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Swelling effects on mechanical behaviour of natural London Clay

Effets du gonflement sur le comportement mécanique de l'argile naturelle de Londres

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ABSTRACT
This paper reports a study into the potential effects of swelling on destructuration of a natural London Clay. Preliminary results are presented from a conventional direct shear tests conducted under a constant height condition. These suggest that the changes in soil structure induced by one-dimensional swelling affect global stiffness behaviour more than the peak shear strengths.

RÉSUMÉ
Cet article expose une étude des effets potentiels du gonflement sur la perte de structure de l'argile naturelle de Londres. Des résultats préliminaires sont présentés, issus de tests conventionnels de cisaillement direct conduits en maintenant la hauteur constante. Ces résultats suggèrent que les changements induits dans la structure du sol par un gonflement unidimensionnel affectent la rigidité plus que l'intensité maximale du cisaillement.

1 INTRODUCTION

It is well known that changes of soil structure may be induced by compression and shearing in natural soils. Swelling may also lead to such effects. Leroueil & Vaughan (1990) pointed out that swelling from an in-situ effective stress may be sufficient to cause yield of a bonded structure in some soils. Such yielding was found in isotropic swelling tests on heavily overconsoidated London Clay samples obtained by hand-cut block sampling (Bishop *et al.*, 1965). They also reported a marked change in undrained shear behaviour caused by swelling-induced yield. Calabresi & Scarpelli (1985) investigated effects of swelling on overconsolidated clay behaviour and found that the swelling indices C_s for the natural Todi Clay and Ancona Clay increase as the stress decreases in one-dimensional oedometer tests. They also showed the remarkable difference in peak strength when the undrained triaxial compression test results for consolidated and swelled-reconsolidated samples were compared.

These previous studies indicate that destructuration of a natural clay may be induced not only by compression and shearing, but also by swelling. The construction of deep excavations in strata such as London Clay may lead to such structural changes, as a result of the unloading in mean effective stress. This paper reports a study into the potential effects of such swelling on London Clay. Preliminary results are presented from a conventional direct shear experiments tests conducted under a constant height condition (Fung, 2003). The work is now being continued with more advanced triaxial and hollow cylinder testing.

2 SOIL TESTED AND TEST PROCEDURES

The test specimens were cut from rotary-cored samples taken at the construction site of the new Terminal 5 at Heathrow Airport in London. The samples used were taken at depths of 26 and 37m, from the lithological units derived by King (1981) as B(2) and A3(2), respectively (Hight *et al.*, 2002). They mainly consist of silty clay and the liquid and plastic limits are around 70 and 25 and the natural water content is close to the plastic limit.

The direct shear box specimens were rectangular prisms 60mm long, 60mm wide and 25.4mm high. The effective stress histories followed prior to shearing are schematically illustrated in Fig. 1. All the samples were first reloaded to their in-situ vertical stress, σ'_{vi} (Point A in Fig. 1). They were then either consolidated (Point A, or A⇒D)/swelled (A⇒B) to the vertical stress, σ'_{v0}, at which shearing would start, or swelled to very low vertical stress, σ'_{vs}, before being consolidated back to σ'_{v0} (A⇒B⇒C). The vertical movement of the top-platen was restrained during shearing by a load cell that kept the specimen height constant. With saturated samples, the vertical stress change measured by the load cell is equivalent to the excess pore water pressure that would be developed in the undrained shear test. The samples were sheared at a loading rate of 0.2mm/min. The samples' stress histories are tabulated in Table 1 together with a summary of the test results, where e_0 =void ratio at the end of consolidation, σ'_{ve} =vertical effective stress on the normal compression line for the reconstituted London Clay at e_0 and τ_f =undrained direct shear strength. The first letter of the test identification code indicates the lithological unit where the sample was taken, the following numbers indicate the stress history given to the sample before shearing (e.g. S1/6=being swelled to one-sixth of σ'_{vi} and C4=being consolidated to four times of σ'_{vi}).

