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Some aspects of the compression and collapse behaviour of an unsaturated natural loess

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Abstract

The compression and collapse behaviour of a natural unsaturated loess from Northern France was investigated by running a series of constant rate of strain oedometric compression tests (together with some step loading tests) while monitoring suction by means of a high capacity tensiometer. The reasonably constant suction measured during constant water compression tests was linked to the collapse of the largest dry pores. A time dependent behaviour was also observed, with different responses obtained at different strain rates. In a standard fashion, collapse tests appeared to bring the representative point from the constant water content curve to the zero suction compression curve, evidencing the existence of a maximum collapse stress. Data were qualitatively interpreted by using the Loading Collapse (LC) yield curve of the Barcelona Basic Model. Changes in the LC curve inclinations could account for the existence of a maximum collapse value.

Keywords: natural loess, collapse, unsaturated, suction, loading collapse, time dependent.

Introduction

Some problems related to the collapsibility of loess deposits in Northern France (Antoine *et al.* 2003) in areas crossed by the “TGV Nord” high speed train line have been described in Cui *et al.* (2004). As seen in Figure 1, impressive sinkholes were observed during the construction period when loess layers that were previously protected from rain by an upper superficial illuviated clayey layer were exposed to climatic effects (drying and raining).



Figure 1. Collapse behaviour in shallow layers of loess directly exposed to climatic actions

Following Jennings and Knight (1957), soil collapse has been investigated either by using the double oedometer technique or by performing soaking tests under constant stress. The

developments carried out in the past decades in the mechanics of unsaturated soils allow a better understanding of collapse thanks to a relevant theoretical framework (BBM model, LC curve, Alonso *et al.* 1987, 1990) and to advanced techniques of either controlling (e.g. Maâtouk *et al.* 1995) or measuring suction (e.g. Jotisankasa *et al.* 2007) in collapsible samples. To date, these approaches were mainly applied to reconstituted collapsible soils. This work is devoted to the behaviour of a natural aeolian loess, investigated by running constant water content oedometer compression tests with suction measurements. Results were interpreted by using the LC curve concept developed within the BBM model.

Experimental programme

Tests were performed on good quality samples trimmed from a block that was manually extracted at a depth of 1 m in October 2007 during a rather cool, dry and sunny autumn. As seen in Table 1, the loess has a 9% plasticity index and contains 6% carbonate, a component known to provide inter-particles bonding (“Loess is not just the accumulation of dust”, Pécsi 1990). Its water retention properties have been investigated in details in Muñoz-Castelblanco *et al.* (2011).

Table 1. Geotechnical characteristics of the Bapaume loess

Sample depth	1 m
Natural water content w (%)	14.4
Natural void ratio e	0.84
Dry unit mass ρ_d (Mg/m ³)	1.45
Natural degree of saturation S_r	0.46
Natural suction (HTC) (kPa)	40
Clay fraction (% < 2 μ m)	16
Silt fraction (%)	82
Sand fraction (%)	2
Plastic limit w_p	19
Liquid limit w_l	28
Plasticity index I_p	9
Carbonate content (%)	6

A series of oedometric compression tests (Table 2) in which, like in Jotisankasa *et al.* (2007), suction changes were monitored by using an in-house constructed high capacity tensiometer (HCT) located at the base of the sample (Figure 2), was carried out. Oedometer testing was selected in a purpose of simplicity (K_0 tests in the triaxial apparatus would have been preferable to get rid of the friction effects along the ring that may overestimate the specimen’s mechanical response). Most tests were performed at constant water content starting from the natural unsaturated state (w_i between 14.3% and 14.9%) with initial suctions s_i between 38 and 47 kPa (Table 2). Evaporation was prevented by isolating the sample from laboratory atmosphere with a plastic film as indicated in the Figure. In one of the tests, the sample was soaked at very low stress (1.5 kPa) prior to compression by carefully pouring water through the annular gap between the piston and the ring. Water infiltrated the soil through the porous disk and filter paper placed on top of the sample (Figure 2).

