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The Use of Engineering Index Correlations with the Shrink-Swell Test

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ABSTRACT

Expansive soils are a very common in many parts of the world and are often a direct cause of damage to housing, through their tendency to undergo significant volumetric change in reaction to changes in moisture content. The shrink-swell test (AS1289.7.1.1-2003) has become a widely adopted laboratory test in Australia for estimating the degree of reactivity of an in-situ soil due to its simplicity, low cost and ability to generate relatively reliable data which is independent of soil suction and initial water content. Anecdotal reports indicate that it has become increasingly common to use engineering index properties such as the Liquid Limit (LL), Plasticity Index (PI) and Linear Shrinkage (LS) in place of a shrink-swell test, with the results being correlated to a Shrink-Swell Index (I_{ss}) value, using a variety of published correlations. This is typically occurring both in response to cost and time pressures placed on the geotechnical consultant, as well as in certain situations where an undisturbed sample (required for the shrink-swell test) is not able to be obtained in the field. However, the use of such correlations without regard for the context in which they were developed, together with conservative interpretation, can have a significant effect on the resulting site classification and construction cost. This paper examines and discusses the use of these correlations in Australian geotechnical consulting practice within the context of site classification to AS2870-2011. It is demonstrated that using a non-geologically specific correlation between I_{ss} and engineering index in the calculation of ground surface movement and subsequent site classification is not able to be achieved without an unacceptable likelihood of significant error and adverse cost implications.

Keywords: expansive soils, engineering index properties, Atterberg limits, site classification, AS2870

1 INTRODUCTION

Reactive soils are one of the most common causes of damage to engineering works and residential structures in the world, with projected costs of remediation in the billions of dollars annually (eg. Zhao et al. 2013). Reactive soils, commonly known as expansive soils or swelling clays, are clay soils that exhibit significant volumetric change in response to a change in moisture content. This extreme volume change in response to moisture content variation is typically attributable to a high proportion of certain types of clay minerals present, such as those of the smectite group that produce this effect in the soil (e.g. Fityus et al., 2005, Johnston et al., 2015).

While the damage due to reactive soils has long been recognised, the history of treating or designing for the movements of reactive soils in Australia is relatively recent. The first Australian Standard to provide methods of estimating and designing for the effects of reactive soils was issued as recently as 1986 (AS2870-1986, Residential Slabs and Footings). Preliminary experimental methods to quantify expansive soil movements due to reactive clays specific to Australia and subsequently used in AS2870 are detailed in Cameron and Walsh (1984). In that study, several test methods were used to derive an “instability” index, used as a quantitative measure of a soil’s expansive potential, for input into the calculation of the free surface movement due to reactive soils expected at a particular site. Of these early test methods, the shrink-swell test has been most widely adopted as a measure of soil reactivity due to its relative simplicity and cost effectiveness as much as for the quality of data that is able to be obtained (Johnston et al. 2015, Fityus et al. 2005).

The current version of Australian Standard 2870 (Standards Australia, 2011) allows for design according to a site classification. Site Classification is based on an estimated characteristic surface movement (y_s) which assesses the reactivity of the soil profile. Methods to assess instability index that are currently permissible by AS2870 include direct laboratory tests (such as the shrink swell test), correlations between the instability index and other clay index tests for the soil type (with which this paper deals) or visual-tactile identification of the soil by an engineer or engineering geologist having appropriate expertise and local experience.

It is generally considered that the visual-tactile method is appropriate for simple geological situations, however when the visual-tactle method is applied in complex geological sequences, it is highly unreliable (Fityus and Delaney, 1995; Jayasekera and Mohajerani, 2003). However, estimations of shrink-swell potential via the results of engineering index property tests are considered by some consulting geotechnical engineers to be useful for estimation of instability index (Mitchell and Avalle 1984, Davenport 2007).

