A Soil Moisture Based Method of Estimating y_S

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Summary A method is presented which estimates free surface ground movements due to reactive soils using moisture based soil volume change parameters and upper and lower bound design moisture profiles. The volume change index used in this approach relates increments of gravimetric moisture content change to increments of volume change, subject to in situ confining stresses. Upper bound moisture profiles are estimated from laboratory measured moisture contents in samples which are swelled to saturation under a vertical surcharge equivalent to in situ conditions. Lower bound moisture contents, expressed in terms of the limit of shrinkage value, are estimated from statistical soil test data. Predictions for two soils are presented. These are compared with suction based predictions, as well as field surface movement observations. The method is validated using measured moisture profiles predict ground movements which are found to compare well with surface level measurements.

1. INTRODUCTION

Characteristic free surface ground movements are usually calculated by the method outlined in AS2870.1996, Residential Slabs and Footings.

This method calculates volumetric strains as a function of suction changes in a soil, and then integrates these strains with respect to depth, in order to predict ground surface movements. The use of suction change as an independent variable has both advantages and disadvantages.

The advantages arise mainly because the moisture related properties of different clay soils are highly variable, while the suction characteristics are more typically consistent (Walsh, 1998).

In particular, moisture characteristic relationships for clay soils are known to vary greatly (Mualem, 1979). As a result, field saturated soils commonly have gravimetric moisture contents anywhere in the range from 20 to 50% (Welbourne, 1996), whilst the suctions at field saturation are typically close to 3 pF units, regardless of the particular soil. A similar behaviour is noted in clays subject to similar extremes of drying: air dry clays commonly have gravimetric moisture contents anywhere in the range from 5 to 20% (Welbourne, 1996), whilst the suctions at field dry extremes (e g. wilting point) are typically close to 4.2 pF units; again, regardless of the particular soil.

The consistency in suctions arises because the wet and dry soil moisture extremes are mostly controlled by climate, and the climatic potential for soil moisture extraction under both wet and dry climatic conditions is relatively consistent, and largely independent of the soil type. This consistency is relied upon in both the determination of the shrink swell index, I_{SS}, and the estimation of characteristic surface movements, y_S, as described in AS2870.

The disadvantages of using suction change as a variable are due mainly to the degree of difficulty involved in its measurement. The measurement of soil suction is specialised and difficult, and complicated in that there are osmotic and matric components contributing to the total suction. The prediction of ground surface movements other than the characteristic movement, or the confirmation of the suction change assumptions in the calculation of both I_{SS} and y_S, would both require the specific measurement of suctions at a range of different soil moisture contents. This is not an insignificant task.

By contrast, the measurement of gravimetric moisture contents is almost trivial, and so, a moisture content based prediction method has the advantage of being able to predict ground movements due to any changes in moisture content. It also employs moisture based volume change indices which are determined from actual, and not assumed changes in moisture content.

Fityus and Smith (1998) have already demonstrated that, with a suitable moisture based volume change index, accurate ground surface movement predictions can be made based on measured changes in gravimetric moisture content, and that this type of approach is consistent with more rigorous unsaturated soil volume change prediction methods. This approach is well suited to general surface movement predictions where changes in gravimetric moisture content are known. It can be extended to the prediction of the characteristic surface movement, y_S, if the extreme wet and dry gravimetric moisture content profiles at a site are known, or can be reasonably estimated.

This paper describes the method for determining a soil volume change index which can be used to relate moisture content changes to soil volume changes; it presents the indices for two clay soils, and demonstrates the accuracy of predictions made using these values. It also explores a generalised approach to the estimation of extreme wet and dry moisture profiles which can be adopted to facilitate the estimation of the characteristic ground surface movements, and compares estimates with predictions made using the AS2870 approach, and with actual field site measurements.

