The Relationship Between Matrix and Solute Suction, Swelling Pressure, and Magnitude of Swelling in Reactive Clays

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SUMMARY The results of a series of one-dimensional swelling tests on reactive clays are reported, in which chemical analyses of salts in the porewater were first carried out to enable control of solute suction during testing. It is shown that for saline clays, the magnitude of swelling is dominated by solute suction changes. Total and solute suction values for the soils are compared, and comments are made on the significance of salt diffusion in measuring volume changes in reactive soils.

1 INTRODUCTION

The prediction of vertical movement of reactive (or expansive) clay soil profiles resulting from soil moisture changes is of concern to many geotechnical engineers. The problem arises in those parts of the world where the climate is arid for all or part of the year. Such a climate exists over large regions of Australia, and considerable damage to road pavements and light structures is the result. In particular, wall cracking in masonry domestic houses is often severe, and has attracted wide public interest.

Experience has shown that soil movement may be caused by

(i) Seasonal moisture changes, that is, due to natural rainfall and to drying by sun and wind.

(ii) Wetting of a soil profile by man-made or artificial effects, such as garden watering, leaking pipes, discharge of roof run-off close to footings, and build-up of moisture beneath impervious floors and pavements.

(iii) Drying of a soil profile as a result of ventilation under floors, air conditioning, heated areas, or moisture extracted from the soil by trees.

In Adelaide, South Australia, which has a Mediterranean climate, case-studies indicate that artificial wetting and drying are the major causes of cracking of masonry houses (Fargher, 1979, Aitchison et al, 1977).

This paper reports the results of a laboratory investigation into the swelling characteristics of soils from three sites near the City of Adelaide. The approach differs from any previous studies, in that chemical analyses for the solutes in the pore-water were carried out first, and then pairs of swelling tests using oedometers were made, in which the solute suction was kept constant in one test but allowed to vary in the other. It is postulated that these two cases represent extremes of possible wetting states beneath, say, a light building with a concrete floor. The first four causes of wetting in (ii) above will result in a dilution of solutes in the soil, or a lowering of osmotic pressure (solute suction). The last cause, i.e. build-up of moisture below an impervious floor, is likely to be due to rising saline moisture, and will result in a smaller or zero change in solute suction.

In each pair of oedometer tests, the one with distilled water in the cell measured swelling pressure and magnitude of swell due to a change in both solute and matrix (or capillary) suction, whereas that with saline water measured the effects of change in matrix suction alone.

2 EXPERIMENTAL WORK

2.1 Soil Profiles

Three soil profiles were selected for study:

- At the South Australian Institute of Technology Levels Campus, 14 km north of Adelaide, a red brown earth of pedological profile RB9b.
- At the Arboretum, Waite Agricultural Institute, 5 km south of Adelaide, a red-brown earth type RB3.
- From O'Halloran Hill, 18 km south of Adelaide, a black earth overlying Hindmarsh clay.

The annual rainfall is 500 - 600 mm.

Descriptions of soil profiles and average moisture contents are shown in Figure 1. The upper 3 m of Levels clay has nodules containing lime surrounded by relatively lime-free clay. Moisture contents may vary by ±3% from the values plotted.

2.2 Total Suction

It is now recognized that total suction, that is, the sum of solute and matrix suction, is a more useful parameter than moisture content in studying the swelling of reactive clays. (Peter, 1979). Total suction determinations were made on samples from each site using a thermister psychrometer similar to that described by Peter and Martin (1973). The results are shown in Figure 2. The pF scale has been used for plotting total suction values, where $pF = \log_{10} h$, and h = equivalent capillary rise in centimeters.
Figure 2 also plots the results of comparison tests done on Levels soil using three other psychrometers, with the kind co-operation of their owners. Considering the technical difficulties of measurement, the results must be regarded as in good

