The Effect of Initial Moisture Content and Remoulding on the Shrink-Swell Index, I_{SS}

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Summary The effect of initial moisture content on the measured shrink-swell index, I_{SS}, has been assessed in an experimental study. The aim of the study was to assess the appropriateness of the factor, α, by which the swell strain is divided in the calculation of I_{SS}. The factor, α, is used to correct a measured axial strain for a sample constrained to swell in one dimension, to an equivalent axial strain in a sample allowed to swell simultaneously in all directions. Tests were performed on an idealised soil and remoulded Maryland clay, prepared to a range of different initial moisture contents. They found that, on average, the typically assumed factor of 2 gave reasonably uniform I_{SS} values over the range of moistures typically encountered in natural soils. This was not supported by a simplified theoretical discussion. In addition, the effect of sample loss in swell tests with large strains was assessed and found to be significant. Remoulding of Maryland clay was found to have little effect on the range and magnitude of I_{SS} results, when compared to tests on undisturbed soil samples taken from similar depths.

1. INTRODUCTION

A study was conduced to assess the effect of initial moisture content on the shrink-swell instability index, I_{SS}, as measured in the shrink-swell test. The shrink swell test, described in A.S. 1289.7.1.1–1992, is the most commonly used laboratory test to assess the reactive potential of soil, in Australian geotechnical practice. Large numbers of tests are carried out in areas where geological conditions defy broad scale categorisation and where there is insufficient established development from which to infer the long-term performance characteristics of local designs. Newcastle is one such area. (Fityus and Welbourne, 1996)

The shrink swell test involves the measurement of the axial strain of soil specimens between extreme moisture limits: oven dry and saturation. The resulting instability index, I_{SS}, describes the rate of axial strain per unit change in suction (assumed linear for the purposes of routine design). It is calculated as the ratio of total axial strain and an assumed suction range of 1.8 pF units.

There are inherent problems in the measurement of the axial strain between the above extremes in moisture. Both saturated and oven dry clay samples are difficult to work with. The test standard allows for undisturbed samples to be tested at their field moisture contents, always somewhere between the extreme moisture limits. At these intermediate moisture contents, they have the potential to both shrink and swell. To accommodate this, a pair of samples is used in the test, each involving a separate procedure.

To measure the shrinkage strain component, ε_{sh}, an unloaded core shrinkage test is used. The value obtained is strictly the axial strain component of a sample which is undergoing simultaneous strains in 3-dimensions. It must therefore be less than the volumetric strain.

To measure the swell component, ε_{sw}, a consolidation cell apparatus is used. This apparatus provides rigid lateral confinement to the expanding soil and so, strictly, the measured axial strain is the only strain occurring in the sample, and is equal to the volumetric strain.

Clearly, the strains measured in each component of the test are incompatible. It is obvious that the application of lateral confinement to a swelling soil will produce increased strain in the axial direction. This is accounted for in the calculation of the shrink-swell index, and involves division of the swell strain component by an appropriate factor, α. A factor of 2 is typically adopted for all soils. Thus, the I_{SS} is given by

$$I_{ss} = \frac{\frac{\varepsilon_{sw}}{2} + \varepsilon_{sh}}{1.8} \qquad (1)$$

The specific purpose of this factor is to convert the axial strain measured in a sample swelling in one dimension, to an equivalent axial strain in a sample swelling in three dimensions. The aim of this study was to experimentally assess the suitability of the assumed value of 2, when the relative proportions of shrink and swell strain in a soil varied due to a wide range in the initial moisture contents.

The study was initiated as a final year project in the Department of Civil Engineering and Surveying at the University of Newcastle. A large part of the sample preparation and testing was performed by Mr. Paul Wilson. His diligence and dedication is acknowledged and appreciated.

2. EXPERIMENTAL APPROACH

2.1 Procedural Formulation

The adopted experimental approach involved the testing of a number of similar soil samples from a range of initial moisture contents. Important details of the sample testing procedure are listed and discussed below.