2. A MOISTURE CONTENT BASED VOLUME CHANGE INDEX

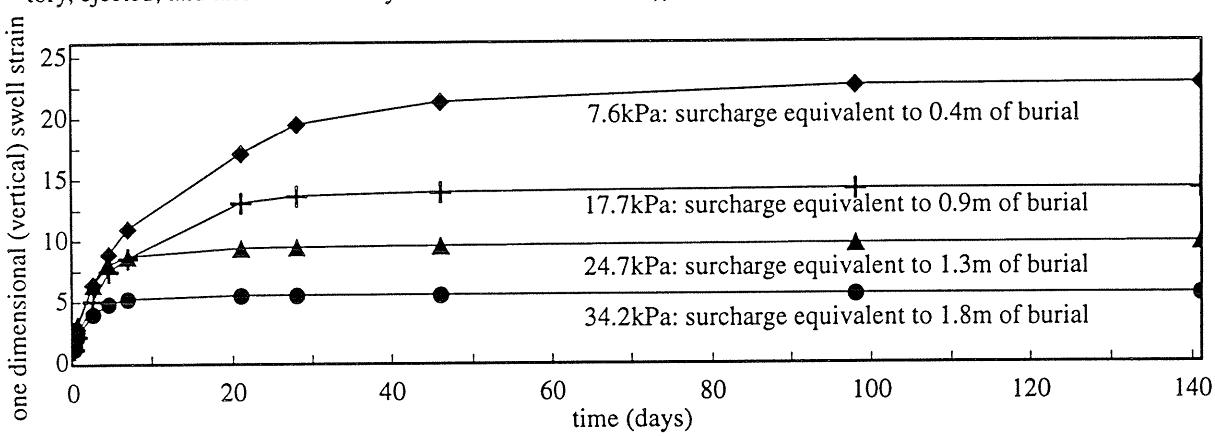
The ground surface movement method used here is described in detail in Fityus and Smith (1998). It employs a load dependent volume change index, I_v, which is found from a series of simple, one dimensional swell tests, in which a clay sample is allowed to swell whilst subjected to a vertical confining stress simulating the vertical stress experienced under natural field conditions. It is determined as follows:

- "undisturbed" samples are collected from appropriate depths using thin walled sample tubes.
- samples are returned immediately to the laboratory, ejected, and allowed to air dry under vertical confining stresses, simulating their in situ burial condition.
- after air drying, the relatively non–plastic samples are pressed into oedometer rings, trimmed, and inundated to swell in an oedometer apparatus, again under vertical confining stresses, simulating their in situ burial condition.

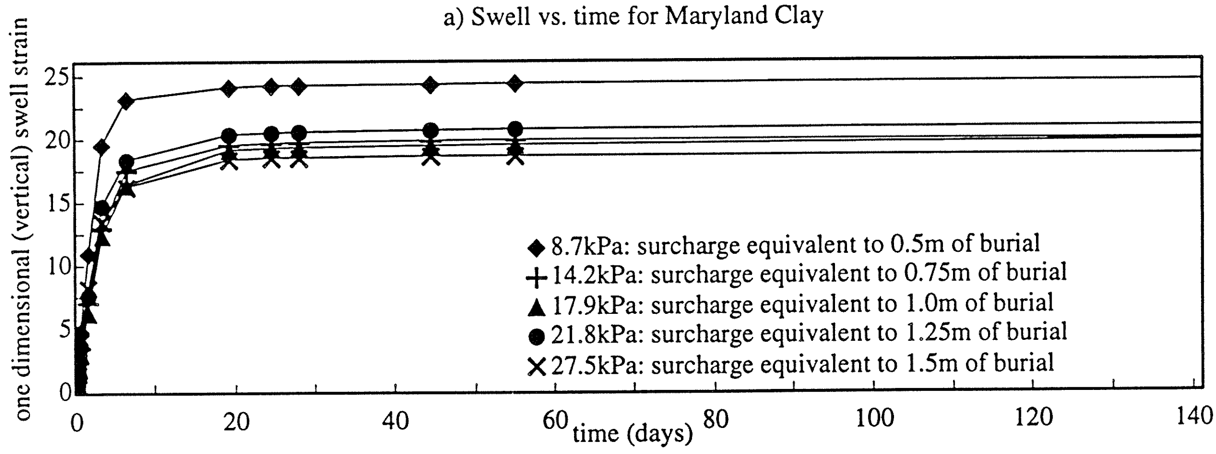
It is important that the odometer ring is fitted with extension rings, as described in Fityus (1996), as swelling takes place from a dry initial condition, causing large swell strains to be realised.

