Effects of swelling caused by unloading in overconsolidated clays

Effets du gonflement par décompression des argiles surconsolidées

G. CALABRESI, Professor of Soil Mechanics, Faculty of Engineering, University of Rome, Italy
G. SCARPELLI, Researcher in Soil Mechanics, Faculty of Engineering, University of Rome, Italy

SYNOPSIS Effects of swelling have been investigated by unloading two heavily overconsolidated natural clays at very low stress, both in one dimensional and isotropic tests. The response of the swelling soils is examined with respect to their compressibility and failure characteristics. The behaviour of the clays subjected to swelling is compared with the one shown by remoulded reconstituted samples from the same material.

INTRODUCTION

Heavily overconsolidated clays of medium and high plasticity, when unloaded at very low stresses, show a large swelling and a corresponding increase of water content which causes softening and a decrease of their original strength.

Swelling effects caused by unloading of natural overconsolidated clays have been investigated for quite some time now. It is generally accepted that swelling induces a progressive deterioration of the soil properties, due to the breakdown of diagenetic bonds, and loss of cementation acquired in the past (Terzaghi 1936, Bjerrum 1967). These are time-dependent phenomena which appear to be enhanced by the presence of shear stresses acting on the soil and are believed to be connected with delayed slope failures often observed in overconsolidated clays (Morgenstern 1977, Chandler 1984). In fact, swelling processes seem to contribute to the decrease in shear strength with time, from the peak to what is called fully-softened strength, through the reduction of true cohesion.

The change of mechanical properties experienced by overconsolidated clays due to unloading has been examined in a number of experimental researches mainly on remoulded and reconstituted materials. In most of them one-dimensional consolidation tests were used to simulate geological loading and unloading history, and attention has been focused on the change of the compressibility and consolidation characteristics of soil (Ullrich 1975; Mesri, Ullrich & Choi 1978) . The results seem to support the hypothes s that large swelling due to one-dimensional unloading of soil is associated with shearing strains and with passive failure phenomena (Yudhbir 1969; Singh 1973). Shearing strains increase the swelling index Cs of the soil when OCR increases (Yudhbir 1969). Direct evidence of shear sliding surfaces due to passive failure has not been produced yet and many authors refer to fissures at very small scale or microshears (Amerasinghe 1973). Parry and Amerasinghe (1973) have suggested that microshears result in a "reverse" plasticity for the soil which, upon unloading, progressively deviates from the elastic behaviour and partially loses the hardening acquired during its past stress history. More recently, these hypotheses have been used by Carter, Booker and Wroth (1982) to predict the behaviour of clays subjected to cyclic loading and by Amerasinghe and Kraft (1983) to account for the reduction of the undrained shear strength due to swelling. With the hypothesis of reverse plastic volume strains on rebound, the behaviour of an overconsolidated clay can be described through plastic domains which suffer a progressive shrinking during swelling and which therefore erase the memory of the past stress hystory.

The present experimental research has been directed to investigate the response of some natural heavily overconsolidated clays of recent origin (plio-pleistocenic) to long-duration unloading both in one-dimensional and isotropic tests. Since natural heavily overconsolidated clays are generally fissured test results are affected by some uncertainties, especially when dealing with shear strength. Nevertheless the study of swelling phenomena and of their mechanical effects requires the experimental observation of the behaviour of natural materials having micro and macro structures, which cannot be reproduced in remoulded and reconstituted elements.

EXPERIMENTAL TESTS

Two typical clay deposits of Central Italy were selected to study the swelling and softening characteristics of natural overconsolidated clays. Todi clay is a pleistocenic heavily overconsolidated medium plastic clay of lacustrine origin, intensely fissured. Samples of this soil were obtained from blocks taken in a brick factory quarry. Ancona clay is a pliocenic heavily overconsolidated clay of high plasticity formed in a marine environment, generally homogeneous and moderately fissured. Samples of Ancona clay were taken from boreholes at a depth of 40 to 80 m . Table I reports the main physical properties of the tested soils. Both of them can be classified as clayey silts having a clay fraction close to 40% . Ancona clay is more

Table I - Geotechnical characteristics of the tests clays.