3 TEST RESULTS AND DISCUSSION

3.1 *One-dimensional swelling and recompression*

Figure 2 shows the observed vertical strain changes of the intact London Clay samples under one-dimensional swelling, together

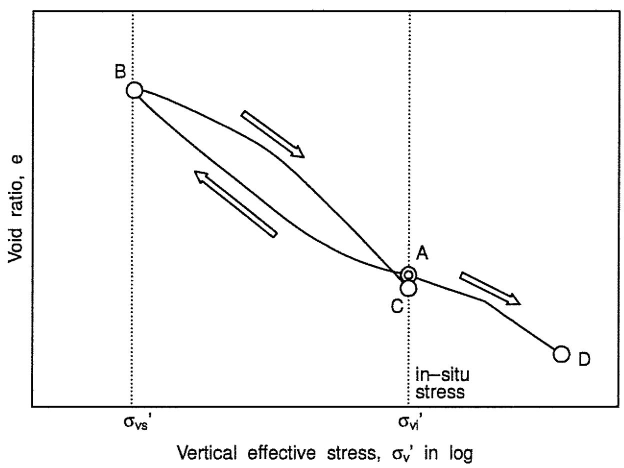

Figure 1. Effective stress histories followed prior to shearing.

Table 1. Summary of test conditions and results.

Test No.	Depth (m)	σ'_{vi} (kPa)	σ'_{vs} (kPa)	σ'_{v0} (kPa)	e_0	σ'_{ve} (kPa)	τ_f (kPa)	τ_f/σ'_{v0}	τ_f/σ'_{ve}	Disp. at peak (mm)
B-S1/6	26	300	-	51	0.82	320	39	0.76	0.12	1.2
B-C1	26	300	-	300	0.77	420	120	0.41	0.29	1.7
B-S1/12-C1	26	300	26	300	0.69	690	150	0.52	0.23	2.8
B-C4	26	300	-	1250	0.59	1200	340	0.27	0.28	2.6
A-S1/8	37	400	-	51	0.68	740	73	1.4	0.099	2.2
A-C1	37	400	-	400	0.59	1300	180	0.46	0.14	2.0
A-S1/16-C1	37	400	26	400	0.60	1200	160	0.41	0.14	2.0
A-C3	37	400	-	1250	0.58	1300	520	0.42	0.40	3.2

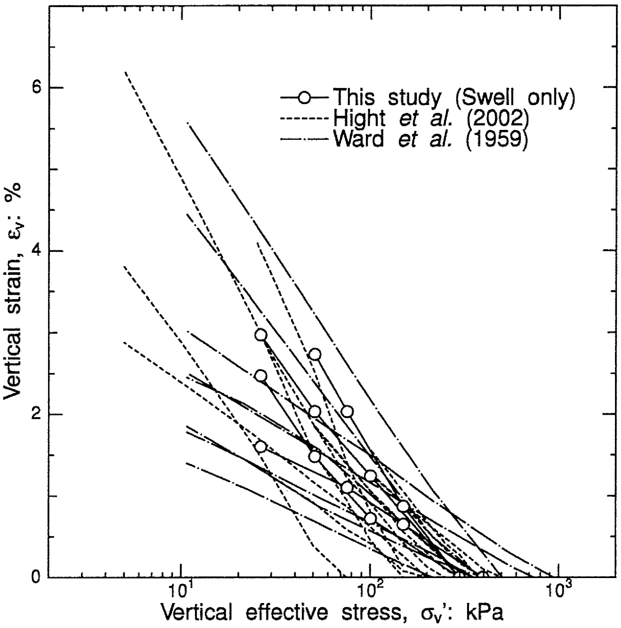

Figure 2. Vertical strain changes in one-dimensional swelling tests.

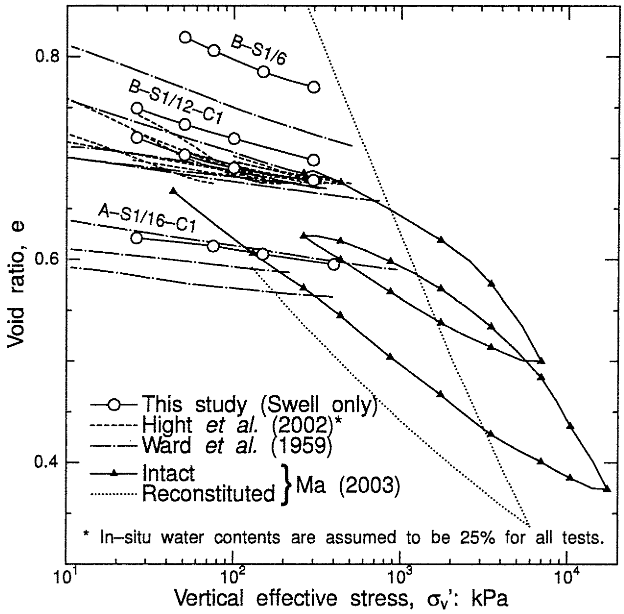

Figure 3. Volume change in one-dimensional swelling together with those in compression and unloading curves on intact and reconstituted samples.