The results of a series of such tests on clay soils from 2 different sites clay, are shown in Figure 1 The clay soils originate from the Maryland and Elermore Vale field sites (Allman et al., 1998, Delaney et al., 1996) They are both of a residual nature, deriving from siltstone and tuffaceous parent rocks, respectively. Figure 1 shows that the swelling behaviour for each soil profile is quite different, both in the magnitude of swell as a function of confinement, and in the rate at which swelling occurs.

From each test, the axial strain in the sample is plotted against its water content, with the slope of the plot defining a value of the I_v index, for the surcharge pressure under which the test was carried out (see Figure 2 a)).

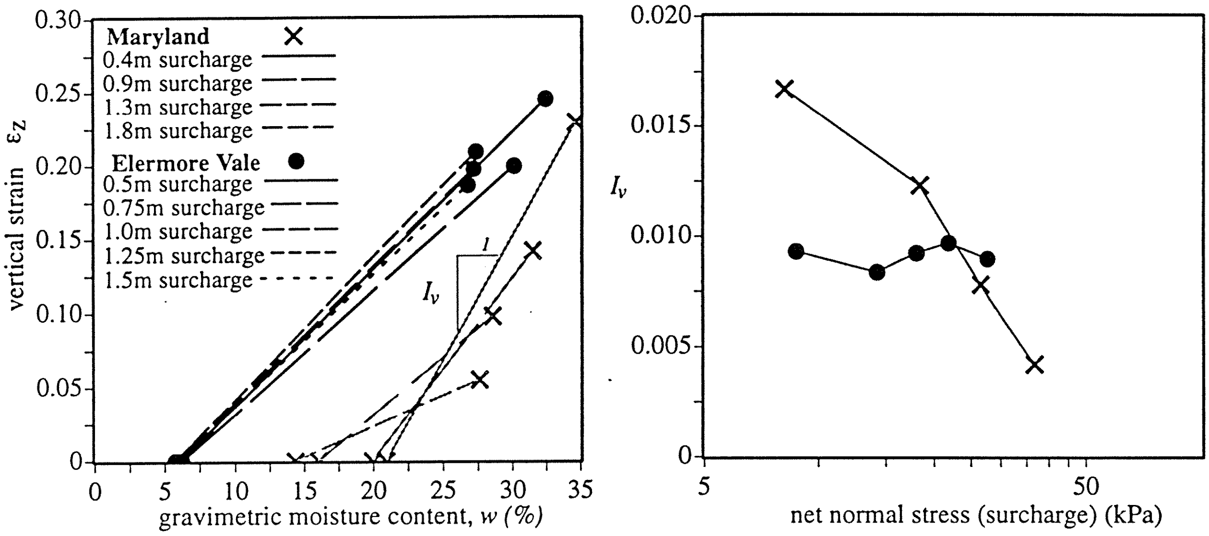


a) Swell vs. time for Maryland Clay



b) Swell vs. time for Elermore Vale clay

Figure 1. One dimensional swelling test results for Maryland and Elermore Vale clays, subject to a range of different surcharge pressures.



a) Vertical strain vs. moisture change for different surcharge loads.

b) volume change index as a function of load.

Figure 2. Determination of the volume change index, I_v, for Maryland clay.

The vertical strain in the sample is defined by

$$vertical\ strain = \varepsilon_z = \frac{\Delta h}{h_o} \quad (1)$$

where Δh and h_o refer to the change in height and initial height of the sample, respectively. The I_v value at pressure p is thus given by

$$I_{v,p} = \frac{\varepsilon_z}{\Delta w} \quad (2)$$

where Δw is the change in water content during swelling. The I_v values determined from the tests in Figure 1 are plotted against the corresponding confining stresses in Figure 2 b).

It is again evident from Figure 2 b) that the physical properties of the two clay soils considered here are significantly different.