Engineering index property tests, for the most part, are able to adequately characterise soils for use in geotechnical works and enjoy widespread acceptance within the geotechnical community for this purpose. However while these engineering index tests are able to provide a general indication of the degree of reactivity, there is a view that they are able to provide quantitative data for direct use in the classification of residential building sites in accordance with AS2870-2011 without significant risk or conservatism. This paper tests this view.

2 REVIEW OF CURRENT CORRELATIONS

Eleven consultancies, predominantly practicing in NSW, were contacted regarding relationships between the shrink-swell index and engineering index properties. Typical published correlations between shrink-swell index and LS, PI and LL currently in general use by consulting geotechnical engineers in Australia are those presented by Cameron, and Walsh, (1984); Earl, (2005); Reynolds, (2013) and Davenport, (2007). These correlations, together with a number of other studies that have been reported in the literature, are presented in Table 1. The table also summarises the number of data used in the development of the correlation and the region from where the data was derived.

Table 1. Correlations Analysed and Used in this Study

Correlation	PI	LL	LS	Geological Origin
Cameron (1989)	0	0	55	Nonspecific Geological Formations Throughout Australia
Davenport (2007)	64	0	0	Various formations (Guildford formation, Darling Range Region, Goldfields Region, Wheatbelt region, Southwest Region), WA.
Delaney (2005)	43	42	44	Nonspecific Geological Formations, Sydney Basin, NSW
Earl (2005)	29	29	29	Quaternary basalt, Shepparton Formation, Vic
Jaska (1997)	0	4	0	Geological Formations Throughout Metropolitan Adelaide, SA.
Jayasekera (2003)	9	9	0	Remoulded Basaltic Clay of Unknown Origin
Reynolds (2013)	66	63	65	Nonspecific Geological Formations, Queensland
Seo and Mersne (2014)	0	37	32	Various formations throughout Brisbane (Ipswitch), Qld
Zou (2015)	44	44	44	Geological formations Throughout Metropolitan Melbourne, Vic
Total	255	228	269	

In analysing the above correlations and accompanying literature, it was found that while index property tests generally show a visual correlation with shrink-swell index, significant uncertainty is associated with the correlation relationships for all correlations with large data, with coefficient of correlation (r^2) values ranging from 21% (Delaney, 2005, PI vs. Iss) to 65% (Zou, 2015, LL vs Iss). No study reported a consistent, viable correlation for shrink-swell index with any single engineering index property test for natural soils that could be used without likelihood of significant error.

The geologically-specific correlations contained in Zou (2015) and Davenport (2007) in some cases showed a decrease in uncertainty in the correlation compared to other methods. Importantly though, these methods still result in correlations between engineering index properties and the shrink-swell index that cannot be utilised with sufficient confidence that a reliable prediction of instability index can be achieved. It was also noted during the literature review that despite a common view that a geologically-specific correlation improved the reliability of estimated ground movements (e.g. Davenport (2007), the most commonly referenced correlation by the consultants contacted was the

Australia-wide correlation provided by Cameron (1989), and subsequently reproduced in Fityus (2005), that did not limit the scope of the study to any regional geological formation or soil type.

3 EVALUATION OF CORRELATIONS WITH ENGINEERING INDEX PROPERTIES

In response to the above review findings, an evaluation of correlations between I_{ss} and the three commonly adopted engineering index properties (LS, PI and PI) was undertaken. Despite the commonly-held belief that geologically-specific correlations are likely to be more reliable, there is also a general principle that more statistically-reliable correlations can be established for larger data sets. To evaluate the potential for reliable index-based predictions, three general non-regional and non-geology-specific correlations have been generated based on the data contained in all the studies referenced in Table 1. The combined data are presented in Figure 1, Figure 2 and Figure 3 with the best fit linear regression lines and the 10th and 90th percentiles shown.

