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Shrink-swell prediction using the water balance method

Gareth E. Swarbrick
University of NSW, Australia

ABSTRACT: Some possible inconsistencies within AS2870 are discussed with particular reference to the measurement of soil suction. An alternative design method is proposed which provides a means of predicting seasonal fluctuations in soil suction in response to climatic changes. An example is given which shows good agreement between observed and predicted. The benefits of the method include the incorporation of site specific factors such as slope and soil type, and the ability to incorporate risk assessment in the design.

1. INTRODUCTION

The tendency for clays to exhibit shrink-swell behaviour is a major cause of damage to engineering works. Jones and Holtz (1973) estimated that in 1973 the US suffered \$2.3 (US) billion dollars in damages to buildings, roads and services due to expansive soils. This figure had grown to \$6 (US) billion by 1985 (Koerner and Robins (1986)).

The phenomenon is not only costly but is widespread within Australia as well as other parts of the World. Most states in Australia have areas of expansive soils which require costly foundation and/or structural design. The widespread existence of expansive soils in Australia has resulted in the development of some of the most advanced design methods in the world.

1.1. Current emphasis

Since the development of the Residential Slabs and Footings Australian Standard in 1986 - AS2870 (SAA (1986)), the use of the instability index coupled with changes in suction has become the standard means of predicting maximum surface movements. The AS2870 recognises the need for the determination of two important aspects for surface movement calculation (AS2870 appendix D):

i) The determination of the shrink-swell response due to changes in soil suction
ii) The determination of the soil suction response to seasonal moisture changes

The first of these aspects has received much attention and discussion (eg Cameron and Walsh (1984); Coffeys (1985); Chen (1988)) with the almost exclusive use of the instability index being the preferred approach. Subsequently the use of the instability index has become widespread with three alternative methods for its determination:

- The core shrinkage index
- The loaded shrinkage index
- The shrink-swell index

The first two of these methods require measurement of soil suction on the sample, thereby correctly determining the change in soil suction of the sample during the test. The third method simply assumes a value of 1.8 pF to be the soil suction difference imposed upon the sample during the test. To the authors best knowledge, the third method is by far the most commonly used approach within Australia.

The second most important aspect (ii) stressed within AS2870 is knowledge of the soil suction response due to seasonal moisture changes. AS2870 recommends that: "The design suction profile for the determination of y_S [maximum surface movement] should be related to local experimental data to give the characteristic wet and dry profiles." However, recommended maximum soil suction changes are given for certain locations, thus eliminating the need for determining suction profiles. Additionally, one of these recommended values is often adopted for other locations as a substitute, without undertaking any soil suction measurements. The value given for Sydney, for example, is often adopted for Newcastle.

The conclusion to be made from the above two paragraphs is that in general, the measurement of soil suction for the purposes of surface movement prediction is avoided. This is despite the importance of soil suction being stressed throughout AS2870 and by most researchers. It is also noted that usual method adopted for determining the instability index assumes a pF change over the test of 1.8, regardless of test location. However, the standard suggests a maximum change in suction of only 1.5 over the life of the structure which does vary with location.

1.2. Risk assessment

It is noted by the author that current trends within geotechnical engineering (and elsewhere) are calling for the determination of risk associated with a given design procedure. At present there is limited provision within AS2870 for such assessment. The design method mentions that the adopted value for maximum change in pF should have a 95% chance of occurrence during the life of the structure. As little or no measurement of soil suction changes are undertaken, determination of this level of risk seems questionable.

2. WATER BALANCE METHOD

In order to address some of the possible shortcomings of AS2870 as it is currently applied, the author proposes the use of the water balance method to predict seasonal moisture content fluctuations and hence soil suction changes. The method has the advantage of incorporating readily available climate data for the prediction of suction changes. This allows the incorporation of well established methods of risk assessment associated with climatic events. In addition, other site specific data relevant to surface movement can be accounted for such as soil type and slope.

It is important to recognise that the water balance method is a very simplistic representation of moisture movement. The method has been adopted because of the need to maintain accuracy over long periods (usually a year). The use of "more accurate" finite difference or analytical methods to model moisture movement suffer from drift when applied for long periods. Having said this, however, the water balance method also suffers from the same problems if the adopted time step is not representative of the time duration being modelled.

Water balance methods (or rational methods) have long been recognised as a useful method for modelling hydrological processes (Domenico and Schwartz (1990)). The almost exclusive use of the water balance method in the area of leachate quantity estimation is another example of its successful application (Schroeder *et al.* (1983); Baldi *et al.* (1991)). For these applications a time step of one month is usually adopted. This period appears to give the best results over a simulation period of one year and is recommended for the method given here.