3. GROUND SURFACE MOVEMENT PREDICTIONS.

The approach described here has similarities with the approach of Richards (1967) Comparisons were made in Fityus and Smith, (1998). The ground surface movement occurring as the result of changes in water content is calculated according to

$$z_o = \frac{1}{\alpha} \sum_{i=1}^{N} I_v \, (w_{oi} - w_{of}) \, \Delta H_i \quad (3)$$

z_o is the ground surface movement,
w_{oi} is the average initial water content of layer i,
w_{of} is the average final water content of layer i,
ΔH_i is the thickness of layer i,
N is the number of sublayers in the profile, and
α is an empirical factor accounting for stress differences between the laboratory and the field.

An appropriate value of I_v can be interpolated from Figure 2 b).

The approach described here contains a number of important assumptions. Firstly, it is assumed that a given change in water content will always correspond with the same change in strain, regardless of the actual value of water content in the soil. This assumption is justified on theoretical grounds in Fityus and Smith (1998).

Secondly, it is assumed that an expansion index determined from swelling clay tests can be employed to predict both swelling and shrinking phenomena in wetting and drying soils, respectively. Whilst hysteresis effects in expansive clay soils are not insignificant, they remain difficult to quantify accurately. In this work, it is assumed that the loss in accuracy from the omission of hysteresis effects is justified by the overall simplifications it brings to the approach. The merit of this assumption can be assessed by considering the results provided here.

Thirdly, it is assumed that the difference between one and three dimensional volume changes can be reasonably accommodated using a factor (α; see Equation (3)) of one third. The premise is, that subject to lateral confinement, a swelling soil will realise the same net volume increase as an unconfined soil, for a given change in water content. If this is so, it follows that a laterally confined soil element must swell 3 times as much in the vertical direction to accommodate the total volume change.

In these analyses, the one third reduction will be applied to both shrink and swell predictions, effectively assuming that the soil is always cracked. While this differs from the assumptions used in some areas of existing reactive soils practice, its merit here can be assessed from the results in the following section. Ongoing research is attempting to resolve this issue further.

4. VALIDATION OF THE METHOD.

In this study, to enable the accuracy of the method to be assessed, measured gravimetric field moisture content profiles are employed to predict surface movements, which are then compared with corresponding field level measurements. This has been done for the two soils discussed in Section 2. The results are presented in Figure 3 and Figure 4.

Figures 3 and 4 demonstrate that the moisture based ground surface movement prediction method described above, is capable of making relatively accurate estimates of ground movements, when reliable ground moisture data are available. The predictions are typically within 5mm of observation, and commonly within 2mm, at most depths within the soil profile.

It is interesting to note that this method of prediction seems to work equally well for both wetting and drying events, despite the volume change index being determined from swell test results only.

It is also interesting to note that these predictions include the one third factor of Equation (3) in all calculations, regardless of the moisture content or the movement direction of the moisture. Thus, on the basis of the limited applications presented here, the method appears to give reliable predictions, without taking specific account of soil cracking.

