Laboratory modelling of natural structured clays

ABSTRACT: Natural soft clays created by slow sedimentation, often under marine conditions, develop a structure, which allows the clay to exist at a higher specific volume at a given mean effective stress than the equivalent reconstituted soil. Often for natural soft clays this structure breaks down during plastic shearing and compression. Nevertheless, the structure of some clays, which have not undergone additional diagenetic processes such as bonding, is undamaged even when subjected to considerable plastic shearing. To examine these issues without uncertainties due to variations in geological history and sample disturbance, clay has been prepared in the laboratory by slow sedimentation in order to develop a structure similar to the structure of natural clay. The mechanical behaviour of this artificial clay has been studied under K_0 stress conditions and compared to reconstituted clay. Data obtained indicate that the structure created by sedimentation in the laboratory is stable.

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1 INTRODUCTION

Many natural soft clays are deposited by sedimentation. They may then undergo a number of additional geological and chemical processes before reaching their current state. When sampled and tested in the laboratory in an “undisturbed” state these clays have a structure that leads to a response that is different to the equivalent soil reconstituted in the laboratory. Cotecchia and Chandler (2000) have demonstrated that this response can be described using the framework of critical state soil mechanics, by characterising the structure using sensitivity, S_t, which is a measure of the difference in size of the state boundary surface for the natural soil and that of the same soil reconstituted. For many soils the structure measured in this way breaks down during plastic straining, such that the value of sensitivity, S_t, varies with plastic strain. Nevertheless for soils that have not undergone diagenetic processes that lead to bonding there may not be a significant break down in structure. Coop and Cotecchia (1995) found that for Sibari clay, a layered clay deposited in a coastal alluvial environment, with a sensitivity of between 3 and 5 the structure did not break down even at very large strains approaching critical state. They concluded that in this case the sensitivity resulted from soil fabric rather than bonding between particles. This fabric was due to layering of clays and silts and possibly orientation of particles during the sedimentation process.

To investigate the behaviour of these types of soils in more detail soil samples have been sedimented in the laboratory under carefully controlled conditions to create reproducible soil specimens for a programme of triaxial testing. The aim of these tests is ultimately to examine in detail the pre-failure deformation of these soils, but initial tests were used to examine behaviour at large strains during one dimensional compression and near to failure at a critical state. It was also necessary to establish the sensitivity of sedimented samples.

2 PREPARATION OF TEST SAMPLES

2.1 *Sedimented specimens*

Previous studies of artificially sedimented soil samples, by for example Ting, Sills and Wijeyesekera (1994) and Olson (1962) indicate that mineralogy has a strong influence on the structure obtained. For this study, London clay was used to sediment soil samples, which is a typical example of a natural clay in which illite is the predominant mineral. It has also been found that both for conventionally reconstituted samples and sedimented samples of natural clays a pore fluid that causes flocculation will result in a more open structure and also faster sedimentation (Locat and Lefebvre, 1985). For these tests the London Clay was sedimented in salt water with a salinity of 3.51%.

The London clay at its natural water content was first reconstituted into a slurry with a water content of about 1250% and then poured into the top of a 2m high, 94.2mm diameter, sedimentation column filled with salt water, resulting in an initial water content for the slurry of approximately 5800%. The clay was left to sediment until there was no change in the slurry/water interface, usually 3 days, and the cycle was repeated 3 times. This resulted in layered sediment with four layers, because although the particles flocculated they were still separated according to their size (Been and Sills, 1981). In each layer the silty particles were at the base with finer particles uppermost, similar to sediment prepared by Edge and Sills (1989). After sedimentation the slurry was loaded by a submergible piston using discrete increments of load up to an effective vertical stress of 70kPa. At this point the sample is approximately 140mm long. To facilitate this process the sedimentation tube was provided with base drainage and the top 1m of the tube could be removed. Three thin-walled tubes were carefully pushed into the resulting sample to create three 38mm diameter specimens that could be extruded into a triaxial cell for testing. The data presented here is from three specimens obtained in this way from a single sedimented sample.

2.2 *Reconstituted specimens*

Reconstituted specimens of London clay have been prepared from clay at its natural water content reconstituted to an initial water content of 125%. Three of the samples were reconstituted in distilled water and the fourth in salt water with the same salinity as the sedimented samples. The slurry was then placed in a floating ring consolidometer and loaded in increments to a vertical effective stress of 70kPa.