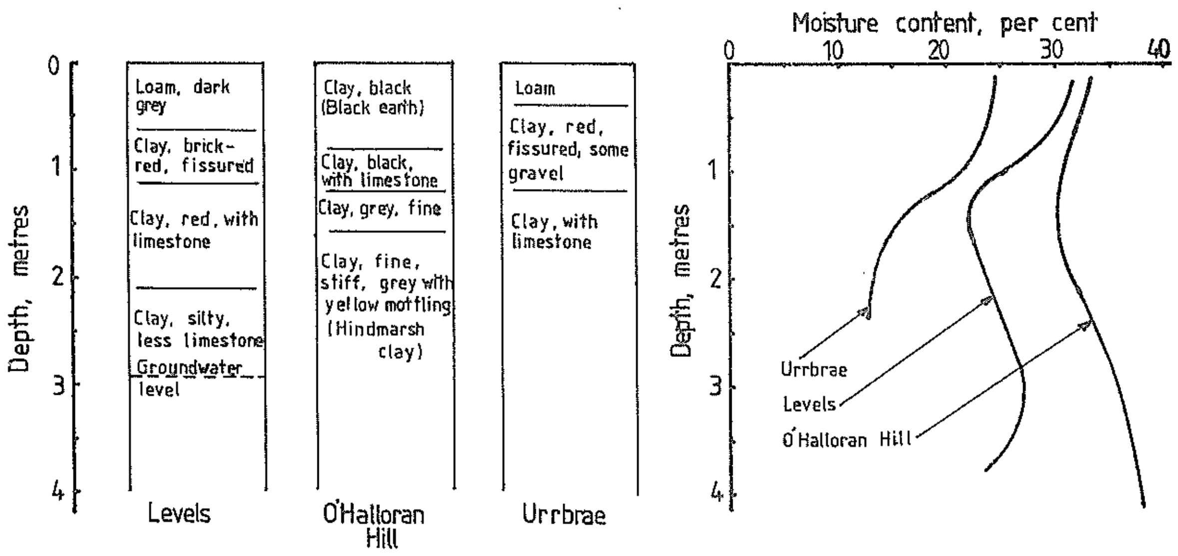

Figure 1. Soil Profiles and Moisture Contents

agreement.

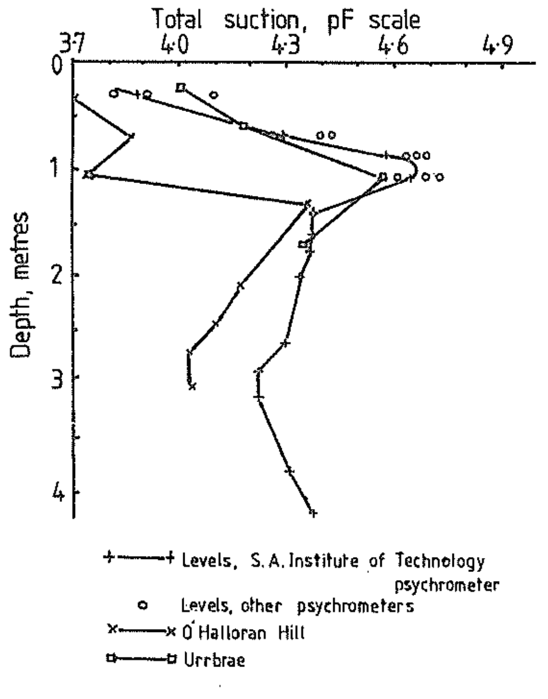

Figure 2. Suction Profiles

2.3 Chemical Analyses

Chemical analysis for salts in the pore-water involved firstly extracting moisture at several depths and then carrying out a series of chemical tests. Both were done with substantial help from the C.S.I.R.O., Division of Soils, Adelaide, South Australia.

2.3.1 Moisture extraction

Initially, three methods of extraction were tried on Levels soil samples:

- Standard 1:5 extraction as used by soil scientists, i.e. mixing 1 part of soil to 5 parts of weight of water, and using end-over-end mixing.
- Mixing soil and water to approximately the liquid limit and extracting some water using suction with a Buschner funnel.
- For a depth of 0.9 m, extraction by all-round pressure of 45 mPa in a high pressure triaxial cell.

Fine suspended matter was removed by centrifuging, and chemical testing carried out. Allowing for the dilution in the first two extraction methods, all gave the same amounts of solutes in the soil. For the Urrbrae and O'Halloran Hill soils, only 1:5 extraction was used, chiefly because it is the easiest and quickest method.

2.3.2 Methods of chemical analysis

For metal ions in solution, the atomic absorption spectro-photometer (AAS) was used. This device is now widely used in analytical chemistry, although its application to soils appear to be not widely known to engineers. A brief description of the AAS was given in Engineers Australia, May 4, 1979, p.27. Basically, it depends on spraying diluted soil pore-water into a hot flame and observing the absorption of selected wave lengths of light. The AAS is capable of measuring the concentration of metal ions accurately and quickly. It does, however, require some experience to use properly.

For non-metal ions, the methods of analyses were:

- Chlorides - titration with silver nitrate, using an electrometric method for precise determination of the null point.
- Carbonates and bicarbonates - titration with hydrochloric acid.
- Sulphates - gravimetric method as described in Australian Standard 1289 - Testing Soil for Engineering Purposes.

Figure 3 shows the concentration of salts (or rather ions) in solution in the pore-water. The concentration is given in milli-equivalents per litre (m.e/l). A normal solution is 1000 m.e/l.