- Number of soils: it was decided that the study should assess the behaviour of two different soil types, to accommodate more generalised conclusions. The two soils chosen include one natural soil, **Maryland clay**, and an **idealised** soil, created in the laboratory from commercially separated sand and clay components
- Range of Initial Moisture Contents: to establish trends with certainty, it was decided that results for at least 6 different initial moisture contents would be necessary, and that these should range from the moisture content at the shrinkage limit up to saturation.
- Sample Preparation: To eliminate possible effects due to natural differences between the composition and structure of undisturbed samples, as well as anisotropy and inhomogeneity within individual samples, the samples used in the study were remoulded from homogenised clay. The methods used are described in sections 2.2 and 2.3.
- Moisture Conditioning: Remoulded soils require compaction to produce samples which are suitable for testing. If the moistures were conditioned prior to compaction, it would be extremely difficult to achieve similar structures and densities in all samples. It was thus decided to compact all test samples at similar moisture contents using a standardised compactive effort, prior to conditioning their moisture contents.

  Homogenised soil, prepared to a moisture just above optimum, was compacted in a 150mm high/ 106mm diameter mould, in 5 equal layers using a standard Proctor hammer. Pairs of samples were taken from each by pressing two 200mm long U50 tubes directly into the mould using a large screw press. The samples were then centred in the tubes using a hydraulic ram, to leave 25 mm of empty tube at either end.

  After calculation of the total final weight corresponding to the desired initial moisture content, the tubed samples were either soaked or oven dried. At the desired weight, the tubes were plugged with styrofoam discs, positioned 5 mm from the ends of the soil, at each end of the tube. Wax seals were then formed on the styrofoam.

  The sealed tubes were stored, in a horizontal position, for a minimum of 8 weeks to allow the moisture throughout the sample to equilibrate. Shrink-swell testing was then performed.
- Test Procedure: The tests were generally carried out according to A.S. 1289.7.1.1 with the following departures.
  1) The ring in the consolidation cell was not fixed to the base. It was positioned between the porous discs so as to allow soil expansion from both its top and its base.
  2) The consolidation ring was not smeared with silicon grease prior to installing the sample.
  It was considered that these departures would not significantly affect the validity of the conclusions drawn from this study.

2.2 Idealised Soil Preparation

It was desired that the idealised soil should have an I_{ss} value of around 5 to 7 %. To this end, the selected component mix was

20 % Stockfeed C.E. grade Bentonite,
40 % Kaolinite and
40 % fine to medium Beach Sand.

The soil was prepared in a single batch, of sufficient quantity to produce all of the required samples. Before moisture conditioning, it was thoroughly blended in a large rotary mixer. Because of size limitations, it was halved prior to wetting and compaction. The average moistures of each half, at compaction, were 25.5% and 27.4% (gravimetric). Compacted dry densities ranged between 1494 and 1552 kg/m^3.

2.3 Maryland Soil Preparation

As suggested by its name, Maryland clay is a heavy clay soil which occurs naturally at the Maryland reactive soils field site near Newcastle. (Allman et al,1994)

While relatively uniform on a large scale, Maryland clay exhibits large structural and compositional variability on the scale of shrink and swell specimens. Localised plant roots and bioturbation, shrinkage cracking (with or without topsoil infilling) and fine to medium gravels all occur to a greater or lesser extent in undisturbed samples.

In order to achieve a soil which would be consistently homogeneous on a test sample scale, the following preparation was performed.

- Soil was collected from depths of 300 to 600 mm at the Maryland field site and returned to the laboratory. There, it was dried in a blow oven at about 250°C until it became non plastic.
- The dried soil was crushed using a Los Angeles abrasion machine.
- The crushed soil was sieved using a 600 µm screen to remove all coarse sands, vegetable matter and gravels.
- The sievings were combined and blended before being halved for wetting and compaction.

Average moisture contents at compaction were 32.5 and 35.4 % and the compacted sample densities ranged between 1331 and 1403 kg/m^3.