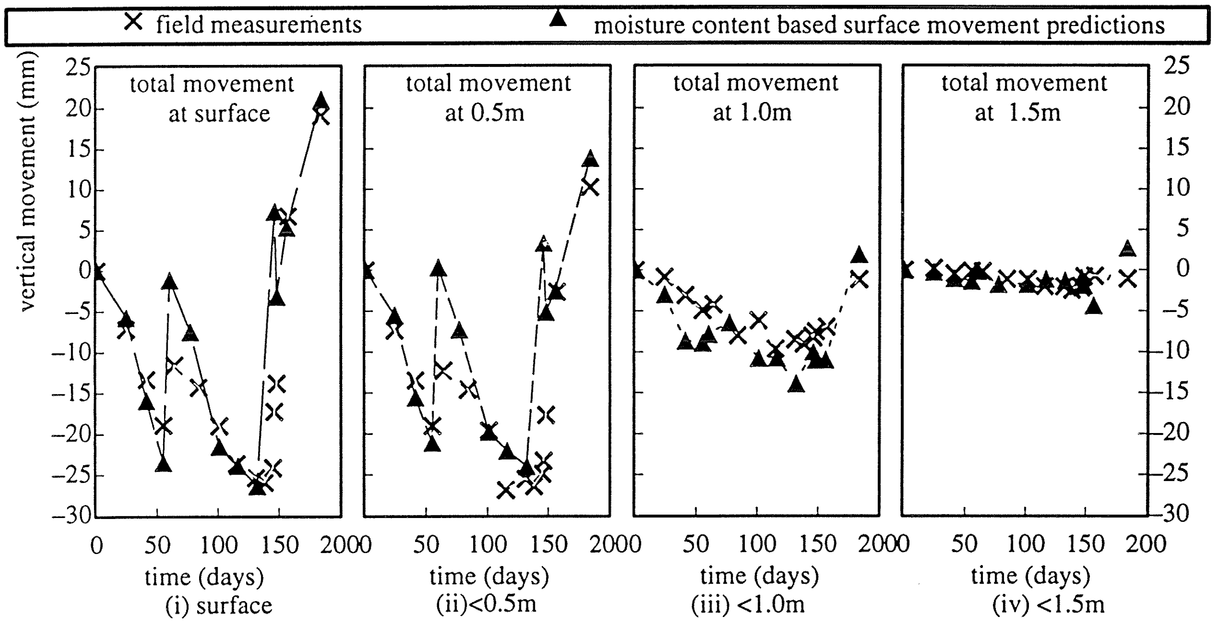


Figure 3. Comparison of surface movement observations and moisture based predictions at the Maryland field site.

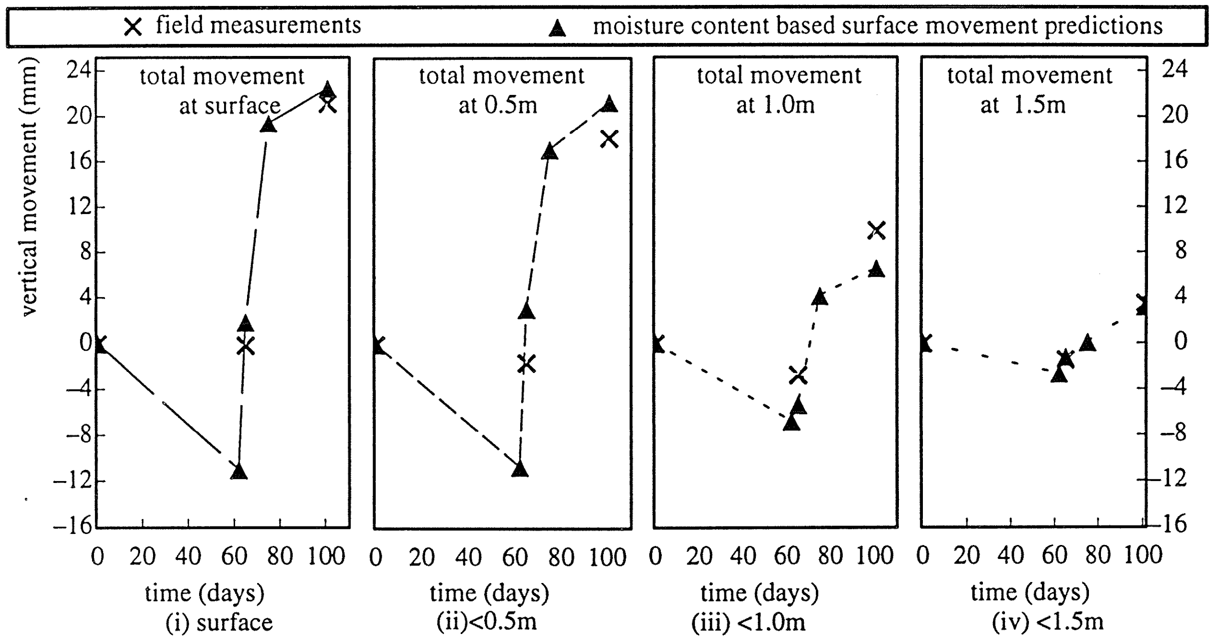


Figure 4. Comparison of surface movement observations and moisture based predictions at the Elermore Vale field site.

5. A LOWER BOUND MOISTURE PROFILE FOR PREDICTION OF y_s

Definition of a suitable lower bound moisture condition poses the greatest difficulty in the application of the above ground surface movement prediction method to the estimation of y_s.