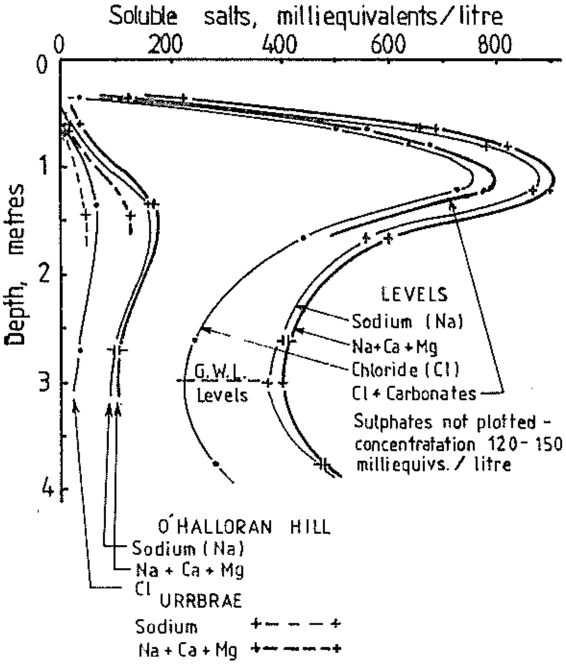

Figure 3. Solutes in pore-water

2.4 Oedometer Tests

Table 1 shows the results of tests carried out following the chemical analyses. The procedure was to prepare pairs of specimens, load to overburden pressure, and then add distilled water to one cell and water of the same salinity as the soil moisture to the other. As swelling commenced, vertical load was added in small steps to just prevent net vertical heave. The swelling pressures in Table 1, based on no volume change, were reached in a few hours.

Following the swelling pressure being reached, the vertical load on each specimen was reduced to approximately overburden pressure and the magnitude of resultant heave was observed. For the saline Levels clay, the tests with distilled water showed heave for several weeks, and of magnitude significantly greater than in the test with saline water. It became obvious that salt from the soil was diffusing out of the voids into the initially salt-free water, even though the sample was swelling.

In Table I the column for solute suction shows either 0 for distilled water or the normality of saline water used, chiefly sodium chloride. Test No. 3 was an attempt to examine the consequence of using a very dilute solute, and test No. 10 used a salt concentration of twice that in the soil water.

2.5 Pressure Plate and Vacuum Desiccator Tests

An attempt was made to measure matrix suction using pressure plates set at 1, 4 and 15 bars. These experiments did not lead to reliable results, probably because of lack of good contact with the Visking membrane.

It was attempted to check total suction determinations by placing Levels soil in vacuum desicators at pF 4.0, 4.5 and 5.0, using the null point technique. After 1 - 2 months, psychrometer check tests showed that the soil had reached equilibrium at pF 4.5 and 5.0, but not at pF 4.0, which would have required a moisture increase. It was also found that the moisture content changes for pF 4.5 and 5.0 were too erratic to enable the original soil pF to be determined accurately.

2.6 Solute Suction

Efforts were made to measure solute suction independently. For the Levels clay at 0.9 m, undiluted pore-water extracted by pressure (Section 2.3.1) was found by psychrometer testing to have a pF of 4.62, virtually the same as the total soil suction shown for 0.9 m in Fig. 2. The implication is that matrix suction is very small.

The known concentration of solute salts may also be used to calculate solute suction using vapour pressure tables. The method has been described by Aitchison and Richards (1965). At 0.9 m, Fig. 3 shows that Levels clay has a normality of about 0.9, mostly due to dissolved sodium chloride. The corresponding osmotic pressure calculated from tables is pF 4.61

2.7 Salt Diffusion

When the oedometer tests were found to exhibit long-term heave, additional testing was done on sample 6, table I. The water in the consolidation cell was syphoned out at the end of the test (35 days) and its salinity determined by the A.A.S. method. The specimen itself was tested for total suction in the psychrometer.

It was found that the pF of the specimen had been reduced from 4.37 (2300 kPa) to 3.7 (500 kPa), suggesting that more than 75% of the salt had moved from the soil into the surrounding water.

The measured salinity of the surrounding water confirmed that about 70% of the salts in the soil had indeed diffused into the cell water. The diffusion was not assisted by consolidation at any stage, as the specimen had swelled continuously during the test.

3 ANALYSIS OF RESULTS

Consideration of the experimental results suggests that

(1) The existence of a high total suction is not in itself an indication that a soil is reactive. Tests 8 and 9, Table I, show that Levels clay at 2.65 m has no capacity to swell under overburden pressure despite its pF of 4.25, whereas tests 18 and 19 on O'Halloran Hill clay at 2.75 m indicate a capacity to swell against a vertical pressure of over 150 kPa, despite an initial suction of only pF 4.03.