CLAY	$\gamma_S(g/cm^3)$	$\gamma(g/cm^3)$	W_L (%)	I_P (%)	CF (%)	W (%)
TODI	2.78	2.1	50	28	35	19
ANCONA	2.73	2.05	82	60	42	20

plastic and active than Todi clay. Compressibility tests of both materials show that the preconsolidation pressure p_c' greater than 2 Mpa. These high values of p_c' do not correspond to the present cover and have to be explained as the result of past, intense, erosive phenomena and of diagenetic bonding.

The consolidation tests were carried out in conventional oedometers. The samples were cut lower than the ring height so that at the end of swelling they were always laterally contained. At the top and bottom surfaces they were kept in contact with filter paper and porous stones saturated with distilled water. During cycles of loading and unloading tests, effective stress ranged between 2.5 MPa and 1 KPa; the latter value corresponds to the weight of the loading head only. Load increments were generally applied every 24 hours, however the final swelling at the lowest load was allowed for some weeks.

Consolidation undrained compression tests were performed with a conventional triaxial apparatus on samples 7.62 cm high and 3.57 cm in diameter. In order to shorten the consolidation time, a sand drain of 2.5 mm diameter was placed along the axis of the sample and drainage was allowed to occur through both ends and radial boundaries. Back pressure was applied during tests to ensure full saturation. Swelling at zero effective stress under isotropic conditions was obtained by setting the cell pressure at the same value as the back pressure. Volume changes during compression or swelling were determined by the water level variations in the pore water burette and eventually checked through a comparison between measured and calculated water contents. These measurements showed that the water content was uniformly distributed through the whole sample. Undrained compression tests were performed on samples isotropically reconsolidated after swelling.

An analogous experimental program was carried out on remoulded samples from the same clays. These were prepared by airdrying, pulverizing and mixing large quantities of clay, to prepare a slurry at a water content approximately twice the liquid limit. Then samples for tests were trimmed from the clay cake obtained through one-dimensional consolidation of the slurry at a vertical stress of 0.1 MPa.

One-dimensional consolidation and swelling tests

The relationship between the void ratio and effective stresses as obtained in a typical test on Todi clay is shown in Fig. 1. The sample was first loaded up to maximum pressure then fully unloaded allowing for swelling for about 20 days, and finally loaded and unloaded again. The volume increase at the end of swelling was about 12% . The slope of the loading and unloading curves are the compression and the swelling indexes Cc and Cs respectively. It appears that Cs is not a constant but increases as the stresses

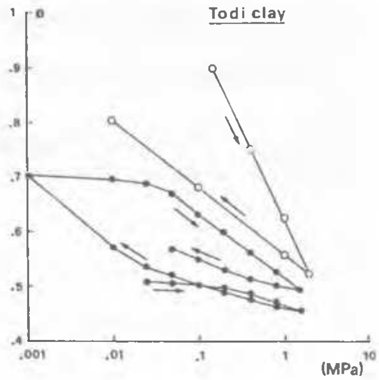

Fig. 1 - One dimensional tests of Todi clay: loading-reloading curves for intact samples (●) and for remoulded-reconstituted samples (O).

decrease. Upon reloading for the first few load increments Todi clay exhibiys very small values of Cc. Then it suddenly increases and keeps almost constant. The slope changes therefore result in a certain hysteresis of the loading-unloading cycle. The typical behaviour of the Ancona clay in the same test is shown in Fig. 2. At the end of the long-duration swelling the volume change of the sample was about 40%. The unloading-reloading cycle shows little hysteresis compared with that of the Todi clay. Accordingly, slope changes are less pronounced.

The development of swelling with time at the lowest applied stress is shown in Fig. 3 and 4 for both Todi and Ancona clays.