2.4 Additional Considerations

In addition, this study was extended to examine an aspect of the shrink-swell test procedure itself. The idea stemmed from the observation that clay often spills from swell specimens which undergo large strains. This is because soil which has expanded out of the swell ring is no longer laterally confined. In some instances, the volume of soil appears large, and could lead to an underestimate of the swell potential. To examine this effect, all tests were performed in duplicate: one set were performed using the **conventional** test apparatus, as described in section 2.1, and one set was performed using a **modified** apparatus in which the consolidation ring was extended to accommodate an expanded volume of soil. The general modified arrangement used is shown in Figure 1.

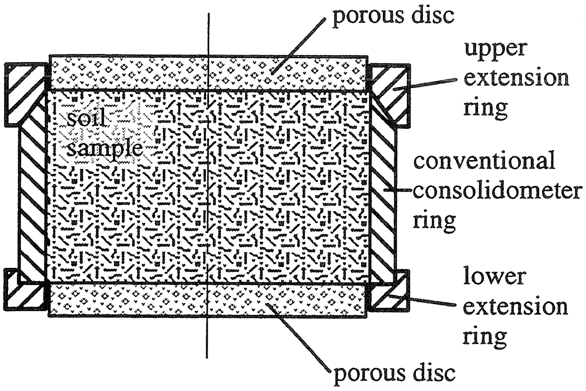

Figure 1. Modified Swell Test Apparatus: section. (not to scale)

3. EXPERIMENTAL FINDINGS

3.1 Method of Comparison

Due to inadequacies in the moisture equilibration procedure, it is not possible to make a direct comparison of the I_{SS} values for each initial moisture content. This is because many of the samples failed to attain a uniform moisture content prior to testing. In some instances, this was due to insufficient equilibration time, in others, it was due to moisture leakage at the wax seals. The net effect in either case was that the moisture contents of the shrink and swell samples were not necessarily identical; differences were as great as 5%. Thus the total of the measured strains in each pair of samples will correspond to greater or lesser total changes in moisture and suction.

The desired assessment is still possible, however, if the results of the shrink and swell tests are considered separately, and their overall trends compared. Thus, in the following presentation of results, two trends are plotted: axial strain of a soil sample shrinking simultaneously in three dimensions, and, axial strain of a soil sample swelling simultaneously in 3 dimensions. The latter is estimated by dividing the measured axial strain of a soil sample constrained to swell in one dimension only, by an α factor of 2, as recommended in the test standard. For the I_{SS} to be independent of initial moisture content using the correction factor of 2, the slopes of the trend lines should be equal but opposite, and the combined trend line should be horizontal.

Also plotted for each soil, are separate trend lines for swell tests using conventional and modified apparatus (refer to section 2.4). Note that the shrinkage test procedures are identical despite differences in the swell test apparatus, and so have not been differentiated.

3.2 Results for the Idealised Soil

Results for the tests performed on the idealised soil samples are shown in Figure 2.

Several important observations can be made from Figure 2. These are

1) The modified apparatus appears to record significantly higher swell strains for samples with initially low moisture contents. This is consistent with the observation of substantial soil losses in drier soil samples during testing with the conventional apparatus.

2) The total strain, taken as the sum of the shrink and corrected swell strains, shows only a very slight decrease with increasing initial moisture content, if the trend given by the modified apparatus is used. This suggests that the factor of 2 used to correct for lateral confinement is an appropriate value, provided that the full one dimensional swell strain is realised. Using the trend given by the conventional apparatus, a significant increase in total strain for higher initial moisture contents would be predicted.

3) The shrinkage limit for the idealised soil is around 14%.

4) The moisture content at the end of the swell test tends to be lower for samples with higher initial moisture contents. In some instances the results were anomalous: in the two tests with the highest initial moisture contents, the final sample moistures were actually found to be lower after the samples had swelled by 2%.

3.3 Results for Remoulded Maryland Clay

Results for the tests performed on remoulded Maryland clay samples are shown in Figure 3.

Important observations include the following:

1) Differences in swell results between the conventional and modified apparatus are smaller for remoulded Maryland soil than for the idealised soil. The swells measured using the conventional apparatus actually appear larger than those measured by the modified apparatus. The apparent difference is likely to result mainly from random differences in sample texture and preparation, and not from an inherent difference in the apparatus, as similar swell strains are measured in samples tested from either extreme moisture content. This result suggests that loss of sample at large swell strains is less of a problem than it was for the idealised soil. It is consistent with the observation of little or no soil loss in any of the remoulded Maryland samples during testing.