One means of dealing with this is to establish, in a general way, a relationship between a readily and repeatably measurable soil moisture parameter, and the minimum field dry moisture content of the soil. This approach has been adopted here.

The adopted approach has been formulated on the premise that the minimum field moisture content of a clay soil will be, in some definable way, related to other dry soil parameters. One possible parameter is the air–dry moisture content. Whilst this would seem reasonable, it would require a extensive amount of soil testing and data collation to establish the relationship. Such data, or relevant previous study, are unknown.

An alternative is to consider the shrinkage limit as a possible related parameter. This quantity is indirectly determined during a standard shrink-swell test, and is recorded in test results by many consultants, either numerically, or graphically. Welbourne (1996), in his collation of a database of 902 shrink-swell results from soils in the Newcastle region, recorded both field, and estimated shrinkage limit moisture contents, for 773 samples. The tests were performed over a period of about 14 years. Unfortunately, it is impossible to determine precisely which of these samples were at their minimum field moisture contents at the time of testing.

It is reasonable to assume, however, that at least some of the samples were at their minimum field moisture contents. It follows that these samples should have the lowest (i e. lower bound) ratios of field moisture to shrinkage limit moisture contents. It is also considered reasonable to expect that the minimum field moisture content will be a function of depth, with deeper clays being somewhat protected from surface wetting and drying by shallower soils. A lower bound ratio of field moisture content to shrinkage limit moisture contents was thus obtained by plotting this ratio against sample depth, for the available 773 data values. The results are shown in Figure 5.

Figure 5 suggests that the lower bound ratio is around 1.3, down to a depth of around 1.2m, and that below this, the ratio decreases, although the trends below 1.5m are speculative due to a scarcity of data. The relatively small number of data points which appear to lie below the strong lower bound trend, as shown in Figure 5, are attributed either to anomalous soils or more likely, to poor measurements/determinations of one or both of the moisture contents used in calculating the ratio.

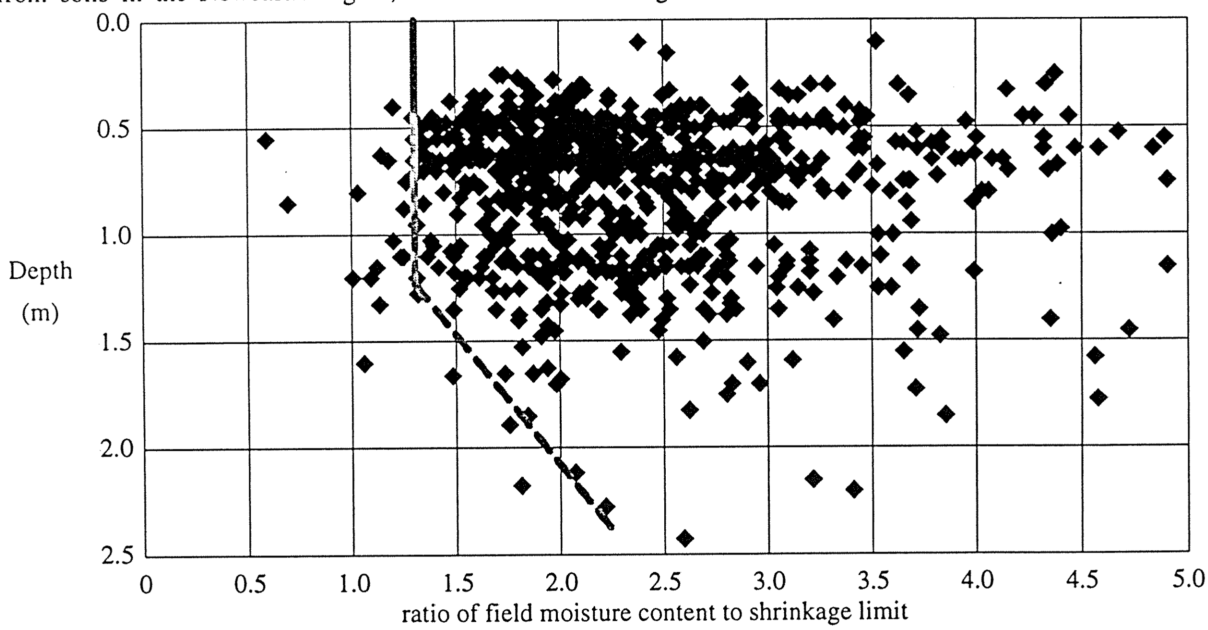


Figure 5. Plot of the ratio of field moisture content to shrinkage limit vs. depth for 773 clay samples.