with data obtained by Hight *et al.* (2002, in other tests from the Heathrow Terminal 5 site) and Ward *et al.* (1959, at various sites). Even though the data vary widely, it is clear that unloading from several hundred kPa to 10 or so kPa causes two to six per cent vertical swelling strain. Hight *et al.* pointed out that this significant expansibility of London Clay at effective stress below 50–100kPa in the oedometer swelling tests may have been associated with progressive destructuation during the swelling process.

In order to compare these results with the one-dimensional compression and unloading curves (Ma, 2003) of the intact and reconstituted samples obtained from the samples taken at a depth of 27m, whose lithological unit is the same as the test series B, the data are plotted in $e - \log \sigma'_v$ co-ordinates as shown in Fig. 3. Here the initial water contents prior to swelling were assumed to be 25% (0.68 in void ratio) in the test results reported by Hight *et al.* so that their volume strain plot can be added. It is clear that the swelling index, C_s, increases as the samples swell, especially for the higher void ratio samples. C_s is a sensitive indicator of fabric and inter-particle bonding in the natural soil, and it is known that destructuration by compression makes the soil more expansive (increasing C_s) (Burland, 1990). The present tests reinforce this finding; the intact samples show C_s values on unloading that increase markedly with the level of maximum applied σ'_v. The data shown in Fig. 3 also suggest that destructuration may also occur during swelling.

Fig. 4 compares the one-dimensional compression and unloading curves for the samples taken at a depth of 27m (Ma, 2003) in a similar $e - \log \sigma'_v$ diagram. One test involved swelling from the in-situ stress before compression, and the second was simply compressed from the in-situ stress. The pre-swelled sample compresses more steeply than the un-swelled one and the yield stresses estimated by the Casagrande method are 1.2MPa for the former and 3.8MPa for the latter. These tests also support the hypothesis of destructuration by swelling.

3.2 *Undrained shear behaviour in direct shear box*

The shear strength measurements made in the constant height direct shear box tests are summarised in Table 1. The stress paths followed in the tests involving $\sigma'_{v0} \leq 400$kPa are illustrated in Fig. 5 together with strength envelopes from conventional constant normal stress direct shear box tests performed under drained conditions, taken from Hight *et al.* (2002). In the figure, the double circle and square symbols indicate the stress points at the peak condition and that at a horizontal displacement, $d = 7$mm, respectively. Some variation in σ'_v took place during the early stage of shearing due to practical testing difficulties as reported also by Tanaka *et al.* (2003).

The strength, τ_f, for the soil recompressed at its in-situ stress (A-C1) is almost the same as that in the pre-swelled sample (A-S1/16-C1) at a depth of 37m, while the former (B-C1) is paradoxically smaller than the latter (B-S1/12-C1) at a depth of 26m. When normalised by the vertical effective stresses projected onto the normal compression line for the reconstituted soil at e_0, σ'_{ve}, the pre-swelled samples show smaller strengths as expected, since the difference in void ratio for the 26m-depth cases (B-C1