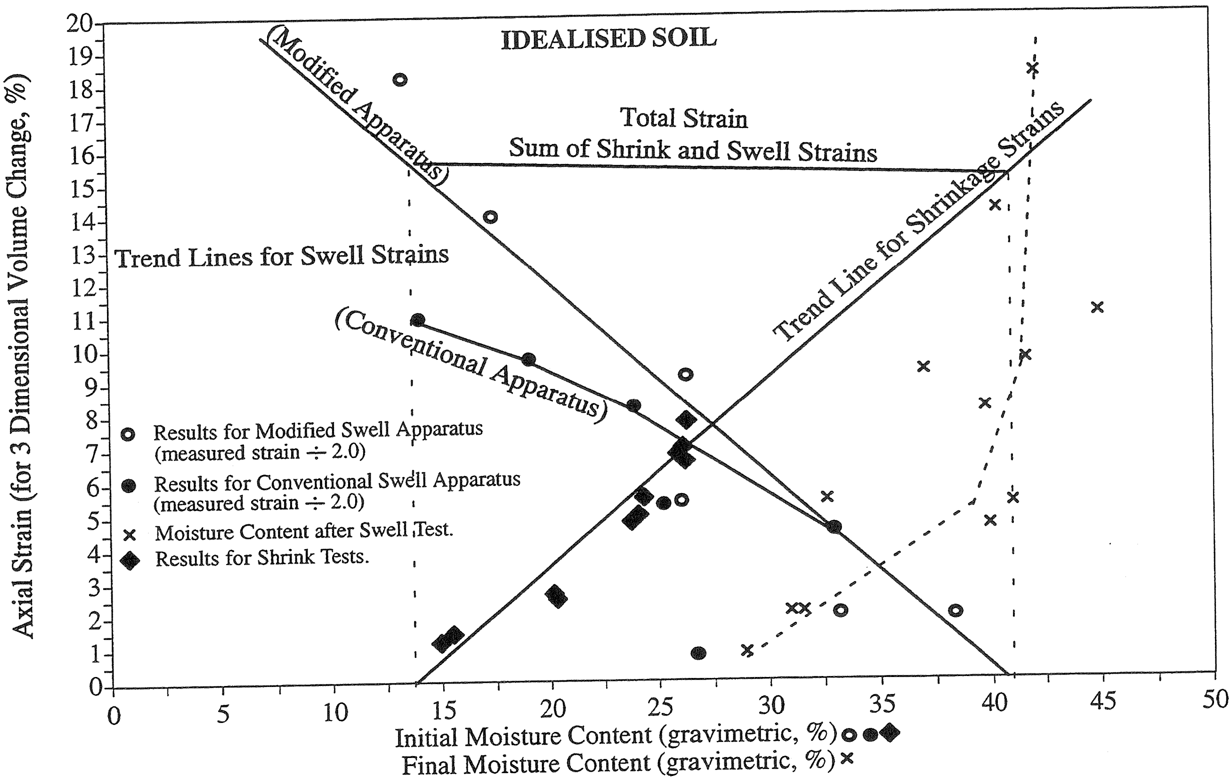

Figure 2. Results for Idealised Soil Samples.