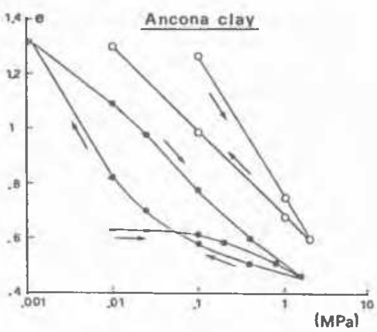

Fig. 2 - One dimensional tests of Ancona clay: loading-reloading curves for intact samples (●) and for remoulded - reconstituted samples (O).

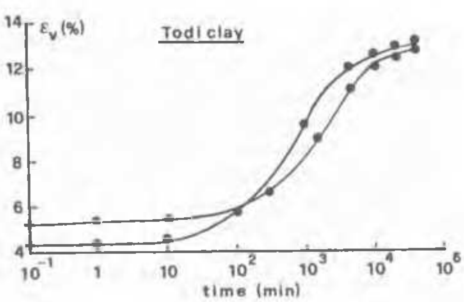

Fig. 3 - Development of swelling with time in one dimensional tests of Todi clay at σ_v' = .001 MPa .

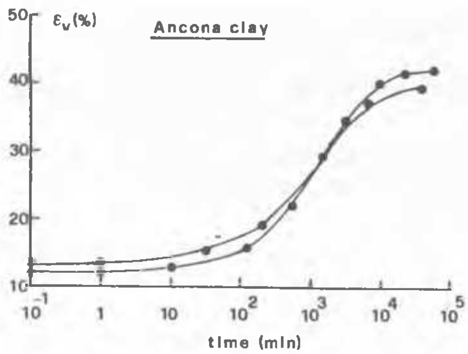

Fig. 4 - Development of swelling with time in one dimensional tests of Ancona clay at σ'_v = .001 MPa.

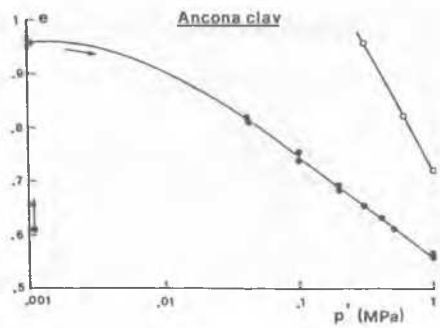

Fig. 6 - Isotropic consolidation and swelling of Ancona clay (●) intact samples and (O) remoulded-reconstituted samples.

These curves can be analysed as standard consolidation test results in terms of primary and secondary swelling (Mesri *et al.*, 1978). It results that the development of 50 percent of primary swelling requires about 1000 min . Secondary swelling was never allowed for more than one log cycle after the end of primary swelling. Within these limitations, the secondary compression index $C_{\alpha s}$ = De/Dlogt , is fairly constant. For the Todi clay $C_{\alpha s}$ = 0.025 and for the Ancona clay $C_{\alpha s}$ =0.033.

Triaxial tests

Unloading-reloading cycles for isotropic swelling and consolidation for both Todi and Ancona clays are shown in Fig. 5 and 6. Each plot of void ratios versus the logarithm of mean effective pressure $p' = (\sigma'_1 + 2\sigma'_3) / 3$ shows the behaviour of various samples. This is very similar to the one shown by the same materials in one-dimensional tests. The Todi clay presents a large loop, due to significant changes in the slope of the unloading curve with the applied mean pressure.

Samples were taken to failure after being reconsolidated at pressure p' ranging between 0.05 and 1.0 MPa. Normalized effective stress paths are also shown in Fig. 7 and 8. Significant negative pore pressure are developed during shearing: failure is very brittle and accompanied by the formation of rupture surfaces.

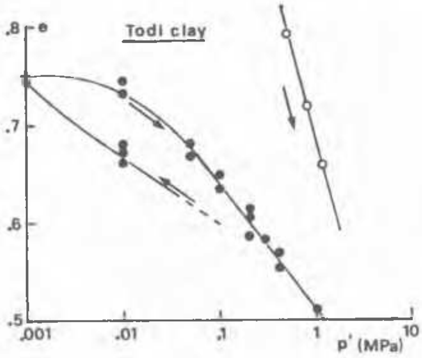

Fig. 5 - Isotropic consolidation and swelling of Todi clay: (●) intact samples and (O) remoulded-reconstituted samples.

