituted overconsolidated samples (broken line). These last two envelopes show significant curvature and appear to be characterised by about the same intercept on the q axis. Concerning the position of the data from two drained tests on intact samples sheared from $p'_o \geq 0.8$ MPa, a close scrutiny of the results revealed that despite experiencing large axial strains (~14%), both the samples were slightly decreasing in volume at the end of the tests. Thus, the state of the soil was still moving towards the attainment of the critical state.

The differences observed in peak strength are due to a number of factors, stemming from the influence of what has come to be called, increasingly in recent years, *structure*. Referring to it at the micro-scale, structure is determined by the combination of fabric and interparticle bonding (Mitchell 1976), where fabric means arrangement of particles and involves the geometry of particle spacing and contacts. In this sense, any soil in any particular state is endowed with a structure, resulting from its past history, in the widest sense of the term (time effects plus stress history).

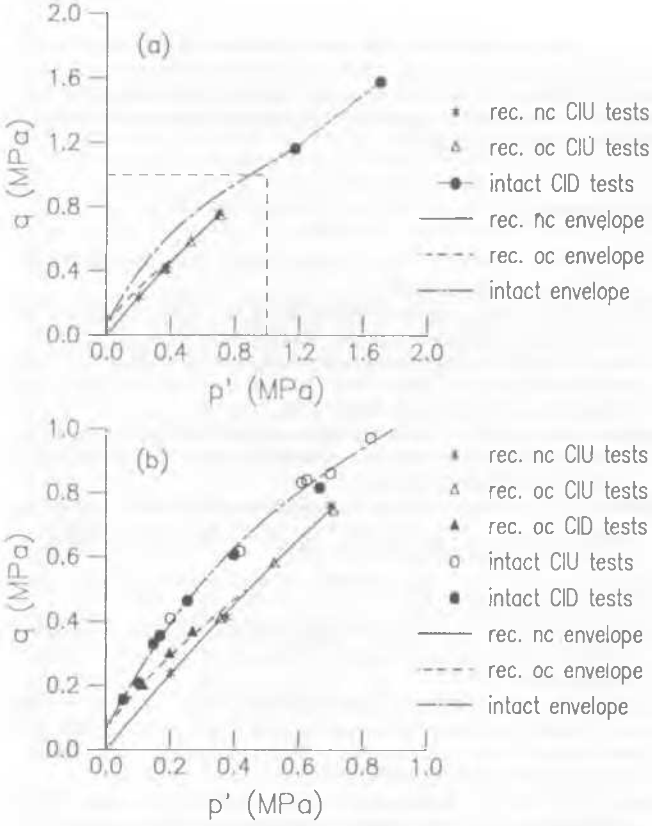

Fig. 3. Failure envelopes for (a) high pressures and (b) low to medium stresses.

To eliminate the influence of differences in void ratio at failure, the stress invariants q and p' at the point of peak deviator stress were normalised with respect to the equivalent consolidation pressure p'_e appropriate to the void ratio at that point. For the purpose of comparing the strength of natural and reconstituted samples, reference was made to the reconstituted soil, and thus p'_e was read on the relevant isotropic compression line. The results of this normalisation procedure, first developed by Hvorslev (1937), are shown in fig. 4.

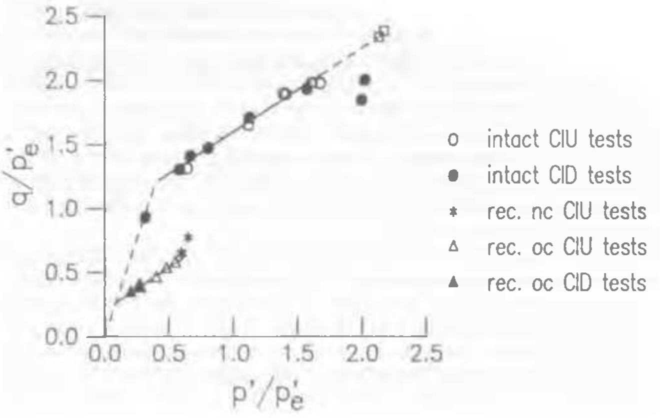

Fig. 4. Strength envelopes normalised by the equivalent pressure p'_e at failure.