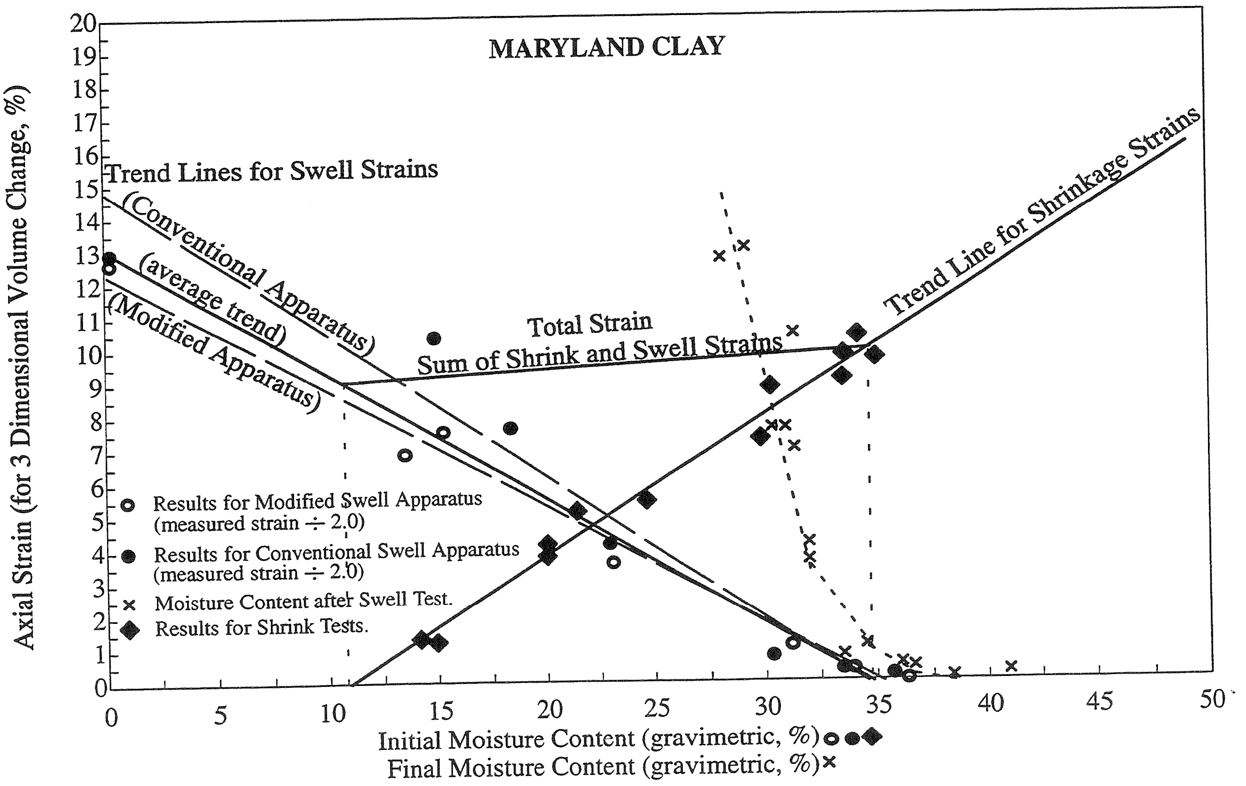

Figure 3. Results for Maryland Clay Samples.

2) The total strain, taken as the sum of the shrink and corrected swell strains, shows only a slight increase with increasing initial moisture content, if the average trend for all swell tests is used. This again suggests that the factor of 2 used to correct for lateral confinement is an appropriate value, when the full one dimensional swell strain is realised. The opposite direction in the slight trend is interesting, and suggests that an α of 2 may be a reasonable value for different soils with various volume change characteristics.

3) The shrinkage limit for remoulded Maryland clay is around 11%. This is in good agreement with results in undisturbed soils. (M. Delaney, pers. comm.)

4) The moisture content at the end of the swell test

tends to be higher for samples with higher initial moisture contents. This is in contrast to the results for the idealised soil.

4. THEORETICAL CONSIDERATIONS

The theoretical value of the factor, α, was considered briefly by Cameron (1989). Cameron quotes a personal communication from Peter Yttrup in which it is suggested that α should take the form of (2) where ε_H and ε_z are the diametral and axial strains and μ is Poissons ratio. Using this expression, Cameron predicted that the value of α should lie between 1.7 and 2.15. The theoretical form of α has been reconsidered here.

