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1 **Exploring one-dimensional compression of compacted clay under constant**
2 **degree of saturation paths**

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9

Abstract

10 This note presents a novel approach for controlling the degree of saturation during one-
11 dimensional compression of unsaturated soils. This technique offers a simple and versatile
12 way to study the hydro-mechanical response of unsaturated soils as well as the unsaturated-
13 saturated soil transition. By using a multi-stage approach, the same specimen can be used to
14 evaluate the compressibility of unsaturated specimens at different degrees of saturation which
15 may reduce the long testing periods commonly required for unsaturated soil testing. The
16 experimental results described in this paper shows that the proposed technique is capable of
17 controlling the degree of saturation within reasonable limits and provides an interesting
18 approach to analyse the coupled hydraulic and mechanical behaviour of unsaturated soils.

19 **Keywords:** unsaturated soil, degree of saturation, compressibility, axis-translation.

20

1. INTRODUCTION

The relationship between hydraulic and mechanical properties, or hydro-mechanical coupling, plays an important role in unsaturated soil behaviour. However, the description of this coupling is not an easy task, from either a theoretical or an experimental perspective. Drawbacks found during early attempts to describe unsaturated soil behaviour based on Bishop's effective stress (Jennings and Burland, 1962, Bishop and Blight, 1963) and the degree of saturation (S_r), led to the now well-known two independent stress variable approach (net stress, $\bar{\sigma} (\sigma - u_a)$ and suction, $s (u_a - u_w)$, where σ is the total stress, u_a is the pore-air pressure and u_w is the pore-water pressure). This allows for convenient application and control of stress paths in laboratory experiments. However, the influence of hydro-mechanical coupling is not easily captured by this approach.

This paper describes one-dimensional (1-D) compression behaviour of compacted clay along constant degree of saturation paths. Despite the theoretical and practical relevance of degree of saturation in unsaturated soil mechanics, to the authors' knowledge, only one other attempt (Al-Badran, 2011) has been made to control the degree of saturation in laboratory investigations. Al-Badran (2011) adopted the axis-translation technique and adjusted suction to achieve a target degree of saturation after application of vertical stress increments. An alternative simple and versatile approach for controlling the degree of saturation based on controlling pore-water volume during one-dimensional compression is presented in this paper. Experimental results show the success of the method and are used to evaluate the one-dimensional compression response of unsaturated compacted clay.

2. MATERIALS, EQUIPMENT AND EXPERIMENTAL PROGRAM

Soil tested

The soil tested was commercial Kaolin (Sanyo Clay Industrial Co. Ltd., Japan) and the properties are summarised in Table 1. Oedometer specimens (10mm high and 60mm in diameter) were compacted in one layer directly into the oedometer ring at target water contents of 21.6% (dry of optimum) and 33.6% (wet of optimum) with target void ratios of 1.59 ($\rho_d=1.02 \text{ t/m}^3$) and 1.2 (1.19 t/m^3). For specimens with the relatively low initial dry density, in comparison to the standard Proctor maximum (see Table 1), the material produced was highly compressible with initial states located above the NCL. Initial states below the NCL were obtained for specimens with the relatively higher initial dry density. The compression of these specimens produced large volume changes, and subsequently large pore-water volume changes which have enabled evaluation of the degree of saturation control.

Table 1: Characteristics of soil tested.

Liquid limit w_L [%]	Plasticity index I_p [%]	Specific gravity G_s [%]	Standard Proctor maximum dry density ρ_d [t/m^3] (void ratio)	Standard Proctor optimum water content [%]
57	15	2.638	1.45 (0.819)	27.5

Equipment and procedures

The tests were completed in an axis-translation oedometer, as shown in Figure 1. Suction was controlled and/or measured by the difference between pore-air pressure (u_a) and pore-water pressure (u_w). Pore-air pressure was applied to the top of the sample whereas pore-water pressure was controlled/measured by a high air-entry value ceramic disc (AEV=1500 kPa) at the base of the sample. Pore-water pressure was applied using a pressure/volume controller (PVC) and the pore-air pressure was applied using a pneumatic regulator. The air-over pressure technique (e.g. Romero, 2001) was used to reduce air diffusion through the ceramic

disc into the hydraulic lines along with provision for flushing to a graduated burette (item 6, Figure 1).

66

Figure 1: Schematic of oedometer layout.