This data set was used as a basis for estimating lower bound field moisture profiles. The procedure to estimate the field dry moisture content of a clay soil at a particular depth would thus involve multiplying the shrinkage limit moisture content of the soil by an appropriate factor, taken from Figure 5 (1.3, for depths less than 1.2m). The shrinkage limit moisture content can be determined from a core shrinkage test of a sample taken from an appropriate level in the soil profile.

6. AN UPPER BOUND MOISTURE PROFILE FOR PREDICTION OF y_s

Definition of an upper bound moisture profile for use in the prediction of y_s is more straight forward. It is considered reasonable to assume that, even in drier climates, the wettest soil profiles will occur at a time when there is an excess of water available to enter the ground. It is thus likely that, under the wettest conditions, the ground will be effectively saturated, at least in the upper levels.

This assumption can be qualified by accounting for the fact that the moisture content at saturation will be a function of both soil type and surcharge pressure (depth). Unlike field dry conditions, field saturated conditions can be reasonably simulated in the laboratory. Surcharge effects due to depth of burial can be easily included, and the effects of spatially varying soil type can be included by testing a number of samples from appropriate depths. In fact, this is already done in the determination of the load dependent volume change index, I_V, described in Section 2.

Thus, the field saturated moisture contents, and hence upper bound moisture profiles, can be estimated from the final moisture contents of the samples tested to determine I_V.

7. A DESIGN MOISTURE CHANGE PROFILE FOR PREDICTION OF y_s

Sections 5. and 6. discuss upper and lower bound moisture content profiles which can be employed in the calculation of y_S. When appropriate measured soil test data is employed in this approach, it becomes obvious that the upper and lower bound moistures do not coincide at the prescribed maximum depth of moisture change, H_S. This is clearly unacceptable. It is apparent that clays at deeper levels are protected from the climatic extremes experienced by the soils which overly them. Some insight into accounting for these effects can be gained from field observations.

Unpublished observations from the Maryland field study site, suggest that the rate of moisture flux through a field soil layer is profoundly controlled by the presence of shrinkage cracking. Where shrinkage cracks exist, the soils dry rapidly toward their dry extremes, and wet rapidly toward field saturation. Below the depth of cracking, the changes in moisture are much slower, and much less extreme.

Using these observations as a guide, the design moisture profiles are modified as follows:

- The design lower bound moisture content profile will be taken as 1.3 times the shrinkage limit, down to the design depth of cracking.
- The design upper bound moisture content profile will be based on the values measured in the determination of the volume change indices, down to the design depth of cracking.
- Each of the above moisture content profiles is assumed to vary approximately linearly below the depth of cracking, so that a common value is reached at the design depth of moisture content, H_S.

The value of the moisture content at depth H_S is not important, as the volume change prediction depends only on the change in moisture content, and not on the absolute magnitudes.

8. RESULTS AND DISCUSSION

Characteristic ground surface movement predictions have been made for the Maryland and Elermore Vale field sites. Predictions were made using both the moisture content change method described above, and the conventional suction change based approach, in strict accordance with the guidelines of AS2870.1996.

The upper and lower bound design moisture content profiles used in this exercise are shown in Figure 6.