$$\alpha = 1 + 2\mu\left[\frac{\varepsilon_H}{\varepsilon_z}\right] \quad (2)$$

The stress-strain behaviour of a swelling clay soil in a confining ring is complicated. It is likely that the true behaviour involves both elastic and plastic phenomena and that the transition occurs at different times in different regions of the sample. A crude theoretical approximation can be obtained if the soil is assumed to be isotropic, and its behaviour, purely elastic. The stresses and strains are assumed to be related by

$$\begin{bmatrix}\varepsilon_z\\ \varepsilon_H\\ \varepsilon_H\end{bmatrix} = \frac{1}{E}\begin{bmatrix}1 & -\mu & -\mu\\ -\mu & 1 & -\mu\\ -\mu & -\mu & 1\end{bmatrix}.\begin{bmatrix}\sigma_z\\ \sigma_H\\ \sigma_H\end{bmatrix} + \begin{bmatrix}\varepsilon_{z.ss}\\ \varepsilon_{H.ss}\\ \varepsilon_{H.ss}\end{bmatrix} \quad (3)$$

where ε_z and ε_H are the net axial and net diametral strain components, $\varepsilon_{z.ss}$ and $\varepsilon_{H.ss}$ are the axial and diametral strain components due to unconfined shrinkage/swell, σ_z and σ_H are the stresses at the sample surfaces and μ and E are the elastic parameters. It can be shown (Peter Kleeman, personal communication) that if $\varepsilon_{z,ss} = \varepsilon_{H,ss}$,

$$\alpha = \frac{\varepsilon_z}{\varepsilon_{z.ss}} = \frac{\sigma_z}{E.\varepsilon_z}\left(1 - \frac{2\mu^2}{(1-\mu)}\right) + 1 + \frac{2\mu}{(1-\mu)}.\left[\frac{\varepsilon_H}{\varepsilon_z}\right] \quad (4)$$

The first term on the right hand side contains the ratio of axial stress to modulus. The axial stress is, by definition, 25 kPa. The modulus is typically of the order of megapascals, even for softened clays at high moistures. Thus, this term is small, typically contributing less than 5 % to the total expression. As a first approximation, it might be neglected leaving only the leftmost two terms, which are of similar form to (2). In the special case of a saturated clay with $\mu = 0.5$, the first term is actually equal to zero, and (4) predicts that α is equal to 3. This result is consistent with expectation for an incompressible elastic solid, where the volumetric strain must be zero. It is interesting to note that equation (2) predicts a value of 2 under the same special conditions.

For Maryland clay at 30% moisture, the reload modulus has been measured at 8Mpa. Ratio of diametral to axial strains were measured for Maryland clays shrinking from a number of initial moisture contents. These are plotted in Figure 4.

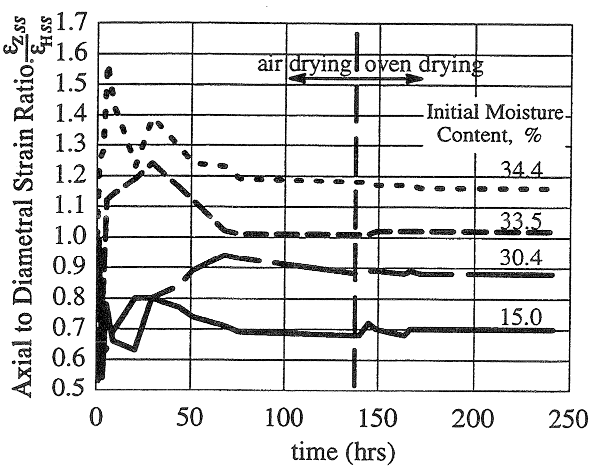

Figure 4. Ratio of axial to diametral strains during shrink tests on Maryland clay.

Using this data, with estimates of Poissons ratio ranging from 0.5 at saturation to 0.3 at the limit of shrinkage, theoretical values of α are found to lie within the range of 2.2 to 2.9.

These results do not agree well with the value of 2 recommended by A.S.1289–7.1.1 or with the experimental findings of this study. It is likely that this is mostly due to the gross simplifications implicit in the formulation of (4).

5. THE EFFECT OF REMOULDING ON THE I_{SS} VALUE

All of the Maryland soil samples tested in this study were remoulded from soils which had been dried, crushed and sieved as described in section 2. The effect of the remoulding process has been assessed by comparing the measured I_{SS} values with I_{SS} values determined for undisturbed samples taken from similar depths at the Maryland field site. The results are presented in Table 1.

Table 1. Comparison of results for undisturbed and remoulded Maryland clays sampled from 0.3–0.6m.