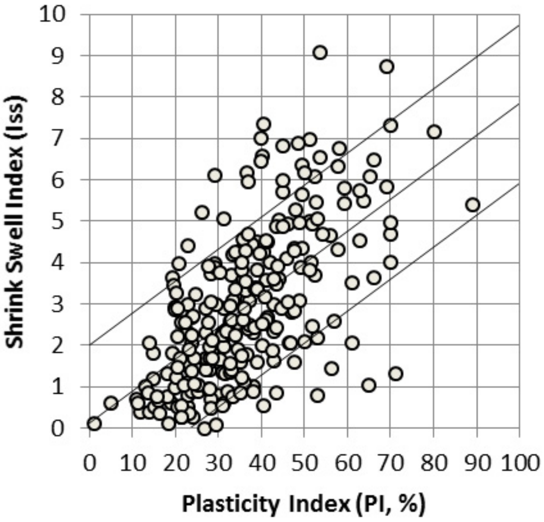

Figure 1. Shrink-swell index (I_{ss}) vs. Plasticity Index (PI)

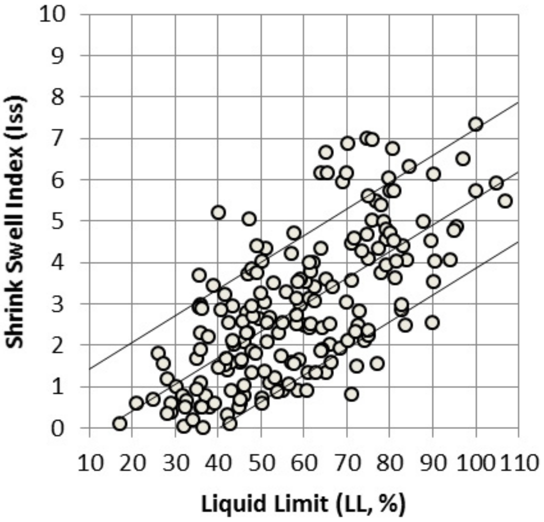

Figure 2. Shrink-swell index (I_{ss}) vs. Liquid Limit (LL)

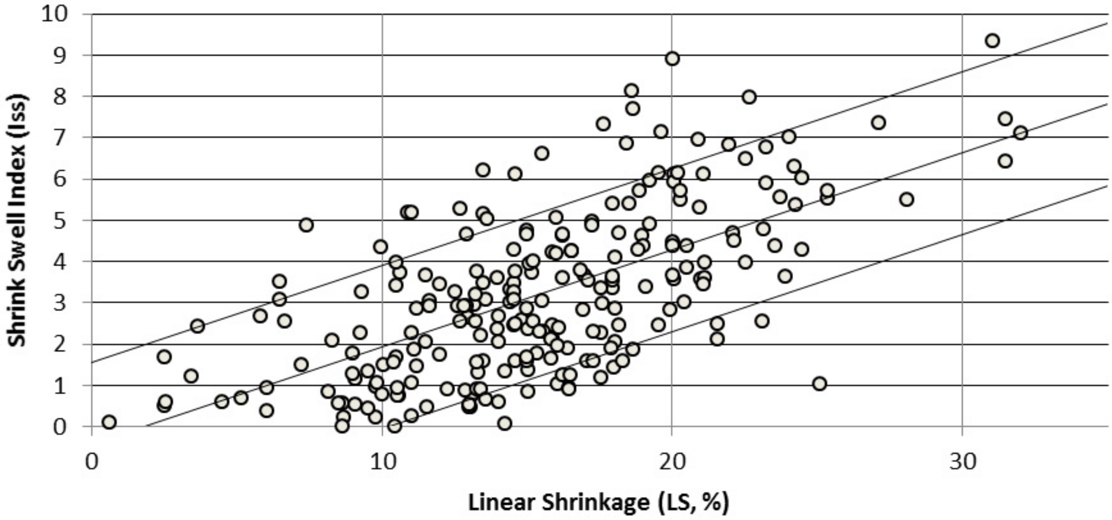

Figure 3. Shrink-swell index (I_{ss}) vs. Linear Shrinkage (LS)

General equations for each of the three engineering index property tests and the shrink-swell index for the data shown in Figures 1 to 3 are given below in Equations 1, 2 and 3.