2.1. Measurement of suction

In addition to the prediction of soil suction changes, the author also suggests the use of the filter paper method for predicting the suction change during the shrink-swell test. The filter paper method, as opposed to the psychrometer and vacuum desiccator methods, is quick and inexpensive (see Hamblin (1981); Chandler and Gutierrez (1986); Richards and Peter (1987); Chandler and Crilly (1992)).

The water balance method provides a value for the change in moisture over time. This change needs to be converted to a change in soil suction using a relationship between soil suction and moisture content. As it is generally accepted that the relationship between pF (logarithm of soil suction) and water content is linear, only one or two measurements of soil suction are needed to establish such a relationship (Coffeys (1985); Chen (1988)). The measurement of soil suction during the shrink-swell test would therefore provide the data required for this relationship.

3. PROPOSED METHOD

The main assumptions adopted for the method are as follows:

- Moisture loss/gain is one dimensional
- The region of moisture storage used for the water balance method is equal to the depth of the active zone
- There is no moisture movement across the lower boundary of the storage region
- Runoff can be reliably estimated using runoff coefficients
- The actual storage within the active zone is not required to calculate moisture losses for the period.

The last assumption is extremely important. Essentially it means that a continuous record of the storage within the storage region is not required. This minimises the effect of drift upon the accuracy of the method. On the other hand, it also means that the methods by which some factors are calculated (eg evaporation and infiltration) is restricted.

3.1. Climate input

The model uses readily available rainfall, temperature and radiation data as the basic climate input. Actual evaporation, E, is calculated using the Turc equation (Baldi *et al.* (1991)). This method has the advantage that knowledge of the current moisture content within the active zone is not required. Another method based upon pan evaporation suggested by Cheremisinoff and Gigliello (1983) was trialed for similar reasons. However, the method was proven to be unsuitable.

The Turc formula is not based upon pan evaporation like many evaporation models. Therefore it does not suffer from the same criticisms of pan evaporation figures. The basic equation is of the form:

$$E_{10} = \frac{P_{10} + a}{\sqrt{1 + \frac{P_{10}+a}{L}}} \qquad 1$$

where E_{10} is the actual evaporation over a 10 day period, P_{10} is the rainfall over that period and a is the maximum evaporation from the soil with no rainfall over that 10 days (varies from 1 to 10 mm). Monthly values must be obtained by averaging summating the evaporation over three 10 day periods.

L is the heliothermic factor which can be found from mean monthly temperatures (°C), T, and the mean monthly solar radiation, I_g, (cal/cm^2 per day) such that:

$$L = \frac{T + 2\sqrt{I_g}}{16} \qquad 2$$

The parameter a is semi-empirical in nature and varies with location. For Australian conditions a value of 10 mm should be adopted. For most locations throughout Australia temperature and solar radiation are readily available. Where they are not, data must be taken from the nearest weather station or estimated from contour maps.

3.2. Runoff coefficient

The use of runoff coefficients, although questionable, allow a reliable and robust means of estimating infiltration. Additionally they generally do not require knowledge of the moisture content within the storage region. Care must be taken to choose the most important factors from the endless variety available when choosing a runoff coefficient. It is recommended that slope, soil type and vegetation be accounted for in the proposed model.

An example set of data is given in Table 1. Note that runoff coefficients, R_C, are often quoted with flood estimation in mind. While conservative for their intended use they underestimate infiltration. Therefore the source of runoff coefficients should be carefully considered.

Table 1. Runoff coefficients (Canziani and Cossu (1989))

Soil cover	Slope (%)	Soil texture		
		Sandy loam	Loamy clay	Clay
Grassed soil	0-5	0.10	0.30	0.40
	5-10	0.16	0.36	0.55
	10-30	0.22	0.42	0.60
Bare soil	0-5	0.30	0.50	0.60
	5-10	0.40	0.60	0.70
	10-30	0.52	0.72	0.82

3.3. Moisture change

The change in storage, ΔS, within the active zone, H, is simply calculated using:

$$\Delta S = P(1 - R_c) - E \qquad 3$$

The associated change in moisture content on a volumetric basis is found by dividing ΔS by the active depth, H. By assuming an average constant void ratio, the change in gravimetric water content can be obtained from:

$$\Delta w = \frac{(1+e)\Delta S}{G_s H} \qquad 4$$

3.4. Change in soil suction

Once the change in moisture has been obtained the corresponding change in soil suction needs to be determined. Essentially this requires knowledge of the moisture retention relationship, ie the dependence of soil suction, u, upon moisture content, w. Here a common assumption that the relationship between moisture content and pF (log of u) is linear. Ideally this relationship should be obtained for the soil type in question. This may be achieved during the oedometer test, for example. If such data is not available, published data is required.