3 ONE DIMENSIONAL COMPRESSION

All sedimented and reconstituted specimens were first compressed one-dimensionally in a hydraulic stress path cell (Bishop and Wesley, 1975) to a vertical effective stress of 400kN/m^2. To obtain a length to diameter ratio of 2:1 after one-dimensional compression the initial length of all the specimens was 91mm. Both the initial water content and the final water content after the tests were determined. It was found that the final water content was a more reliable measure of the specific volume of the sample because initial water contents were obtained from off cuts and the sample is layered and consequently not homogeneous. Where the sample had been prepared in salt water the salt remaining in the sample was allowed for in the calculation of water content.

The variation in the initial states of the samples can be seen in Figure 1 which shows one-dimensional compression curves for all seven tests carried out on both sedimented and reconstituted samples. This variation in the initial state may in part be caused by sample disturbance during preparation of the specimens, but in the case of the sedimented specimens is more likely to be a function of how long the specimens remained in the thin-walled tubes before testing. Although the tubes were sealed, some reduction in water content with time was inevitable. However, irrespective of the initial states of the samples it is clear that there are two distinct groups of curves; one representing all reconstituted samples and one representing all sedimented samples and that plotted as $\ln v$ versus $\ln p'$ these curves are approximately parallel. All the reconstituted samples define a unique line, except for the slight difference in gradient observed for the sample reconstituted in salt water. This may be explained by the build up of excess pore pressure in the specimens during the nominally drained compression and the deviation from a line of constant stress ratio that occurred during compression of this sample, as shown in Figure 2.

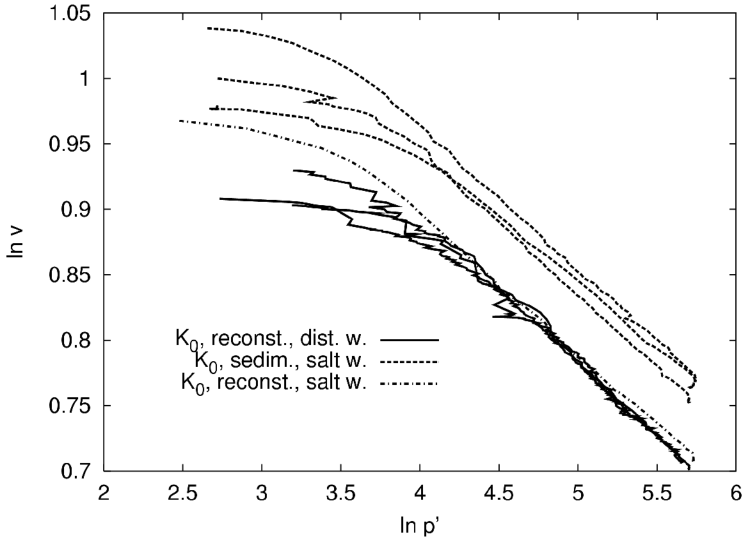

Figure 1. One-dimensional compression data for reconstituted and sedimented samples

The curves plotted for sedimented samples demonstrate that sedimentation in the laboratory has created a stable structure in the soil, which does not break down even after the application of substantial volumetric and shear strains. This structure is not the same in all the specimens tested as the data do not quite define a unique line, even allowing for the build up of excess pore pressures, but the variation is not great. Sensitivity, S_t, as defined by Cotecchia and Chandler (2000) varies between 1.5 and 1.8.

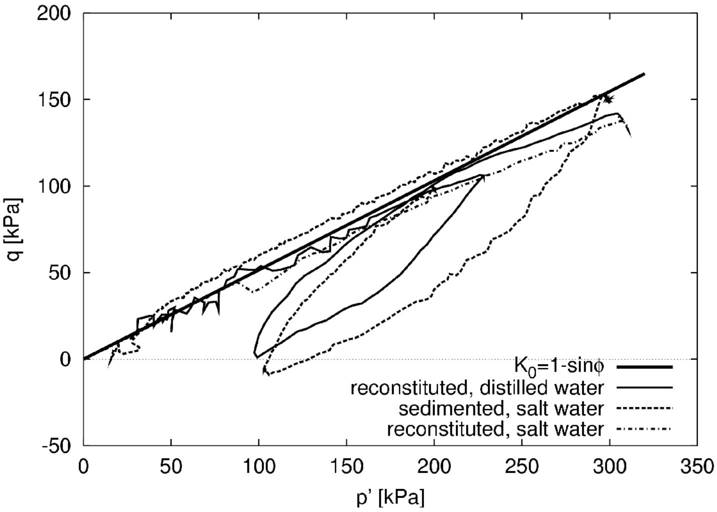

Figure 2. Typical stress paths for one-dimensional compression and swelling

Figure 2 shows typical one-dimensional compression and swelling curves showing the control of the one-dimensional stress paths that was achieved in the triaxial cell. Overall the comparison with the relationship proposed by Jaky (1948) is good and the deviation from the line representing this relationship is typical in magnitude but not necessarily in sign as for all tests the stress paths were equally distributed between states representing higher and lower values of K_0.