It can be seen that the data plot closely around a couple of straight lines (Hvorslev surfaces), the curvature of the strength envelopes being eliminated by such a normalisation. The only two data from drained tests on the intact samples sheared from $p'_o \geq 0.8$ MPa plot slightly below the intact Hvorslev surface. If a correction to these data is applied, accounting for the end points not coinciding with failure and assuming $q/p'=M=1.1$ as for the reconstituted samples at the critical state, the two full squares are obtained in the figure, lying at the right end of the Hvorslev surface. It can also be noted that failure was reached on the no-tension line (q=3p') in one of the drained tests on the intact samples (constant p' = 50 kPa).

Failure data well to the right of the intrinsic critical state (plotting as a single point in the p'/p'_e: q/p'_e plane) are a logical consequence of the natural isotropic compression line lying well to the right of the re-constituted isotropic compression line (e.g. Burland 1990).

In table II the Hvorslev strength parameters c'_e and ϕ'_e are summarised for both the intact and reconstituted clay.

Table II - Hvorslev strength parameters (ϕ'_e in degrees)

samples	c'_e	ϕ'_e	c'_e (1)	ϕ'_e (1)	c'_e (2)	ϕ'_e (2)
intact	0.448	17.1	0.147	24.8	0.113	25.6
reconstituted	0.099	17.2	0.017	25.0	0.012	25.4

(1) after Taylor-Bishop correction; (2) after Rowe's correction

It can be seen that the two Hvorslev surfaces for intact and reconstituted samples are parallel, the effective cohesion of the former being about 5 times greater than $c'_e{}^{*}$. The enhanced strength of the intact clay over the reconstituted one is attributable to differences in micro-structure. In fact, differences in void ratio should be considered as just one of the ways in which a different past history of the soil manifests, void ratio being an important gross measure of structure, but not of its details. It is thus a necessary quantity, but not sufficient to describe the structure of a soil. Peak strength in the intact samples of Vallericca clay is typically reached at axial strain less than 2%. That is unlikely to be sufficient in erasing initial differences in structure. Thus, intact and reconstituted samples may have the same void ratio at failure, but a different structure in the meantime. As a result, clay specimens with different past histories, for which peak strength is reached under different stresses but at the same void ratio, are characterised by different dilatancy rates at failure, dilatancy being related to the arrangement of the particles (fabric).

In the past, the meaning of fundamental parameters was associated with c'_e and ϕ'_e, which were considered as reflecting the mechanism of shear strength in terms of interparticle forces and friction respectively.

Different modifications have been suggested to the Hvorslev strength criterion, in which the rate of dilatancy at failure is expressly accounted for. Taking into account the rate of dilatancy provided an explanation of the differences in the observed strength of initially dense and initially loose samples of sand (Rowe 1962). Gibson (1953), Rowe et al. (1963) and, more recently, Scarpelli (1991) extended the concept of a dilatancy correction to the analysis of test results on overconsolidated clays.

When comparing shear strength of intact and reconstituted samples of the same clay, the identification of a dilatancy component in the peak strength could be helpful in exploring the nature of the observed differences in the normalised envelopes. Shear strain at failure is typically greater for the reconstituted samples than for the intact ones, this corresponding to a greater degree of particle rearrangement at failure in the former case. Thus, the rate of dilatancy is likely to affect the strength of intact and reconstituted clay to a different extent, and correction for it could alter the picture of fig. 4.

In this work, such a correction has been applied to the peak data of both the reconstituted and intact samples of Vallericca clay, following two different procedures. In the first, known in the past as the Taylor-Bishop energy correction (Gibson 1953, Hvorslev 1960), a dilatancy component was subtracted from the measured shear strength. Referring to the stress invariants p' and q, the dilatancy component is given by:

$$q_d = p'_f\,(\delta\varepsilon_v{}^p/\delta\varepsilon_s{}^p) = -p'_f/\tan\beta\,, \qquad (3)$$

q_d being positive for a dilatant behaviour at failure. The second procedure is a direct consequence of Rowe's stress-dilatancy theory. Following Rowe et al. (1963) the stress invariants q and p' at the point of peak deviator stress were replaced by the corresponding corrected quantities:

$$q_{Rf} = (R/D-1)\cdot\sigma'_{3f} \qquad p'_{Rf} = (R/D+2)\cdot\sigma'_{3f}/3\ , \qquad (4)$$

where $R = \sigma'_1/\sigma'_3$ and $D = 1 - \delta\varepsilon_v{}^p/\delta\varepsilon_a{}^p$.

