Variability in soil properties and its consequences for design

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Variability in soil properties and its consequences for design

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ABSTRACT: It has been observed that when samples from one particular layer of one particular test pit are analysed by different laboratories the results may vary over an alarmingly large range. Jakobsz and Day (2007) suggested that materials testing laboratories may be slipshod in their testing procedures. There is no doubt that in some cases testing is not done as rigorously as it should be, but this does not appear to explain the size of discrepancies in all cases. Badenhorst et al (2015) suggested that differences in methods of preparation between laboratories may be a significant cause. Preparation can certainly lead to significant differences (Blight 2012, Stott and Theron 2015a), but will also not convincingly explain some of the discrepancies.

Many soil properties are intimately linked to suction (water retention) potential. A procedure for assessing suction potential of soil samples with very little preparation and minimal disturbance to micro-structure was described by Stott and Thereon (2015b). This technique allows reasonably rapid testing of a number of samples simultaneously with almost no variation in preparation or testing procedure. Tests performed on a range of soils suggest that some show very small variability, whereas others show extremely large difference in suction potential over a very small spatial range. It seems possible that inconsistent results from testing laboratories could be an indication that some soils cannot be reliably assessed with some of the popular procedures of current practice. A reappraisal of design philosophy may need to be considered in some cases, particularly in the case of expansive clays.

1 INTRODUCTION

The variability of soil properties has been noted by many observers, e.g. Singh and Lee (1970), Phoon and Kulhawy (1999). There appears to have been relatively little heed paid to this observation by many practicing engineers. Little attention is usually drawn to it in tertiary level geotechnical engineering courses. Little attention is drawn to it in many well-known soil mechanics text books. “Craig’s Soil Mechanics” mentions variability in three places, Das makes no mention of variability in either “Principles of Geotechnical Engineering” or “Advanced Soil Mechanics”. Fredlund and Rehardjo mention it once in “Soil Mechanics for Unsaturated Soils” and once in “Unsaturated Soil Mechanics in Engineering Practice”. Blight’s “Unsaturated Soil Mechanics in Geotechnical Practice” is one of few texts which not only stress the existence of variability but also point out the dangers of ignoring it.

Perhaps, therefore, it is not surprising that it is common practice, at least in the case of normal “bread and butter” engineering projects, to send one sample from each distinct horizon from a test pit to one laboratory for the performance of one set of a very limited selection of standard tests

There have been clear indications that this method of working may be inadequate. Jakobsz (2013) described a situation resulting from this procedure at an electricity substation. Samples from a test pit were sent to a reputable laboratory where several of the usual TMH tests were performed. Results indicated that the soil was not seriously expansive and no major precautions were taken against heave in the foundation design. Significant heave damage did, however, occur – very shortly after completion of the project. Stott and Theron (2016) noted a case where samples from a housing development were analysed by the commonly termed “foundation indicator” tests from TMH1 (CSIR 1986). These tests indicated no risk of heave and the foundations and superstructures were designed accordingly. Heave did, in fact occur, and one house became structurally unsound and had to be demolished before its construction was even completed.

It is widely suspected that a prime cause of this situation is that engineering materials laboratories may be slipshod in their testing procedures e.g. Jakobsz and Day (2008). It has also been suggested that the tests may be critically dependent on details of sample preparation, which vary between laboratories (Badenhorst et al. (2015), Stott and Theron (2015a). The warning of intrinsic variability noted by, for example, Phoon (2008), however, suggests that it may rather be the normal practice of reliance on a single set of tests from each horizon which could be unsound.

It is almost certain that the main reason for relying on only one test is the expense of multiple testing. This paper outlines an investigation to assess the intrinsic variability of soils which requires relatively little time and input of skilled labour and little increase in these inputs for obtaining a significant number of results. It may therefore have the potential for indicating intrinsic variability in an economically feasible way.

2 TESTING OF SOILS FOR TYPICAL SOUTHERN AFRICAN PROJECTS

The majority of soils tests in Southern Africa deal with sites where moisture content experiences marked seasonal variation and unsaturated conditions are normal. Light structures like roads and low-rise buildings provide a significant fraction of the samples tested. It has long been realized that soil suction is the defining feature of unsaturated soils and unsaturated soil mechanics experts e.g. Fredlund et al. (2012) affirm that the correct way to precede with any unsaturated soils problem requires determining the Soil Suction Curve – also known as the Soil Water Retention Curve or the Soil Water Characteristic Curve. All soils property functions required for non-saturated soils analyses can be derived from this curve. Using these soil property functions, differential equations can be set up, boundary conditions can be defined and fully automated solutions follow. Unfortunately the cost of producing the suction curve is quite high and the time required is considerable. Such a costly, time-consuming procedure is not feasible for most small Southern African engineering projects. Engineers continue to rely on simple, inexpensive tests and analyses which have been in existence for decades, but whose relevance and reliability may be questionable.