4 SHEAR COMPRESSION

After one-dimensional compression the specimens were taken to different states before shearing to failure. The stress state at the start of shearing and the loading path followed to reach failure are given in Table 1. Only in test PhM12 was the specimen sheared from the normally compressed state reached at the end of one-dimensional compression. Tests PhM18 and PhM21 were loaded by a fixed stress path to the isotropic state from which they were sheared undrained to failure and the remaining tests were sheared either under either drained or undrained conditions following one-dimensional swelling or swelling and recompression (PhM14 and PhM17)

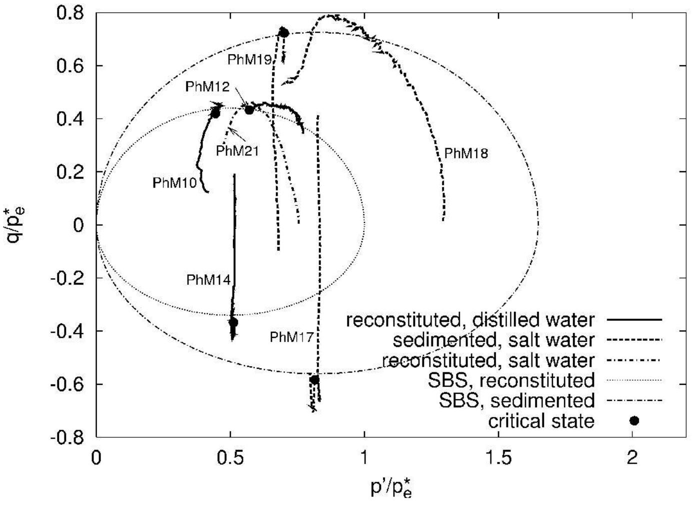

Figure 3. Effective stress paths normalised by equivant pressure

From the Table it may be seen that there are three sets of tests, PhM18 & PhM21, PhM19 & PhM10, PhM17 & PhM14 where approximately the same stress paths before shearing have been followed for both a sedimented and a reconstituted specimen. The pairs of specimens have then also been sheared in the same way. Figure 3 shows effective stress paths from shearing stages for all tests normalised with respect to equivalent pressure, p_e*, where p_e* is the mean effective stress at the same specific volume on the isotropic compression line for the reconstituted soil. Normalising in this way it is again possible to discern the two distinct sets of data from reconstituted and sedimented samples. Reconstituted soil data can be described by a state boundary surface representing a projection of the Modified Cam clay yield surface (Roscoe and Burland, 1968) and consistent with the compression curves for the reconstituted soil. Sedimented soil data can be represented by a similar curve, larger by a factor of 1.67, the average sensitivity of the sedimented samples. In both cases the shape of the state boundary surface has been calculated by assuming different values of critical state coefficient M in compression and extension such that the critical state angle of friction is a constant.

Test	Stress state at start of shearing		Sedimented/ reconstituted	Shear loading
	p′ (kN/m^2)	q′ (kN/m^2)		
PhM10	135	39	Reconstituted	Undrained compression
PhM12	305	138	Reconstituted	Drained constant p′ comp.
PhM14	213	78	Reconstituted	Drained constant p′ exten.
PhM17	200	104	Sedimented	Drained constant p′ exten
PhM18	450	0	Sedimented	Undrained compression
PhM19	110	-17.5	Sedimented	Drained constant p′ comp.
PhM21	450	0	Recon. salt water	Undrained compression

Table 1 Details of shearing stages of all tests.

It is interesting to note that there is no evidence from these tests of any break down in the sedimented structure. Conventionally, this would be indicated by stress paths followed by structured soil specimens moving towards a critical state on the state boundary surface for the reconstituted samples. The stress path followed by test PhM18 might appear to show this behaviour, but in fact this is due to localisation leading to rupture planes in the sample, the equivalent test PhM21 showing the same response. Additional evidence that the sensitivity remains constant is provided in Figure 4, where stress paths have been further normalised by the sensitivity of the specimens that was derived from the one-dimensional compression curves in Figure 1. The normalised stress paths followed by the pairs of tests are now very similar and all tests appear to converge towards the same critical state, although the critical state point is not well defined.