Statistic	n	min. Iss %	max. Iss %	mean Iss %	std. dev. %
Undisturbed Samples.	9	4.6	5.6	5.2	0.38
Remoulded Samples	12	4.5	6.4	5.5	0.66

Range of Field Moisture Contents in Undisturbed Samples:33.2–39%
Range of Initial Moisture Contents in Remoulded Samples:14–38.5%

It is evident from Table 1 that although the results for remoulded samples have a greater spread over a wider range, the effect of remoulding is relatively small. This is particularly surprising when it is considered that the range of initial moisture contents for the remoulded soils was more than 3 times greater than that for the undisturbed samples.

6. DISCUSSION AND CONCLUSIONS

A number of conclusions can be drawn from the results of this study. The most general of these is that reactive clay soils exhibit a variety of behaviours depending upon their mineral constituents and/or their textures. This is evident from the following observations.

- The idealised clay soil and Maryland clay respond differently to lack of confinement at large swell strains. In the case of the idealised soil, lengths of sample which become unconfined due to large swell strains, are prone to spall or collapse. This was observed during testing and reflected in the measured swell strains. The soil loss from the remoulded Maryland swell samples, at similar strains, was negligible. The strong disposition of the idealised soil toward spalling is likely to result from textural deficiencies in its artificially produced particle size grading.
- The idealised soils attain lower saturated moisture contents when swelled from lower initial moisture contents. In contrast, Maryland clay attains higher saturated moisture contents when the initial moisture contents of the swell samples are low.
- It appears that the I_{ss} of the remoulded soil decreases very slightly with increasing initial moisture content, while the I_{ss} of Maryland clay increases very slightly when tested at higher initial moistures.

The implications of this are as follows:

- The appropriate correction factor, α, is likely to be a unique value for different soils. The trends observed in the idealised soil samples suggest that the the factor should be a little lower, say 1.92. From the trends evident in the Maryland clay samples, the factor could perhaps be a little higher, say 2.2. It is thus concluded, based on the results of this study, that the value of 2 is likely to be a reasonable estimate for a range of different clay soils. Using this value, the measured I_{ss} should thus be relatively independent of the initial moisture content of the test sample.
- Loss of sample at large swell strains may result in an underestimation of the I_{ss} for some soil types. In this study, the effect only appeared to be significant in the idealised soil. However, loss of soil from the swell sample has also been observed in a wide range of undisturbed natural soils in local practice. The provision of extended confinement appears to be necessary in these cases to ensure that the full swell strain is realised. This should be considered in the next revision of the test standard.

The simplified theoretical discussion presented in section 4. failed to confirm the experimental findings. Theoretical estimates of 2.2 to 2.9 are likely to reflect the gross simplification implicit in modelling a time dependent, elastoplastic deformation problem as a purely elastic phenomenon. It can be concluded from these results that a simplified isotropic-elastic model is not sufficiently accurate to describe the behaviour of the confined swell test. An elastoplastic finite element analysis would be required to produce more accurate results.

An additional conclusion from the study pertains to the effect of remoulding on the measured I_{ss} value. The I_{ss} values from the remoulded samples were compared with the results of undisturbed samples from the same depth range and found to have only a slightly higher mean and a slightly wider spread. The difference is relatively small when it is considered that the 9 undisturbed test results span a range of initial moisture contents of only 6%, whereas the initial moisture contents of the 12 remoulded results span over 24%. It should also be remembered that the initial moisture contents of the shrink and swell samples of many of the remoulded tests were not identical due to insufficient equilibration time, and that this is likely to affect the spread of results. Indeed, if the average I_{ss} for the remoulded samples is estimated from the average trends in Figure 3, the value is closer to 5.3%; almost the same as the average of the undisturbed samples.

This result suggests that remoulding of samples may have little or no effect on the estimated limit of shrink or the measured I_{ss}. Additional experimental studies are necessary to confirm this as a general rule. Validation of this result would be of great benefit to practitioners in areas such as Newcastle, where soils are frequently gravelly and too friable to be sampled without disturbance.

7. ACKNOWLEDGMENTS

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