In general it is the soil science discipline that has produced the most data on moisture retention relationships. Examples of well known tables are Clapp and Hornberger (1978); Bumb *et al.* (1992). Interpretation of these data sets, however, is often difficult due to the different soil classifications and fitting functions used.

As the relationship between pF and w is linear, ΔpF may be obtained by multiplying Δw by the slope of this line, k, where:

$$pF = a + kw \qquad 5$$

The predicted soil suction changes are *average* changes for the active zone. This differs from AS2870 where the distribution is assumed to be triangular. Therefore, the predicted value of ΔpF is *constant with depth* and roughly half the surface suction as given by AS2870. Combining equations 3 to 5, the value of ΔpF is given by:

$$\Delta pF = \frac{k(1+e)\left[P(1-R_c) - E\right]}{G_s H} \qquad 6$$

3.5. Surface movements

Once the soil suction changes have been predicted surface movements are calculated as per AS1289 using the instability index, I_{pt}. However, a further improvement of accuracy can be obtained by measuring the sample suction during determination of the I_{pt} value. Doing so achieves two things:

- the actual suction change imposed upon the sample is measured
- the linear relationship between pF and moisture content may be determined

Although often criticised, filter papers are an inexpensive, quick and accurate means of measuring either total or matric soil suction.

4. APPLICATION

To date the method has been applied to Blacktown, Moree and Newcastle soils with pleasing results. Only one example from Moree is presented here due to space limitations. The Moree case is particularly interesting due to several factors. Firstly the area is notorious for large seasonal surface movements. Secondly there is a well maintained ground monitoring station. Thirdly there is limited data concerning the maximum seasonal soil suction changes within the area.

From the local topography, vegetation and soil type at the ground monitoring station, an assumed runoff coefficient of 0.5, a measured average void ratio of 0.72 and an assumed soil particle density of 2.7 were obtained. Local knowledge of Moree suggests the active depth to be 1m. Published data by Clapp and Hornberger (1978) was used to assume a value for k of 53.4 (w expressed as a fraction). Substituting these values into Equation 6 gives:

$$\Delta pF = 0.034\left[\tfrac{1}{2}P - E\right] \qquad 7$$

The above parameters, together with locally available climate data, was used to produce Table 2 using Equation 7. The predicted change in surface movement, Δy_{pred}, was obtained using the method given in AS2870 ie:

$$\Delta y_{pred} = \frac{1}{100}\int (\alpha I_{pt}\Delta pF)dz \qquad 8$$

The measured average I_{pt} value for the area was 4.16 and the depth of the cracked zone was assumed to be 0.75 m.

Table 2. Predicted movements (mm)

Date	Rain, P	Evap, E	ΔpF	Δy_{pred}
May 88	21.8	21.2	-0.350	-17.6
June 88	76.6	27.2	0.377	18.9
July 88	63.8	33.5	-0.054	-2.7
Aug 88	64.6	29.9	0.082	4.1
Sept 88	18.6	22.2	-0.439	-22.0
Oct 88	8.4	20.0	-0.537	-27.0
Nov 88	62.6	32.9	-0.054	-2.7
Dec 88	75.2	37.1	0.017	0.9
Jan 89	34.6	27.5	-0.347	-17.4
Feb 89	0.2	17.5	-0.592	-29.7
Mar 89	176.4	51.4	1.251	62.8

Up till now all calculations have proceeded without requiring a continuous record of the soil moisture within the active zone. The relative surface movements can be found by summating these values. They can then be directly compared with observed movements as given in Table 3 and shown in Figure 1.