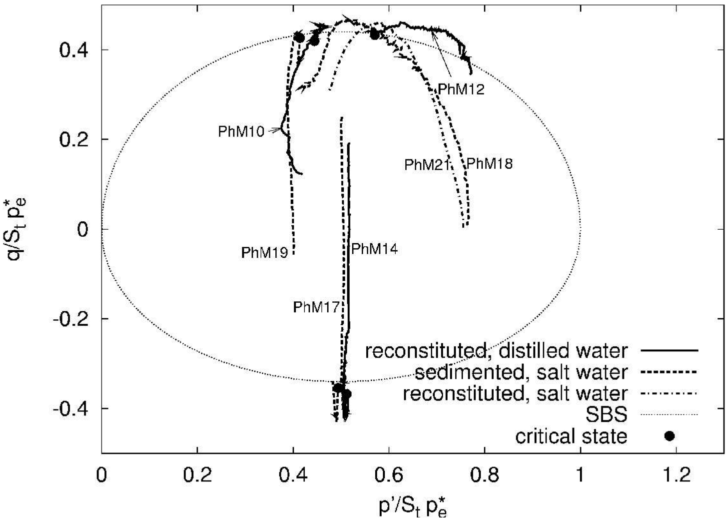

Figure 4 Stress paths from tests on reconstituted and sedimented samples normalised by equivalent pressure on the normal compression line for the reconstituted soil and by sensitivity.

If the structure is not breaking down even at large strains it should also be possible to plot the critical states in lnv versus lnp′ space and see two distinct critical state lines related by the initial sensitivity of the soil. This was found by Coop and Cotecchia (1995) testing artificially layered soils created from clay and sand, but not sedimented.

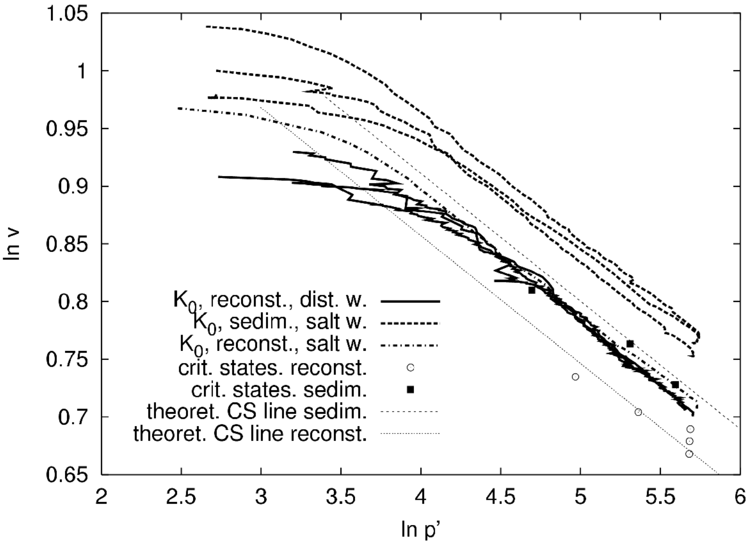

Figure 4. Stress states for sample sheared to failure at critical state compared to one-dimensional compression curves for these samples.

Figure 4 shows critical states from the tests reported here plotted with one dimensional compression data. End states for tests PhM18 and PhM21 have been included, by assuming that critical state would have been reached at a mean effective stress mid way between the peak and ultimate stress ratios in the tests. The Figure also shows critical state lines consistent with no change in sensitivity. It appears from these data that for specimens initially compressed to effective vertical stresses of 400kN/m^2. It would be reasonable to assume that sensitivity remains constant even when samples are sheared to very high shear strains to reach critical state.

5 SUMMARY AND CONCLUSIONS

Tests have been carried out on samples of London Clay that have been sedimented in the laboratory. Data from these tests has been compared to data from tests on reconstituted samples of London clay to establish whether these sedimented samples have a structure that is different from conventionally reconstituted samples and whether this structure changes when the samples undergo significant plastic straining. The samples are relatively soft having all been compressed to a vertical effective stress of 400kPa.

In the limited number of tests undertaken the sedimented soil has a structure that can be characterised by a sensitivity of between 1.5 and 1.8, which is probably a consequence of both the macro fabric caused by the formation of layers of different particle sizes and also the open structure resulting from sedimentation of flocculated soil grains in the salt water that was used as a pore fluid. However, using salt water as a pore fluid to create a reconstituted soil sample did not significantly affect the behaviour of the soil.

The structure that was created in the sedimented samples did not appear to break down with plastic strains even when the soil samples were sheared to a critical state. In fact, when stress paths from tests undertaken on sedimented and reconstituted soil specimens that had followed similar shear loading were normalised by a constant value of sensitivity, the stress paths are approximately superimposed. Plotting critical states as lnv against lnp′ provides further evidence that the sensitivity is constant. Two critical state lines related by the initial sensitivity of the sedimented soil samples can be used to approximate the critical states.

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