$I_{ss} = 0.0774 \times PI + 0.1041$ $R^2 = 0.3733$ $N = 255$ (1)

$I_{ss} = 0.0538 \times LL - 0.0248$ $R^2 = 0.3353$ $N = 228$ (2)

$I_{ss} = 0.2382 \times LS - 0.4493$ $R^2 = 0.4121$ $N = 269$ (3)

Where:

I_{ss} = Shrink-swell Index;
PI = Plasticity Index;
LL= Liquid Limit;
LS = Linear Shrinkage; and
N is number of data used.

As can be seen from the correlations for each engineering index property test, a visual trend is indicated in each figure, implying a valid and expected general correlation between each engineering index property and shrink-swell index. However there is significant variation in the data, which can produce errors in the assessment of shrink-swell index (or instability index).

To quantify the nature of the possible error associated with each correlation, and to assess if any one index is able to give a more reliable correlation than the others, the possible cumulative error associated with each correlation is plotted against its likelihood of occurrence in Figure 4. Similarly, an example case in which the full range of I_{ss} values and their likelihood of occurrence has been normalised to a total range of 1.0%strain/pF is presented in Figure 5.

Figures 4 and 5 indicate that the reliability of correlations based on any of three commonly adopted indices is approximately the same. For example, regardless of the index correlation used, there is only an 82-85% chance that the predicted value of I_{ss} will be within a range of 2 I_{ss} units of the actual value of I_{ss}, either positively or negatively. This can be seen clearly in Figure 5 which shows that approximately 80% of the probable values lie over approximately 55% of the total range of values for each correlation.

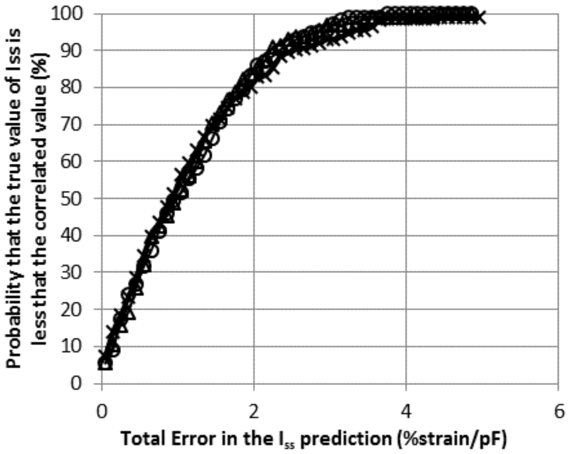

Figure 4. Error in the Prediction of the Shrink-swell index (I_{ss})

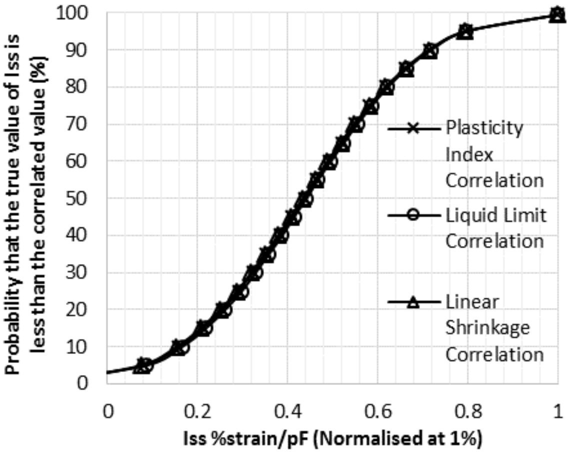

Figure 5. Probability that the actual value of Shrink-swell index (I_{ss}) is obtained

4 SIGNIFICANCE FOR GROUND MOVEMENT PREDICTION AND SITE CLASSIFICATION

Using the developed engineering index correlations, an attempt has been made to quantify the magnitude of the error implicit in each correlation in practice, and show the effect using the correlations has on a typical site classification.