The Central University of Technology's Soil Mechanics Research Group has explored simple and potentially rapid suction tests as described by Stott and Theron (2015b). These tests use well known principles e.g. Blight (2013), maintaining samples at known temperature and humidity and using small sample size and high precision weighing to achieve significant reduction in time to reach moisture content equilibrium. One of the initial aims was to investigate the possibility of using a single suction value to assess a soil's expansive potential. This may seem a very unlikely possibility, but as can be seen in Figure 1, the relative values of water retention between various soils shows reasonable consistency over a considerable range of suctions. It can be seen that equilibrium is reached reasonably quickly for high suction/low water content conditions and much more slowly for low suction/high water content conditions. For most of this test, temperature was maintained at 20 degrees +/- 0.1 degree Celsius. For part of the test the samples were allowed to follow laboratory ambient temperature which varied between19 and 25 degrees. This demonstrates the feasibility of performing such tests in very economical circumstances.

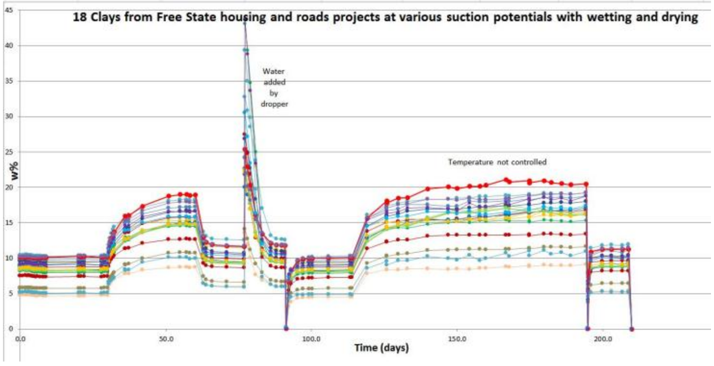

Figure 1. 18 clays at various suction potentials

Not all clays follow this pattern. Figure 2 shows results for five specimens each of four different clays, three of which follow the pattern of consistent relationship of water retention with suction, but the fourth breaks away from the pattern for low suction values and the curves of all five samples cross over the curves of the other three. This clay is not typical; it is an almost pure kaolinite from the Southern Cape. At high suction values the pattern of water content with suction variation is similar to the other clays, but is different for low suction values. The range of suction potential is also much larger than for the other clays at all suction values.

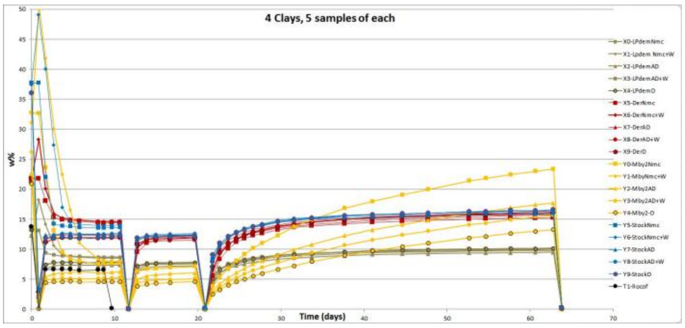

Figure 2. Five samples each of four clays

This break in the normal pattern has been noted in relatively few clays, and usually only for "pure" clays, which are not a common occurrence. An example can be seen in Figure 3, which shows curves of multiple samples for each of five different clays. The five red curves are for a clayey soil from Steelpoort in Limpopo. One of the curves does not maintain the usual pattern of constant relationship with the other samples. The sample showing the non-typical curve is not a natural clay sample, but was isolated from sediment in a settlement test of Steelpoort clay. It is the pure clay from the upper layer of sediment (probably montmorillonite). All of the other curves are for unprepared natural samples and all follow the normal pattern of maintaining a substantially consistent relationship.

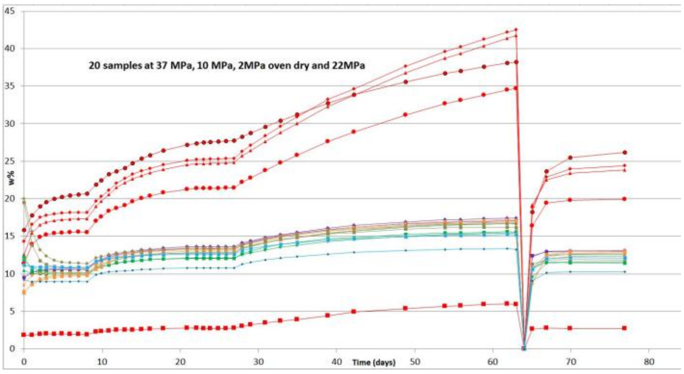

Figure 3. samples at 37MPa, 10MPa, 2Mpa, Oven dry and 22Mpa

3 ASSESSMENT OF VARIABILITY

A noticeable feature of Figure 3 is the variation indicated by the curves for the different clays. Most show little variation, but the Steelpoort clay shows amazing variation from the highest suction by far to the lowest suction by far.