(2) Comparing pairs of tests, Table I, the swelling pressure appears to be relatively independent of the solute used, but the magnitude of swelling under reduced load is greater for the distilled water test which involves a lowering of solute suction due to ingress of fresh water into the voids, and salt diffusion.

TABLE I - RESULTS OF OEDOMETER SWELLING TESTS

								Heave data			Initial total suction	
Test No.	Location	Depth metres	Initial moisture content, %	Initial dry density grms/ml	Solute used - Normality	Duration of test, days	Swelling pressure, kPa	Field overburden, kPa	Vert. pressure during swelling kPa	% heave	pF	kPa
1	Levels	0.4	30.2	1.49	0 *	44	60 approx.	7	26	3.1%	3.9	800
2	"	0.4	34.4	1.38	.066 N	44	40 approx.	7	26	0.2		
3	"	0.4	34.4	1.42	.0001 N	50	>80	7	26	3.5		
4	"	0.7	36.6	1.33	0	24	40 approx.	10	7	0.5	4.30	2000
5	"	0.7	34.0	1.36	0.67 N	24	20 "	10	7	0.1		
6	"	1.4	22.5	1.63	0	35	>25	27	7	0.6	4.37	2300
7	"	1.4	21.8	1.65	0.8 N	21	21 approx.	27	7	0.1		
8	"	2.65	24.2	1.54	0	13	48 approx.	50		Zero - not reactive	4.25	1750
9	"	2.65	23.5	1.58	0.4 N	13	45 "	50				
10	"	2.65	23.0	1.61	0.8 N	13	45 "	50				
11	O'Halloran Hill	0.5	27.9	1.36	0	16	100 "	10	12	1.4	3.7	500
12	"	0.5	27.1	1.35	0.04 N	16	100 "	10	12	1.4		
13	"	1.3	25.8	1.32	0	21	120 "	25	60	2.0	4.38	2350
14	"	1.3	28.4	1.32	0.166 N	21	100 "	25	60	0.5		
15	"	1.65	30.0	1.33	0	10	>200	33	-	-	4.28	1900
16	"	1.65	31.3	1.35	0.166 N	10	>200	33	-	-		
17	"	2.75	39.9	1.26	0	22	200 "	50	50	3.75	4.03	1050
18	"	2.75	38.0	1.24	0.1 N	22	150 "	50	50	1.0		
19	Urrbrae	0.7	29	1.58	0	10	120 "	13			4.15	1400
20	"	0.7	29	1.52	0.03 N	10	<80	13				
21	"	1.5	30	1.56	0	10	>30	28			4.45	2800
22	"	1.5	30	1.58	0.06 N	10	120?	28				

* 0 indicates distilled water

(3) Comparison of Figs. 2 and 3 suggests that for the Levels soil, the psychrometer was really measuring solute suction. Matrix suction appears to be small.

(4) It cannot be inferred from (3) that matrix suction is low in all reactive soils. For example, in test 18 of Table I, the solute was constant at 0.1 Normal, corresponding to a solute suction of 450 kPa. Hence the matrix suction was initially 600 kPa. It appears that the high swelling pressures in tests 15 - 18 are associated with high initial matrix suctions.

(5) The above suggests that the existence of some matrix suction is essential to initiate swelling. Tests (8) and (9) were on clay close to the ground-water level, and must have had virtually zero matrix suction. The mechanism appears to be that once swelling starts, solute suction changes become significant.

(6) In Table I, the heaves reported for the tests with no solute change are due to matrix suction. The additional heaves in the comarison test with distilled water are due to changes in solute suction.

(7) The separate measurement of matrix suction is a difficult problem. Reactive clays generally have micro-fissures, and matrix suction probably varies greatly from fissures to intact groups of soil particles.

(8) The magnitude of swell in Table I is a function of the quantity of distilled water surrounding the soil. The swell figures in themselves have no absolute value, only comparative. In future work, it appears desirable to measure the pF of soil specimens at the beginning and end of oedometer tests involving swelling.

(9) The salts reported in the pore-water, Fig. 3, are soluble salts and do not take any account of exchangeable salts in the clay particles.

4 RECOMMENDATIONS

(a) Both matrix and solute suction have been shown to be important in reactive clays. In design of footings on such soils, possible variations of both must clearly be allowed for.

(b) It is apparent that in oedometer testing of saline soils, the consequences of any change in solute suction due to salt diffusion must be considered. Current laboratory practice appears to ignore this problem.

5 ACKNOWLEDGEMENT

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