The approach proposed here, rather than controlling suction, is to control the pore-water volume and subsequently degree of saturation. With degree of saturation defined as the ratio of pore-water volume (V_w) to the volume of voids (V_v), constant S_r (V_w / V_v) during loading implies:

$$dV_w - S_{r(initial)} dV_v = 0 \quad (1)$$

According to Eq. 1, constant degree of saturation paths can be applied during loading by keeping the change in pore-water volume (dV_w) equal to the product of degree of saturation and the change in volume of voids ($S_{r(initial)} dV_v$). In the 1-D tests described in this paper the change in volume of voids is given by $A dh$ (where A is the specimen area, and dh is the change in sample height).

Compression tests under constant S_r were performed by controlling the loading rate while monitoring the pore-water pressure. Compression of the sample implies a continuous

79 reduction of dV_v so that Eq. 1 is satisfied by reducing dV_w . In other words, pore-water
 80 pressures have to be reduced during loading (suction increased) to keep constant S_r . The
 81 measured pore-water volume was corrected to allow for the compliance of the pore water
 82 system. Calibration tests were performed to establish the relationship between pressure and
 83 volume in the PVC ($\approx 2.86 \text{ kPa/mm}^3$). These were not allowed for in the software control
 84 algorithm, but subsequent analysis showed that the effects of the system volume changes
 85 were small, despite the relatively small specimens used.

86 The pore-water volume was controlled using the PVC in volume control mode (resolution
 87 1 mm^3) which was adjusted to satisfy Eq. 1. A tolerance (or dead band where no change is
 88 applied to avoid oscillation) of $\pm 2 \text{ mm}^3$ was adopted. The error in the pore-water control was
 89 assessed based on the uncertainty of a difference (Drosg, 2009) and substituting Eq. 1:

$$90 \quad \Delta(dV_w - S_{r(\text{init})}dV_v) = \sqrt{\Delta(dV_w)^2 + \Delta(S_{r(\text{init})}dV_v)^2} \quad (2)$$

91 where $\Delta(dV_w)$ is the uncertainty of the pore-water volume measurement (1 mm^3), and
 92 assuming a fixed $S_{r(\text{init})}=1$, $\Delta(dV_v)$ is the uncertainty in the change in dV_v related to
 93 measurements of axial displacement ($\pm 0.002 \text{ mm}$). The absolute error in the volume change is
 94 around 30 mm^3 , i.e. a relative error of $< 0.5\%$ (initial volume of the pore-water: $6,000 \text{ mm}^3$).

95 *Experimental program*

96 The experimental program is summarised in Table 2, Figure 2, and Figure 3. Additional tests,
 97 not reported here, were completed on reconstituted samples to establish the position of the
 98 NCL. The experimental results described below correspond to: 1) loading under constant
 99 suction (OED05 and OED18) to establish a base line, and 2) loading paths under constant
 100 degree of saturation. Following compaction, samples were equilibrated from the as-

101 compacted suction to a suction of 100 kPa ($u_a=500$ kPa; $u_w=400$ kPa), while maintaining a
102 constant vertical net stress of $\bar{\sigma}_v = \sigma - u_a = 20$ kPa, points A1 to A4 shown Figure 3 and
103 Figure 4.

104 A loading rate of 12 kPa/hr was adopted for these preliminary tests to provide a compromise
105 between avoiding evaporation from the top of the sample and air diffusion through the
106 ceramic (affecting the water volume change measurements), while at the same time
107 minimising rate effects on the volume change response. The loading rate was doubled in
108 OED17 for comparison.

109 Following equilibration at points A1 to A4, D1, D2, G and I the samples were compressed at
110 constant degree of saturation. For example, in OED06 loading at constant S_r was completed
111 in two stages following paths A1 to C1 and D1 to E1. See Figure 3 and Table 2 for the paths
112 followed in each test. To minimize diffusion, loading was stopped at $\bar{\sigma}_v = 965$ kPa and
113 suction reduced in steps to either 200 kPa, 100 kPa or 10 kPa (stress path C1 to D1, C2 to D2
114 and H to I). Afterwards, samples were again compressed under constant degree of saturation
115 (stress path D1 to E1, D2 to E2 and I to J).

Figure 2: Standard Proctor compaction and initial points for oedometer tests.

Figure 3: Saturation-net stress path followed in the oedometer tests.

Table 2: Testing program and details.