An example relationship showing potential effect of the error implicit in the use of the developed correlations is shown in Figure 6. For the purposes of illustration, the relationship used was normalised around predicted values of 1%, 3% and 5%strain/pF. The site classification ranges have been based on the predicted ground movement calculated in accordance with AS2870 assuming a depth of suction change of 1.8m, a crack depth of 0.9m, and a uniform clay profile.

From Figure 6 it can be seen that the range of possible site classifications resulting from a single engineering index test are large. It can be observed that the “middle value” correlation for 3.0%strain/pF returns the potential for the full range of possible reactive site classifications (from Class S to Class E), indicating that a large amount of uncertainty exists in the developed correlations. Whilst the range of possible site classifications is large for the 3%strain/pF case, it can be seen that the most likely site classification (with a probability of occurrence of approximately 30% each), was Class M and Class H1.

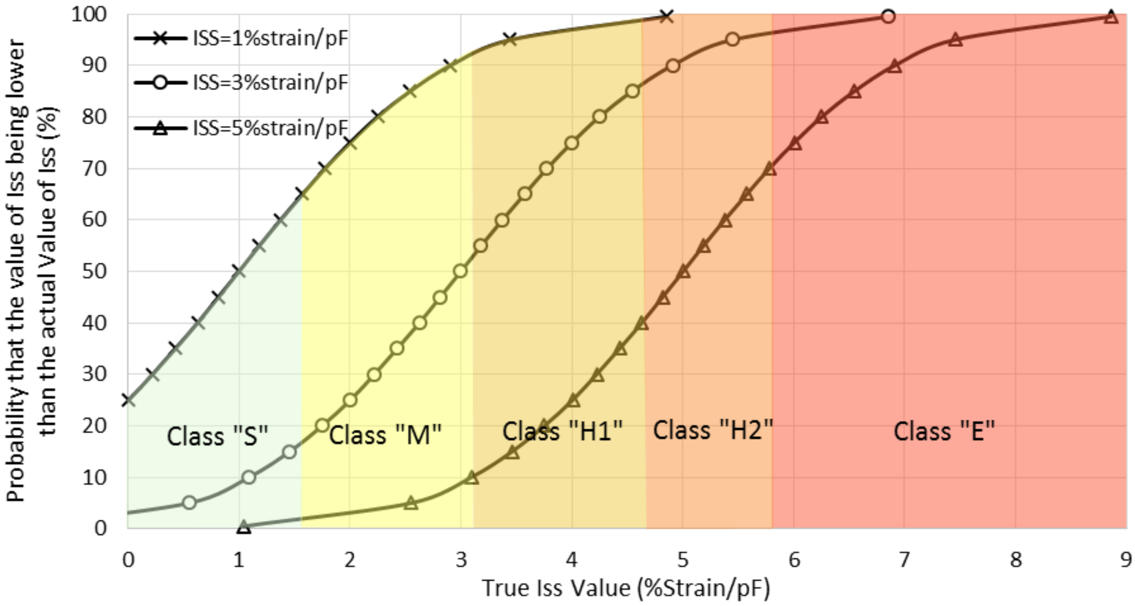

Figure 6. Probability that the Correlated Value of I_{ss} is lower than the Actual Value of I_{ss}

Interestingly, at the lower end value of 1%strain/pF, there is a greater potential of a particular site classification (in this case an approximate 65% chance of Class S) due to the lower bound of the correlation returning a negative (and therefore 0%strain/pF) result.

5 DISCUSSION AND CONCLUSION

As can be seen from Figure 5, it was found that an estimation of shrink swell index using any of the three developed correlations was extremely similar (generally with a final difference of less than 0.1%strain/pF in practice). However the error in the various engineering index properties is large and the correlation coefficient for each index method is relatively low. As displayed in Figure 6, the use of these correlations with any percentile greater than 70% results in an increase in predicted site classification for the examples given. A typical confidence limit of 90% results in a site classification of between one and two classes higher than what the mean value of shrink swell index would give.