ANALYSIS OF THE RESULTS AND CONCLUSIONS

One dimensional tests of the Todi clay apparently show that swelling at very low stresses strongly alters the compressibility characteristics of the soil Fig. 1 . Actually, a bend appears in the compressibility curve of virgin material at about 0.4 MPa, but when during the first loading after having applied a vertical pressure of 2.5 MPa unloading follows and a substantial swelling is allowed, the reloading curve bends at a much lower value of the vertical stress (0.04 MPa). This would suggest that after swelling a clay behaviour of the "wet type" (Roscoe *et al.*, 1958) would be expected. However undrained triaxial tests all show that swelling previously produced in laboratory tests has little influence on the soil behaviour during shear. In Fig. 7 and 8 peak strength envelopes of both undisturbed and reconsolidated samples after swelling are plotted. In order to compare strengths at different void ratios, equivalent pressure values p'_e (Roscoe *et al.*, 1958) referring to isotropic consolidation tests on remoulded soil, were used to normalise the plots. Tests show that peak strengths envelopes for swelled and undisturbed samples are slightly different and significantly higher than the envelope which applies to the remoulded material. Moreover normalized effective stress paths are all very similar in their shape and very different from the effective stress paths obtained by testing remoulded samples.

The results of the compressibility tests on the Ancona clay would suggest that an even bigger influence of swelling on the soil properties should be expected, since softening upon unloading appears to induce a bigger loss of the memory of the past stress history (Fig. 2). However, undrained triaxial tests clearly confirm the kind of behaviour observed on the soil samples which were not subjected to previous swelling and still exhibit a "dry type" of behaviour (Fig. 8).

A more comprehensive picture of the observed phenomena can be obtained by comparing the results of one-dimensional and isotropic consolidation tests with the behaviour of the remoulded materials (Figs. 1-2 and 5-6).

The behaviour of the materials obtained by unloading the

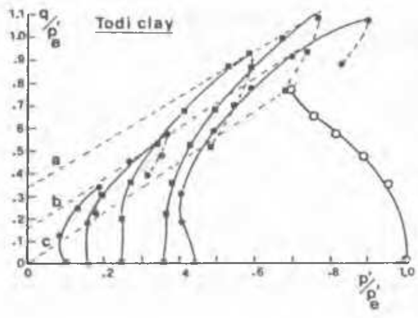

Fig. 7 - Strength envelopes from undrained triaxial compression of Todi clay for (a) consolidated, (b) swelled -reconsolidated and (c) remoulded samples.

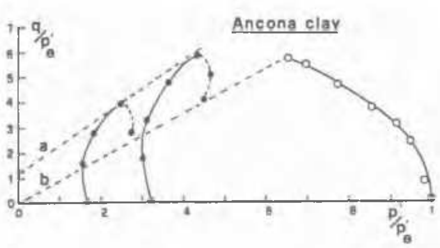

Fig. 8 - Strength envelopes from undrained triaxial compression tests of Ancona clay for (a) swelled reconsolidated and (b) remoulded-reconstituted samples.

natural overconsolidated clays at very low stresses for a long time is still very different from the one shown by remoulded-reconstituted samples.

Swelling alters the shape of the re-loading curve of the natural soil so that the apparent changes of the behaviour upon reloading occur at a lower stress, which is not dependent on the maximum stress reached during the test. However the slopes of the rectilinear portions of re-loading curves are not very different between each other and they appear to be comparable with the slope of the unloading curve for the remoulded soil.

Finally, it is not yet clear how time influences the development of swelling in the performed tests, but the observed phenomena allow to state that larger swelling times at low stresses would not alter the results significantly and therefore would not change the previous conclusions.

ACKNOWLEDGEMENTS

The AA. acknowledge the financial support received by the Italian National Research Council (Research Contracts CTB-CNR 1981-83).

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