Table 2. Experimental program (SL: Step Loading test, CRS : Constant Rate of Strain test)

Test	Description	Initial state				Final state			
		e_i	s_i (kPa)	w_i (%)	S_{ri}	e_f	s_f (kPa)	w_f (%)	S_{rf}
SL001	Natural state	0.85	46.7	14.6	0.46	0.59	41.3	14.5	0.65
SL002	Saturated	0.85	46.3	14.3	0.45	0.55	-2.5	20.8	1.01
SL003	Natural state, collapse/soaking under $\sigma_v = 205$ kPa	0.85	41.2	14.4	0.45	0.53	0.2	19.7	0.99
SL004	Collapse / soaking under σ_v $= 19$ kPa	0.85	47.0	14.6	0.46	0.58	3.3	22.3	1.03
CRS01	Natural state 0.003%/min	0.84	45	14.4	0.46	0.66	29	14.3	0.59
CRS02	Natural state 0.010%/min	0.84	39	14.4	0.46	0.62	33	14.6	0.64
CRS03	Natural state 0.059%/min	0.84	40	14.9	0.48	0.61	35	14.5	0.63
CRS05	Saturated, 0.010%/min	0.84	38	14.4	0.48	0.59	-2.2	22.9	1.04

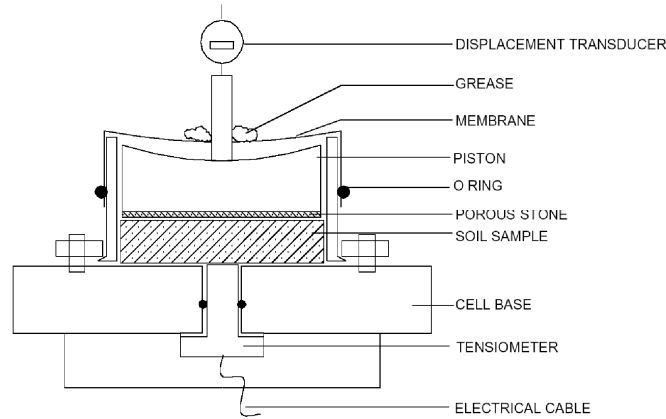


Figure 2. HCT measurement inside an oedometer cell (Delage et al. 2007)

Compression of the soaked sample provided the “saturated” reference compression curve. Constant water content tests were made to compare the unsaturated compression behaviour (with preserved natural structure) with the saturated one, like in the double oedometer test. As noted by Tarantino and De Col (2008), constant rate of strain (CRS) compression tests are preferable when monitoring suction changes. This was done here together with standard 24 h long step loading tests (with suction and displacement rates finally equal to 2 kPa/h and 27 $\mu\text{m/h}$ respectively).

Time dependent behaviour

The response of the CRS tests carried out at rates of 0.003, 0.010 and 0.059 %/mn are presented in Figure 3 in both linear and semi-log plot of the vertical net stress ($\sigma_v - u_a$, where u_a is the air pressure), together with the responses in suction. Given the low values of the

degree of saturation (Table 1), the air phase is continuous and the pore air pressure is equal to the atmospheric pressure that prevails in the upper porous stone, giving $u_a = 0$ at all times.