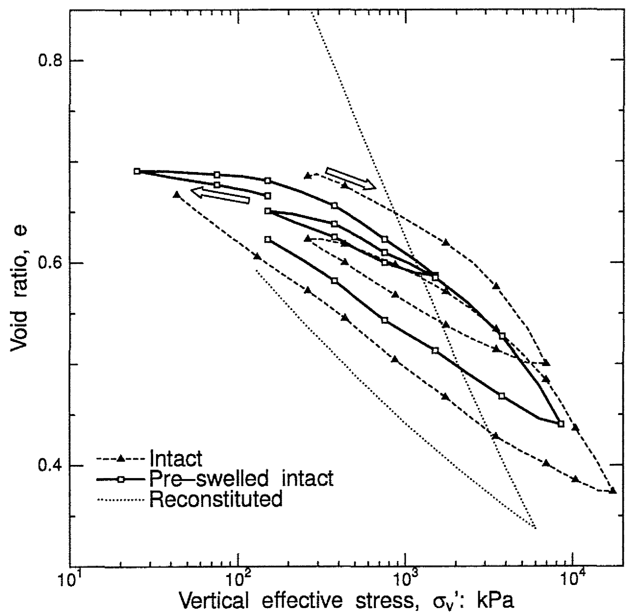

Figure 4. Volume change in one-dimensional compression and unloading (Ma, 2003).

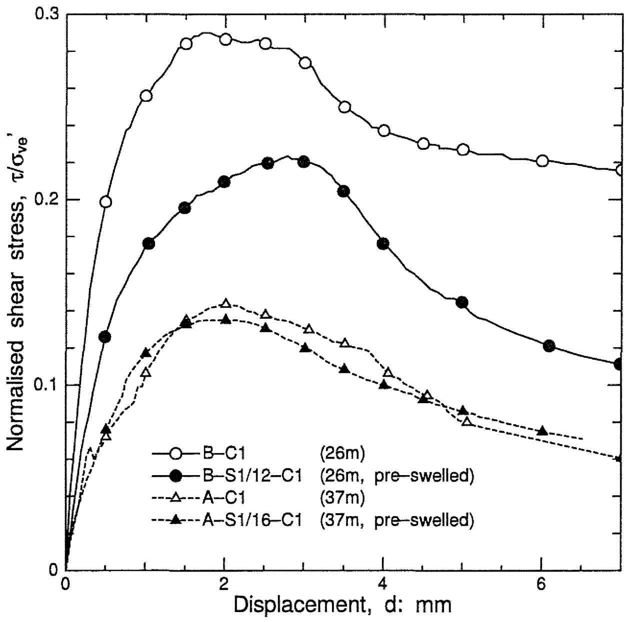

Figure 6. Normalised shear stress–horizontal displacement relations ($\sigma'_{v0} = 300$ & 400kPa).

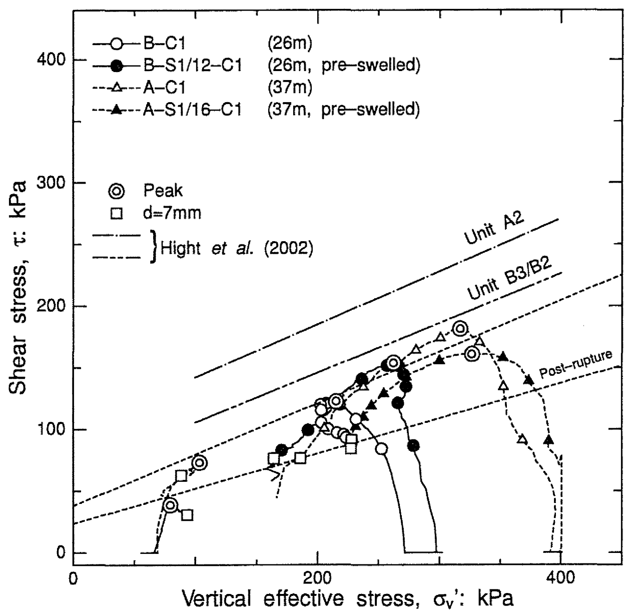

Figure 5. Stress paths in constant-height direct shear box test ($\sigma'_{v0} \leq$ 400kPa).

& B-S1/12-C1) is relatively large and normalisation by σ'_{ve} can eliminate this difference. The losses of τ_f/σ'_{ve} for the pre-swelled samples are 23 and 6% for the 26 and 37m samples, respectively. However, it should be noted that even minor errors in void ratio (water content) measurements can affect the shear strengths normalised by σ'_{ve} considerably. For example, an error of 0.01 in the void leads to a 7% change in the normalised shear strength for samples from 26m depth. As seen in Fig. 5, the peak strength envelope deduced from the constant height shear tests falls slightly below Hight *et al.*'s drained shear test envelopes. The London clay is brittle and the lower shear strength envelope corresponding to the stress points recorded at $d = 7$mm is the same as the post-rupture surface reported by Hight *et al.* (2002). Ring shear tests are required to locate the still lower residual shear strength characteristics that apply on polished shear planes.