Test	Target initial conditions		Stage	Stage type ¹	Stage beginning				Stage end			
	e_0 [-]	w_0 [%]			w_0 [%]	e_0 [-]	S_{r0} [-]	w_f [%]	e_f [%]	S_{rf} [%]		
OED05	1.57	21.6	A1 to B	s	25.2	1.58	0.421	27.00(26.0) ²	0.804	0.886		
OED06 (S_r test)	1.57	21.6	A1 to C1	S_r	23.40	1.558	0.396	14.90	0.969	0.406		
			C1 to D1	s↓	14.90	0.969	0.406	17.60	0.935	0.479		
			D1 to E1	S_r	17.60	0.935	0.479	15.80(-)	0.810	0.515		
OED07 (S_r test)	1.57	21.6	A1 to C1	S_r	24.0	1.575	0.402	14.9	0.968	0.406		
			C1 to D1	s↓	14.9	0.968	0.406	17.2	0.949	0.478		
			D1 to E1	S_r	17.2	0.949	0.478	15.40(15.88)	0.836	0.486		
OED17 ³ (S_r test)	1.57	21.6	A1 to C1	S_r	24.3	1.584	0.405	15.0	1.004	0.394		
			C1 to D1	s↓	15.0	1.004	0.394	23.6	0.926	0.672		
			D1 to E1	S_r	23.6	0.926	0.672	20.6(21.43)	0.816	0.666		
OED25 (S_r test)	1.2	21.6	A3 to C3	S_r	22.2	1.190	0.492	16.6(16.91)	0.889	0.493		
OED18	1.57	33.6	A2 to B	s	34.0	1.597	0.562	27.9(28.0)	0.809	0.910		
OED19 (S_r test)	1.57	33.6	A2 to C2	S_r	33.8	1.577	0.565	21.6	1.009	0.565		
			C2 to D2	s↓	21.6	1.009	0.565	26.7	0.962	0.732		
			D2 to E2	S_r	26.7	0.962	0.732	23.9(23.50)	0.850	0.739		
OED20 (S_r test)	1.57	33.6	A2 to F	s	34.0	1.590	0.564	32.7	1.524	0.566		
			F to G	s↓	32.7	1.524	0.566	41.6	1.341	0.818		
			G ⁴ to H	S_r	41.6	1.341	0.818	28.7	0.949	0.798		
			H to I	s↓	28.7	0.949	0.798	29.6	0.943	0.829		
			I to J	S_r	29.6	0.943	0.829	26.3(25.51)	0.835	0.831		
OED26 ⁵ (S_r test)	1.2	33.6	A4 to C4	S_r	33.3	1.200	0.732	24.1(23.87)	0.876	0.726		

¹ Stage type: “ S_r ” – degree of saturation controlled. “s” constant suction. “s↓” – suction reduction.² Indicates final measured water content.³ Loading rate 24kPa/hr.⁴ Suction of 300kPa applied prior to suction reduction at point H.⁵ Initially loaded at 12kPa/hr then reduced to 3 kPa due to rapid suction increase.

3. TEST PERFORMANCE

Loading rate effects

The adopted loading rate ($d\bar{\sigma}_v=12$ kPa/hr) was assessed by holding the vertical net stress constant at three points during OED06 as shown in Figure 4a. There is some evidence of a reduction in the suction (<10 % of the applied suction), indicative of a redistribution of the pore-water occurring after loading has stopped resulting in an increase of the pore-water pressure. However, the magnitude of this suction change should be viewed in light of the pressure-volume relationship of the pore-water measuring system (around 2.86 kPa/mm³) which indicates that small changes in pore-water pressure are representative of small water volume redistribution (e.g., $\Delta s=20$ kPa equates to around 7 mm³). A further test (OED17) was completed using a rate of 24 kPa/hr which produced a similar magnitude of suction reduction (Figure 4b). From the inspection of Figure 4 it is evident that for a period of about 2 hours after holding the net stress constant there is a slight change in void ratio which is accompanied by a reduction in suction. As these changes are similar despite the faster rate in OED17, this suggests that the loading rate is sufficiently slow in both tests for suction equilibration during the ramped loading. On this basis, the adopted loading rate of 12kPa/hr seems to provide a reasonable compromise between limiting the test duration and minimizing rate effects.

Figure 4: (a) Hold periods in test OED06. Axial loading at a rate of 12 kPa/hr, (b) Hold period in OED17. Axial loading at rate of 24 kPa/hr.

136 Water content – void ratio paths

137 The ability of the tests to maintain a constant degree of saturation is highlighted through the
 138 water content-void ratio (or even dry density) plane as shown in Figure 5. Constant degree of
 139 saturation lines were drawn based on $eS_r = wG_s$. Where the degree of saturation was
 140 controlled, the water content-void ratio paths closely follow the appropriate degree of
 141 saturation line. For instance, the results of OED06 and OED07 closely follow the $S_r=0.4$ line.