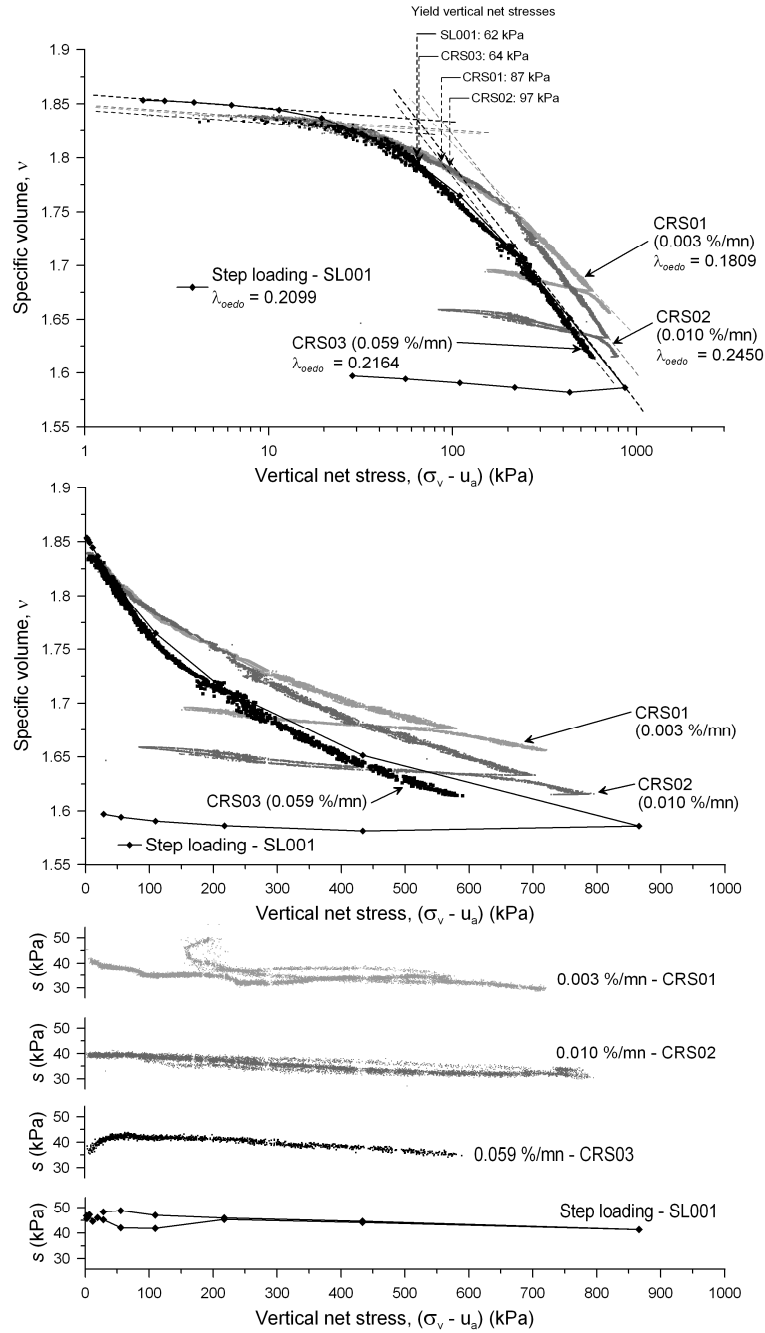


Figure 3. The effect of strain rate in the response at constant water content.

Compared to compacted soils that keep the memory of the compaction stress (Cui and Delage 1996, Maâtouk *et al.* 1995, Jotisankasa *et al.* 2007), the response observed here in a natural soil at all rates is not strictly elasto-plastic and exhibit a less apparent yield stress in the semi-log plot. Indeed, yield is not due to any previous maximum supported stress, given the aeolian origin of the soil. As in structured soils, it is linked to a loose structure and to inter-particle bonding. The various available methods of determining gross yield are known to provide different values. In a purpose of simplification, gross yield was determined here at the intersection of two lines fitted on the pseudo-elastic and plastic section of the compression curve respectively.

Figure 3 shows that the response of the CRS tests is time dependent, in particular in terms of (visco)-plastic compressibility as illustrated by the slope of the curve (λ_{oedo}) in the post-yield regime, that shows that the unsaturated loess appears to be stiffer at smaller strain rates. The ordering of yield stresses with respect to strain rate is less clear, in particular between tests CRS01 (0.003%, 87 kPa) and CRS02 (0.010%, 97 kPa), due to the sensitivity of the determined yield with respect to the lines drawn. The distinction with the fastest test CRS03 (0.059%, 64 kPa, that corresponds well with the step loading test SL001) is more apparent, with a smaller yield at faster rate. This trend, different from what is observed in saturated fine grained soils and/or sands, should obviously be confirmed by further investigation. The smallest yield stress and highest compressibility of the step loading test could come from the dramatic impact of instantaneous loading on a porous metastable unsaturated structure (step loading is better adapted in saturated samples). The reason why tests SL001 and CRS03 correspond so nicely is not straightforward.

The responses in suction are fairly comparable at 0.003 and 0.010%/mn with a progressive decrease from the initial value (40 kPa) to 32 kPa. They are fairly reversible at 0.010%/mn, whereas larger suction variations are observed at 0.003 %/mn (CRS01, CRS04). At higher rate (0.059 %/mn) and with the step loading procedure, the responses are different with a rapid initial increase followed by a progressive decrease that ends at a comparable suction value.

Collapse behaviour

All the initial states of the samples tested in Figure 4 have the same initial void ratio (0.85), showing fairly good homogeneity within the block. Tests include:

- The SL001 step loading test at constant initial water content (14.6%) that presents excellent correspondence with test CRS03 (0.059%/mn, $w = 14.4\%$);
- The SL002 step loading test of a sample previously soaked under 1.5 kPa (no collapse) that presents excellent correspondence with test CRS05 carried out after soaking under 3 kPa (no collapse);
- The SL003 step loading collapse test (soaking at 205 kPa, 2.3% collapse) that presents excellent correspondence with test CRS03 before collapse and with tests SL002 and CRS05 after collapse;
- The SL004 step loading test with soaking at 19 kPa (close to the 16 kPa in-situ stress, 3.8% collapse) that presents excellent correspondence with test CRS03 before collapse and good correspondence with tests SL002 and CRS05 after collapse, confirming the (well known) validity of Jennings and Knight's approach.