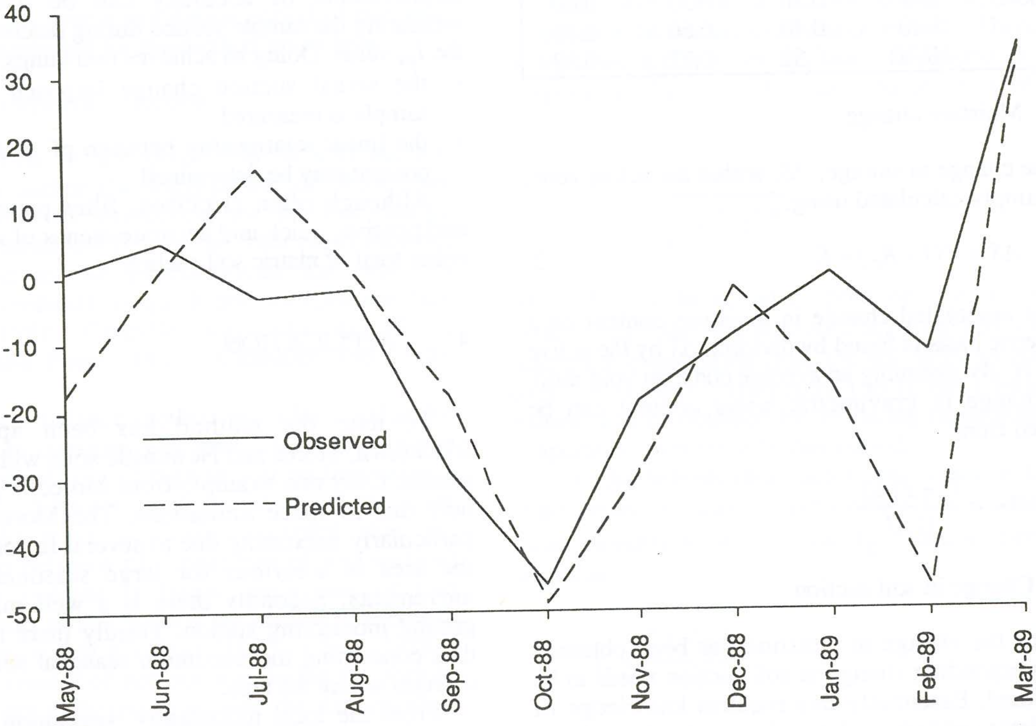

Figure 1. Comparison between observed and predicted surface movements

Table 3. Observed vs predicted (mm)

Date	Δy_{obs}	Δy_{pred}	y_{obs}	y_{pred}
May 88	1	-17.6	1	-17.6
June 88	4	18.9	5	1.3
July 88	-7	-2.7	-3	16.2
Aug 88	5	4.1	-2	1.4
Sept 88	-34	-22.0	-29	-17.9
Oct 88	-12	-27.0	-46	-49.0
Nov 88	-7	-2.7	-19	-29.7
Dec 88	-2	0.9	-9	-1.9
Jan 89	2	-17.4	0	-16.5
Feb 89	-14	-29.7	-12	-47.1
Mar 89	48	62.8	34	33.1
Maximum movement			80	82.1

As mentioned, other sites in Moree were modelled, all with similar agreement. In addition, Blacktown soils have been modelled and compared to the data from the ground monitoring station at Quakers Hill. Currently the applicability of Newcastle soils to this method is being investigated.

4.1. Discussion

The data presented appears to provide a means by which shrink-swell behaviour may be predicted using climate data. As a result, the model can be used to predict surface movements according to a given level of risk associated with a particular climatic event. This enables greater flexibility during design.

The predicted maximum surface movement corresponds to an average ΔpF of 1.635. Translating an average distribution to triangular one (as per AS2870), this corresponds to surface suction change of 3.27 pF (twice the average). Considering that the highest pF change advocated by the AS2870 is 1.5, it would be unlikely that such a large value would be used in the absence of measured data. However, comparison between predicted and observed suggests that this value of ΔpF is very close to the true value.

Although the correlation between observed and predicted is not perfect, the extreme conditions appear to be modelled fairly well. This indicates that although accuracy on a month to month basis may be questionable, overall annual prediction is quite acceptable. The annual maximum difference is, of course, the most important parameter to be obtained from the prediction.

There are several steps taken in the model to alleviate the problem of drift. Even so the use of this model for longer periods than one year is questionable. Therefore a single yearly climatic record corresponding to a desired recurrence interval should be adopted.

The effect of the depth of the active zone has not been included here. This parameter will also have a significant impact upon the models performance. More research is needed in order to assess this impact.

5. CONCLUSIONS

The use of the water balance method provides a consistent and rational means for relating surface movements to climatic events. The chosen time-step of 1 month appears to provide meaningful results. The assumptions made also appear to have been reasonable. Given the very simplistic nature of the method the apparent correlation is very encouraging.

The method provides a means by which climatic events according to a given recurrence interval may be used. This provides a means of prediction according to a given level of risk.

Other important site specific information has been accounted for in the model including soil slope, soil type and climatic factors. This appears to allow good prediction when compared to actual performance. It may also help towards explaining some of the spatial differences in surface movement over some areas.

The method also provides a means by which soil suctions may be predicted. This is very useful for areas where no existing data is present.

Disadvantages of the method include:

- The need to measure soil suction to achieve the full benefits of the method
- Potentially unacceptable drift over long periods (greater than 1 year)
- No allowance for sub surface drainage or three dimensional effects

5.1. Future work

Further work needs to be undertaken in order to test model consistency and applicability. A comparison is currently being undertaken for the Newcastle area and other areas will also be investigated. The question of seasonal drift within the model should also be addressed. This is hampered by the fact that many ground monitoring stations do not have the necessary continuous records (greater than 2 years) for model verification.

Other future work should include more accurate determination of the active depth and investigation into which factors affecting differences in spacial distribution.

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