There are good reasons why an accurate correlation between I_{ss} and indices based on engineering index properties may not achievable. To a large extent, the Plastic Limit, Liquid Limit and Linear Shrinkage limit can be generally correlated to the clay content in the sample. Generally, the higher the clay content, the higher the plastic and liquid limit values will be. While clay content undoubtedly contributes to the overall reactivity of a soil, the degree of reactivity is heavily dependent on the clay soil's specific minerology. A clay soil that has a relatively high proportion of kaolinite in its makeup may hardly swell at all, while a clay with a relatively small proportion of smectite may be highly reactive. Both soils may exhibit similar plastic and liquid limits due to the trade-off between proportion and type of clay in the samples.

Another reason that there may not be a reliable correlation of shrink-swell index to any engineering index property test is due to the nature of the laboratory tests themselves. A shrink-swell test is performed on an "undisturbed" specimen of soil from a site. While there is invariably some measure of sample disturbance from driving a sampling tube and then extruding the sample prior to testing, the sample still retains most of the soil structure and fabric throughout the testing regime. In contrast, all engineering index property tests are completed on a screened and remoulded soil specimen, where no trace of the original soil fabric or structure remains. Johnston et al. (2015) found that even when all other variables were controlled, altering or remoulding the structure of a clay specimen resulted in significantly higher reactivity when tested over its undisturbed counterpart.

In addition to the complete destruction of the soil structure, the sample preparation for all engineering index property tests assessed in this paper requires the removal of all soil particles greater than 425μm, which in cases of gravelly or sandy clays, means that significant inert material is removed from the soil, greatly affecting its reactivity when compared to its in-situ state. Removal of inert material in performing index tests is likely to concentrate the amount of the remaining clay material, and hence, will tend to indicate higher reactive potential. The significance of destroying the soil's fabric is much harder to evaluate, and it is uncertain as to whether a soil in its remoulded condition will consistently reflect greater or reduced reactivity. Regardless of this, Figures 4 and 5 seem to indicate that there is roughly equal likelihood that predictions made using any index value assessed in this study will overestimate or underestimate the true value by the same amount.

In considering the above, it must be remembered that, implicit in this assessment and any correlation that is produced, there is an assumption that both the shrink-swell test and its corresponding index test were correctly carried out and that the results obtained are fully valid for that particular soil unit. Invariably, the standard and quality of laboratory testing varies between laboratories, and so it is likely that, for at least some of the data, either the I_{ss}, or its corresponding index value (or both) are not truly representative of the material tested. Unfortunately, the assumption is unavoidable, as it is not possible to verify the integrity of the data from many sources quoted for this work.

The use of a correlation between I_{ss} and engineering index in the assessment of site classification is not able to be achieved without an unacceptable likelihood of error. This has large ramifications for residential construction cost. Conversely the repair costs for damage to a building for an under-designed residential structure, such as the repair of cracked/warped slabs/walls and other structural elements, would likely be greater than the initial construction cost of the foundation system. Considering the cost of a shrink/swell test is relatively minor and comparable to that of an Atterberg Limit test suite (approximately $150 / test AUD, 2016 dollars), the economics of carrying out Atterberg Limit testing instead of Shrink-swell index testing is questionable.

Whilst in some situations, such as a particularly hard, dry soil where an undisturbed sample cannot be obtained, the general correlations defined herein (Figures 1 to 3) may prove useful to provide a 'somewhat informed' design value. However for general use they are a poor and demonstrably unreliable substitute for the shrink-swell test. Utilisation of the developed correlations requires significant consideration be given to the risk level a geotechnical consultant is prepared to accept, and the large increase in foundation cost associated with unnecessary increases in resulting site classification.

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