The responses in suction are reasonably constant in all tests. As a result, comparable suction decreases occurred during both collapses at 205 and 19 kPa. Constant suction during compression was observed by some authors in samples compacted dry of optimum (e.g. Tarantino and De Col 2009) but not in all cases (Jotisankasa et al. 2007).

Various observations can be made from Figure 4:

- There is excellent correspondence between all tests, showing the good quality and homogeneity of the samples tested and of the experimental procedures;
- All rebound curves are comparable, confirming the independence of the BBM κ parameter (slope of the curve in the elastic range) with respect to suction, a trend also observed by Jotisankasa et al. 2007 in a artificial collapsible soil;
- Irreversible strain appears to develop from low stress in tests at zero suction (CRS05, SL002), reducing the yield stress to about 3 kPa;
- Accordingly, the mutual positions of the constant water content and zero suction curves evidence above 3 kPa the progressive development of collapse (an irreversible

strain) up to a maximum under 30 kPa. Below 30 kPa, the unsaturated sample is less compressible than the saturated one (in agreement with the BBM model). Above, it becomes more compressible, as observed by Wheeler and Sivakumar (1995). The constant water content curve progressively joins the zero suction line, with an intersection probably located between 1000 and 2000 kPa. The existence of a maximum collapse has been integrated in some constitutive models (e.g. Josa *et al.* 1992 and Georgiadis *et al.* 2008);

- The collapse strain at 19 kPa (3.8%) is larger than that at 205 kPa (2.3%). Indeed, 19 kPa is located below yielding (63 kPa) whereas a compressive plastic strain of about 10% developed prior to the plastic collapse strain of 2.3%;
- The changes in collapse with vertical stress are illustrated in Figure 5 that clearly shows the maximum collapse at 30 kPa.

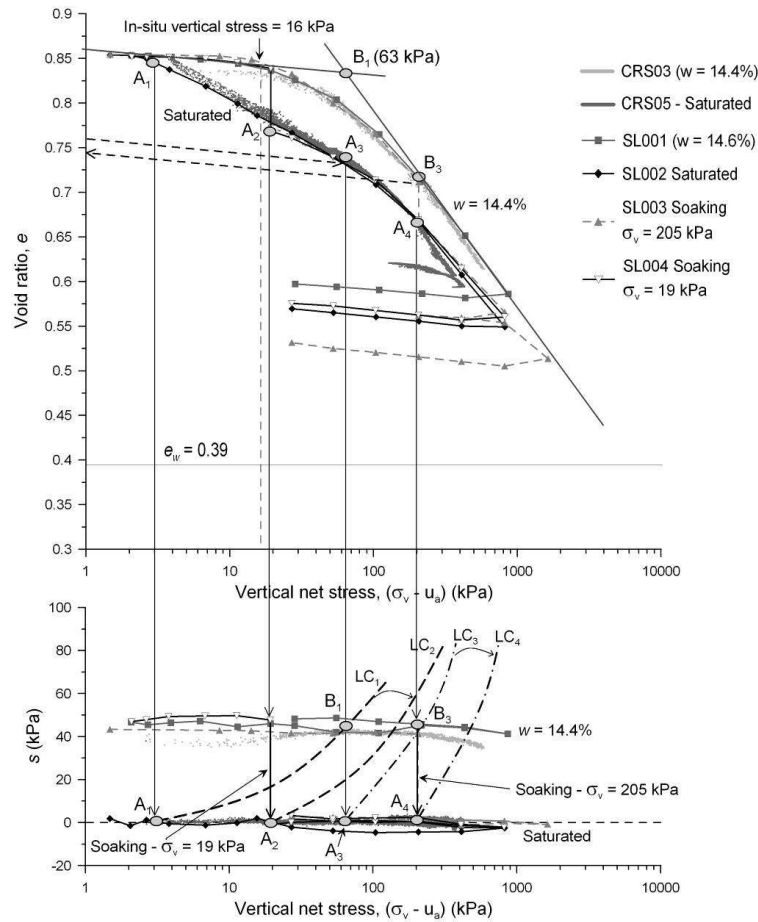


Figure 4. Collapse and compression tests performed

Discussion

The small suction changes observed during compression can be related to the low saturation state of the samples with degrees of saturation increasing from 47% to 62 % (Table 2). Based on Laplace's capillary law and under the approximate hypothesis of cylindrical pores, a 40 kPa suction corresponds to a pore diameter of 7.5 μm , which means that larger pores should be dry. Given that the loess pore size distribution curve (not shown here for brevity, see Munoz-Castelblanco 2011) shows that 6.8% of the pore volume corresponds to larger inter-grains pores with diameter between 16 and 363 μm , it is believed that compression occurs by the breakdown of these larger and weaker dry pores with little effect on smaller water saturated pores that govern suction changes (Delage 2009).