Figure 5: Relationship between void ratio and water content for loading tests under constant suction (OED05 & OED18) and constant S_r compression (OED06 & OED19).

142 Variation of suction during loading at constant S_r

143 As observed in Figure 6, suction was seen to increase during loading as a consequence of the
 144 reduction of dV_w . For OED06 (Figure 6a) suction progressively increased to approximately
 145 360 kPa. The repeatability of the measured suction is evident from the similarity of the
 146 responses in OED06 and OED07. In contrast, in OED25 (compacted to the lower initial void
 147 ratio) suction during S_r loading was initially higher than OED06, but reached a lower suction
 148 at point C3 (350 kPa). The development of an initially higher suction in this case is attributed
 149 to the higher initial S_r of OED25, which led to larger changes in water volume during
 150 loading. Comparatively similar results were obtained for samples prepared with higher initial
 151 water content (Figure 6b).

Figure 6: Selected suction-stress path followed in the tests.

152 Compression paths

153 The variation of void ratio and degree of saturation with vertical net stress is shown in Figure
 154 7. In contrast to the tests where the degree of saturation has been held constant during loading
 155 (OED06 and OED26 in Figure 7a & b and OED19 and OED26 in Figure 7c & d), during the
 156 constant suction tests (OED05 & OED18) the degree of saturation monotonically increases.
 157 The volume change responses of the loading under constant S_r tests are comparatively similar
 158 to the constant suction tests (i.e. similar slopes of the compression line), despite the
 159 differences in the degree of saturation (e.g. Figure 9b). As the vertical net stress increases in
 160 both tests types, the NCL is approached. In test OED20 suction was reduced to 10 kPa at a
 161 vertical net stress of 100 kPa prior to loading at constant S_r (around 0.820). In this case the
 162 compression line is almost parallel to the NCL (see Figure 7c).

Figure 7: Variation of void ratio (a, c) and degree of saturation with vertical net stress (b, d).

Figure 8 shows the variation of void ratio with vertical effective stress (Bishop et al., 1963). It can be seen that the slope of the compression line at constant S_r (0.4-0.56) is larger than the slope of the NCL. This behaviour is in contrast to the response predicted by some constitutive models formulated in terms of S_r (e.g., Zhang & Ikariya, 2011; Zhou et al, 2012). This result highlights the necessity for further experimental evidence aimed at assessing key assumptions of available constitutive models as well as developing new constitutive laws for unsaturated soils.

Figure 8: Variation of void ratio with vertical effective stress.

4. CONCLUDING REMARKS

The transition from saturated to unsaturated behaviour is given by the degree of saturation, a key variable for understanding the coupled response of unsaturated soils. Despite this, there have been limited attempts to directly assess soil behaviour at constant degrees of saturation. A novel technique for directly controlling the degree of saturation during laboratory tests, based on the axis-translation technique, has been proposed in this paper. The degree of saturation is maintained constant during compression through direct control of the pore-water volume and has been shown to remain within reasonable limits.

The proposed technique offers a simple and versatile tool for studying the hydro-mechanical response of unsaturated soils as well as the unsaturated-saturated soil transition by directly controlling the degree of saturation during experimental tests. It will enable assessment of some of the assumptions adopted in constitutive models and develop greater understanding of the role of S_r in unsaturated soil behaviour. The preliminary results described in this paper have shown the potential advantages of the technique. Further applications on different soil

184 types will help to verify its effectiveness and potential in studying the behaviour of
 185 unsaturated soils.

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 188 Minister's Australia Asia Endeavour Award while studying at the Nagoya Institute of
 189 Technology.

190 **NOTATION**

191	u_a	Pore-air pressure
192	u_w	Pore-water pressure
193	s	Suction ($u_a - u_w$)
194	σ	Total stress
195	$\bar{\sigma}$	Net stress ($\sigma - u_a$)
196	$\bar{\sigma}_v$	Vertical net stress ($\sigma_v - u_a$)
197	σ'_v	Vertical effective stress ($\bar{\sigma}_v + S_r s$)
198	V_w	Pore-water volume
199	V_v	Volume of voids
200	S_r	Degree of saturation

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 222

223 7. FIGURES

224 Figure 1: Schematic of oedometer layout

225 Figure 2: Standard Proctor compaction and initial points for oedometer tests

226 Figure 3: Saturation-net stress path followed in the oedometer tests

227 Figure 4:(a) Hold periods in test OED06. Axial loading at a rate of 12 kPa/hr,(b) Hold period
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235 8. TABLES

236 Table 1: Characteristics of soil tested.

237 Table 2: Testing program and details.

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