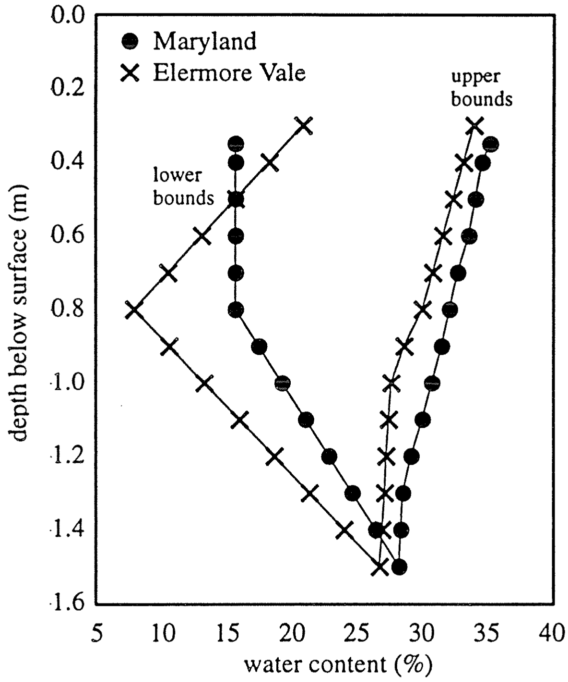


Figure 6. Design moisture content profiles.

Note that the predicted moisture change is far from being linearly varying with depth.

The AS2870 based y_S values used in this comparison were taken from the data of the reactive soils research project at Newcastle University. The Maryland y_S value is calculated using a shrink-swell index profile based on 12 shrink swell tests, on samples from depths of up to 2m. The Elermore Vale value is taken from Delaney et al. (1996).

To enable the relative accuracy of the different prediction methods to be assessed, ground surface levels, monitored over a 5 year period at each site, are used. The results are presented in Table 1.

The results of Table 1 suggest that the moisture based method gives consistently higher estimates of y_S than the conventional suction change model of AS2870. In making comparisons with the measured ground movements it should be remembered that wet and dry climatic extremes of appreciable significance have occurred during the period of monitoring. It is thought that these extremes are less than those which would correspond to the definition of y_S, but that the differential movements experienced to date should represent the major proportion of the true characteristic surface movement.

Table 1. Comparison of predictions with field observations.

	Maryland	Elermore Vale
Moisture content based y_s prediction	63	49
AS2870.1996 (suction) based y_s prediction	41	43
Maximum ground movement at field site	49 (a) 58 (b) 47–75(c)	37

(a) movement at the site control marker
(b) average movement for all surface markers
(c) range of movement values

From Table 1, the AS2870 predictions can be seen to vary widely when compared with the field measurements. Whilst the Elermore Vale site may yet realise another 5mm of movement, the Maryland predictions are obviously inaccurate, having already been exceeded by at least 8mm. Recent work by Fityus, Walsh and Kleeman (1998) suggests that a design depth of suction change of up to 1.7m might be adopted for the Maryland and Elermore Vale field sites, based on assessment of the climate aridity indicator, the Thornthwaite Moisture Index. It is expected that adoption of this value would see a significant increase predictions based on the I_{ss} shrink-swell index.

The moisture based ground movement estimates are 5 and 12mm higher than the field measured values, respectively. While it is conceivable that this additional movement may yet be realised, it is more likely that the moisture based method is, to some extent, overpredicting the vertical movement. Nevertheless, the Maryland moisture based prediction compares favourably with the average of the measured site movements, of 58mm.

The moisture based movement prediction method was shown to be relatively accurate for known changes in gravimetric moisture content. If the moisture based method is over predicting in the estimation of y_s, then it is likely to be due mainly to shortcomings in the prediction method for the lower bound design moisture profile. The values used to define the upper bound design profile are considered rational and likely to constitute a good approximation.

A comparison of the design lower bound moisture contents and the lowest of the gravimetric moistures measured at Maryland suggests that, in this case, the lower bound design profile could be an under prediction by as much as 2 or 3 percent (gravimetric moisture content). Additional research is required in this area.

9. CONCLUSIONS

On the basis of the preliminary studies presented here, it appears that a movement prediction method based on gravimetric moisture content change can be used to make relatively accurate surface movement predictions, if reliable moisture content profiles are available.

The approach can be extended to the prediction of the characteristic surface movement, y_s. While estimates using the approach outlined in this paper appear at least as reliable as those using the approach of AS2870, further work is still required to refine the method.

10. ACKNOWLEDGMENTS

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