At any stress, collapse brings the representative point from the constant water compression curve down to the “saturated” compression curve. Note however, as shown in Figure 4 (in which both the constant saturated void ratio – $e_w = 0.39$), that collapse is far from erasing all the initially dry porosity.

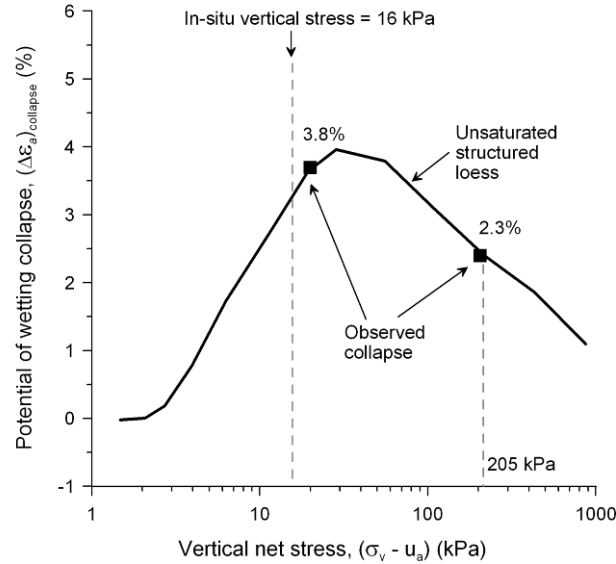


Figure 5. Potential of collapse due to wetting

A qualitative interpretation in terms of change in LC curves with the mobilization of either plastic compression or plastic collapse is proposed in Figure 4 in a $s/\log(\sigma_v - u_a)$ plot. The initial LC_1 curve represented in the Figure is fully determined by the two yield points at zero suction (A_1) and at $s \approx 40$ kPa (B_1 , $\sigma_v - u_a = 63$ kPa). According to the BBM model, soaking under 19 kPa starts in the elastic region and should first induce a slight elastic swelling (not observed here). As drawn in Figure 4, the vertical soaking path curve then reaches the LC_1 curve and plastic collapse corresponds to the moving of point A_1 to A_2 and of curve LC_1 to LC_2 . Plastic compression at constant water content to 205 kPa moves LC_1 to a LC_3 curve. LC_3 is defined by B_3 ($s \approx 40$ kPa, $\sigma_v - u_a = 205$ kPa) and A_3 . The position of A_3 is estimated by (virtually) unloading the sample (using the known κ parameter), soaking it (with a small rebound defined by an estimated κ_s parameter) and compressing it elastically up to the yield defined by the intersection with the saturated compression curve (62 kPa). Indeed, the LC_3 curve appears to have a smaller inclination than LC_2 illustrating a smaller potential collapse (Alonso et al. 1987). LC_3 is afterwards moved to LC_4 during plastic collapse (A_3 moves to A_4) with also a smaller estimated inclination.

Conclusions

Up to date experimental techniques (including collapse tests with suction monitoring) and qualitative constitutive modelling of unsaturated soils have been used in the investigation of the collapse behaviour of a natural aeolian loess from Northern France. Compared to existing data on reconstituted collapsible soils, the following set of conclusions can be drawn for a natural soil:

- Suction measurements showed that constant water content compression tests occurred at a fairly constant suction (even at yielding). This is explained by the compression induced collapse of the largest dry pores of the loess, with little effect on the smaller hydrated pores that control suction changes;

- Given the aeolian origin of the loess, yield is not related to any previous applied stress but to the bonding due to carbonate re-precipitation between the grains, resulting in less apparent yield values compared to compacted soils;
- The response of the loess to compression is time dependent. Whereas the trend governing the changes in yield stress with strain rate is not very clear and needs further investigation, the plastic compression parameter λ appears to be time dependent unlike in saturated fine grained soils that are generally characterised by an isotach-type viscous response;
- A maximum collapse is observed at a vertical net stress of 30 kPa;
- The volume change behaviour has been qualitatively interpreted by means of the LC curve concept, the inclination of which varied to account for the existence of a maximum collapse;
- The magnitude of collapse is known to increase with higher suction. This is the case during dry periods, in particular like in Figure 1 when the layer of collapsible loess has been directly exposed to atmosphere and does experience evaporation. As a result, the magnitude of the collapse observed in the photo could be significantly higher than that measured here.

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