Both the procedures were effective in cancelling the curvature of the strength envelopes in the p': q plane, leading to nearly coincident results. Two distinct failure lines were obtained for the reconstituted and intact samples, the latter lying above the former, with a slightly greater slope. A non zero intercept on the q axis was observed for both the envelopes.

In fig. 5 the normalisation by the equivalent consolidation pressure p'_e has been applied to all the peak data after the correction for the dilatancy component, so that the effect of any difference in both void ratio and rate of dilatancy at failure is eliminated. The peak envelopes of fig. 4 have been reported in the figure for comparison.

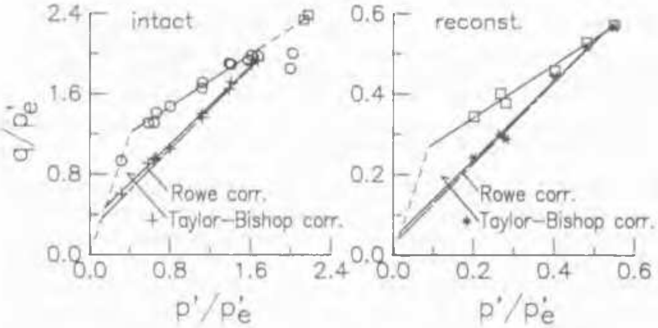

Fig. 5. Strength envelopes corrected for the dilatancy component and normalised by p'_e at failure.

It can be seen that the correction for dilatancy produces an increase in the ϕ'_e values and a correspondent decrease in c'_e (see tab. II), the dilatancy component of peak strength tending to disappear as the critical state is approached. In the non-dimensional p'/p'_e: q/p'_e plane of fig. 5, the two different corrections produced nearly coincident changes in the envelopes, the Rowe's correction yielding to the lowest values of effective cohesion and the highest values of effective angle of friction (Rowe et al. 1963).

The normalised envelopes for intact and reconstituted clay continued to be parallel (i.e. they were characterised by an equal effective angle of friction) even when the dilatancy component was subtracted from the observed peak strength. That $c'_e{}^*$ nearly approached zero after correction indicates that the component of effective cohesion of the peak strength was mainly an effect of dilatancy for the reconstituted samples. This was not the case for the intact clay. It is worth noting that the ratio of c'_e to $c'_e{}^*$ was about 10, two times greater than prior to correction. A greater reduction in $c'_e{}^*$ than in the effective cohesion of the intact envelope is consistent with the strongest interparticle bonding developed in the natural Vallericca clay.

CONCLUSIONS

The shear strength of a natural overconsolidated clay was compared with the corresponding properties of the reconstituted material. The two sets of samples differed in age and stress history, the natural clay having certainly experienced non-isotropic stresses in its past.

The stress-dilatancy relationships of Vallericca clay were examined, and the dilatancy component of the observed peak strength was isolated. The strength envelopes of natural and reconstituted Vallericca clay plotted as parallel lines in the normalised plane p'/p'_e: q/p'_e, irrespectively of the correction for dilatancy, the only significant difference between the envelopes being a greater intercept on the q/p'_e axis for the intact one. While the component of effective cohesion of the peak strength was found to mainly be an effect of dilatancy for the reconstituted clay, a significantly non zero intercept on the q/p'_e axis did exist for the intact clay. This represented a measure of the influence of the natural microstructure on the strength of intact Vallericca clay. While the interplay between dilatancy and strength was investigated in this work for the purpose of exploring such an influence, other recent work exists in which the possibility is suggested of unifying the strength behaviour of natural and normally consolidated reconstituted clays only through the consideration of dilatancy.

The possibility of linking the strength of overconsolidated and normally consolidated samples through dilatancy seems confirmed for reconstituted Vallericca clay. A different picture was shown for the natural clay: in this case the effective component of cohesion cannot be attributed to the effect of dilatancy only.

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