The strength envelope for the stress points at $d = 7$mm is the same as the post-rupture surface reported by Hight *et al.* (2002).

Relationships between the shear stress normalised by σ'_{ve} and horizontal displacement for the soils recompressed at their in-situ stresses (B-C1 & A-C1) and that with swelling prior to the recompression (B-S1/12-C1 & A-S1/16-C1) are plotted in Fig. 6. The peak strengths normalised by σ'_{ve} for the pre-swelled samples are smaller than those for the un-swelled as mentioned above. Considering the swelled 26m sample (B-S1/12-C1), the horizontal displacement at the peak is larger than that for the test conducted from in-situ σ'_{vi} (B-C1), while no marked difference can be seen between the 37m samples (A-C1 & A-S1/16-C1). The greater degree of swelling experienced by the shallower sample probably accounts for the different behaviours of the 26 and 37m depth samples (see Fig. 3). Jardine *et al.* (2003) argue that such features may help to explain the marked influence of the degree of pre-swelling on the responses of London Clay units to tunnel boring operations.

Similar findings have been noted in tests where destructuration is achieved by compression: Tanaka *et al.* (2003) compare the stress–displacement (stress–strain) relations and effective stress paths observed in direct shear and triaxial tests on SHANSEP approach (Ladd & Foott, 1974) and the recompression method (which is similar to that adopted for cases of B-C1 & A-C1). The SHANSEP approach aims to eliminate the influence of soil disturbance by consolidating specimens beyond their yield stresses and then swelling them back to the same overconsolidation ratio as that acting in-situ. Tanaka *et al.* report that the peak strengths obtained from the two methods were nearly the same, even though the SHANSEP method can destroy the structure of naturally deposited soil during consolidation stages (Their reported average differences between the recompression and the SHANSEP are 13% in $\tan\phi'$ and 7% in τ_f/σ'_{v0} for the direct shear tests). Jardine *et al.* (2003) report detailed triaxial test results on the Thames Estuary Clay in Kent, UK, and conclude that the losses of undrained shear strength normalised by the yield stress in the SHANSEP approach are 5 to 10%, but note a marked reduction in the undrained stiffness.

It is well known that shear distortions associated with tube sampling and other such processes can cause drastic reductions in the effective shear failure envelopes of London Clay (Hight *et al.*, 2002). Less well established are the effects of swelling induced by geological overconsolidation, unloading by civil engineering excavations, or operations such as rotary coring in the presence of water based drilling muds. The preliminary tests reported here indicate that the soil structure changes induced by one-dimensional swelling affect the vertical yield stresses and the shear stress–horizontal displacement (stress–strain) relations more markedly than the than the peak shear strengths. Due to the limitations of the direct shear box test (stress and strain non-uniformities and associated progressive failure), the soil responses obtained in the constant height direct shear box tests probably less clear indications of the effects of swelling than, for example, well instrumented stress path triaxial tests. Even so, the preliminary tests reported above appear to offer valuable information on destructuration by swelling.

The next stage of the investigation is underway in which advanced triaxial and hollow cylinder apparatuses are being used to study anisotropy and destructuration.

4 CONCLUSIONS

The potential effects of swelling on the structure of London clay have been examined through preliminary tests undertaken on London Clay samples from the Terminal 5 construction site at Heathrow Airport. This paper reports data from oedometer and constant height direct shear box tests.

The one-dimensional compression/unloading tests described above showed a significant influence of both pre-swelling and pre-compression on the recompression/swelling index, C_s with the latter rising sharply as a result of either loading to elevated stresses, or swelling back to low pressures. Pre-swelling also reduced the vertical yield stresses seen on renewed loading. Both swelling and pre-compression appear to damage the structure of the natural London clay.

While the peak shear strengths observed in constant height direct shear box tests were relatively insensitive to any pre-swelling cycle, the horizontal displacements required reach peak strength were larger for the swelled samples.

The preliminary conclusion is that the changes in soil structure induced by one-dimensional swelling affect global shear stiffness to a greater degree than the peak shear strengths that apply in the overconsolidated region.

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