This observation of marked difference in variability led to a series of tests using multiple samples of several clayey soils and an assessment of the variability exhibited by these clays. Sample size was approximately 2-5 g. All samples were simply selected from appropriately sized pieces in the sample bags, or broken from larger lumps. They were then placed in glass weighing bottles with ground in lids after no further treatment. The samples were maintained at constant suction either in a climate chamber or over solutions of various salts, until constant moisture content was achieved (usually from three to six days).

Figure 4 shows the results for 28 samples of Steelpoort clay at 28MPa suction. These samples were supplied by Prof. SW Jakobsz on two separate occasions. Samples were taken randomly from both batches. Both batches show very similar behaviour.

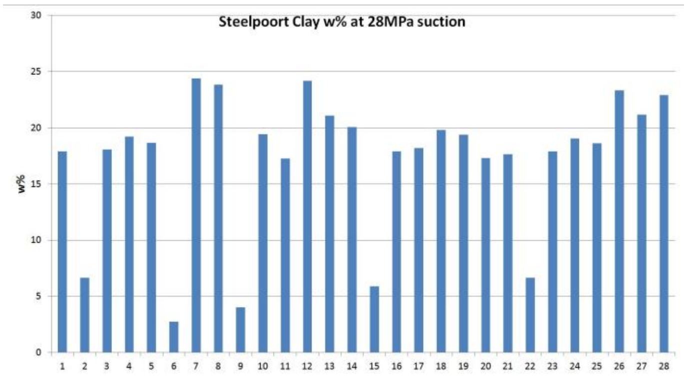

Figure 4. 28 samples of Steelpoort clay

Figure 4 tends to confirm the impression given by Figure 3 that there is huge variability in suction potential between individual samples of this soil. The lowest of the values for water retention (2.7%) suggests an inactive soil with a PI possibly less than10, the highest water retention (24.4%) suggests an extremely active clay with a PI possibly greater than 50. The average water retention of 17.3% suggests a highly active clay with PI probably in the region of 35 to 40. The Coefficient of Variation (COV) is 35.6.

Samples of this clay were sent to seven reputable soils testing laboratories. Figure 5 shows values of PI from these laboratories.

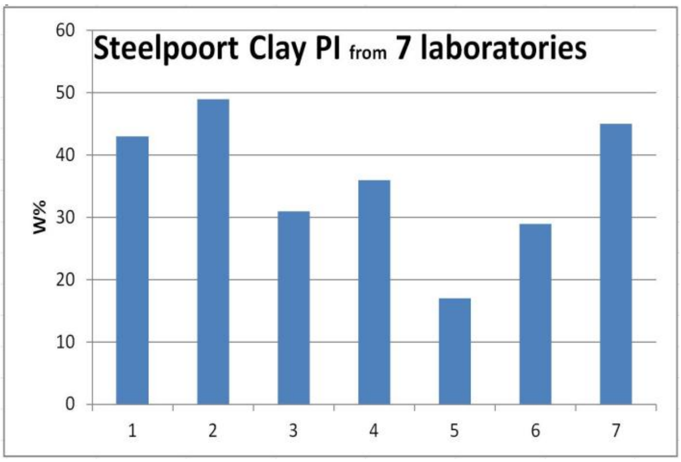

Figure 5. PI values from 7 soils laboratories

The lowest PI is 17, the highest PI is 49 and the average is 34.2. The coefficient of variation is 33. These values correspond well with the suction results. They raise the question whether the discrepancies between commercial laboratories - which have been noted for so long by so many people - may be due not to slipshod testing, as is often thought, but to intrinsic variability in soil properties. Such variability could lead to serious consequences if ignored.

Figure 6 shows suction values, again at 28MPa, for a typical clayey soil from Bloemfontein.

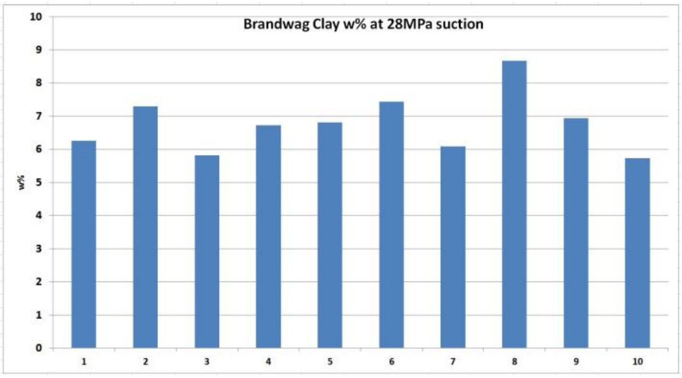

Figure 6. Ten samples of Brandwag clay.

The suction values of figure 6 range from 5.8 to 8.7 with mean of 6.8 and COV 13.1. Samples of this soil were sent to 5 commercial laboratories for testing. Figure 7 shows the values of PI obtained in these tests.

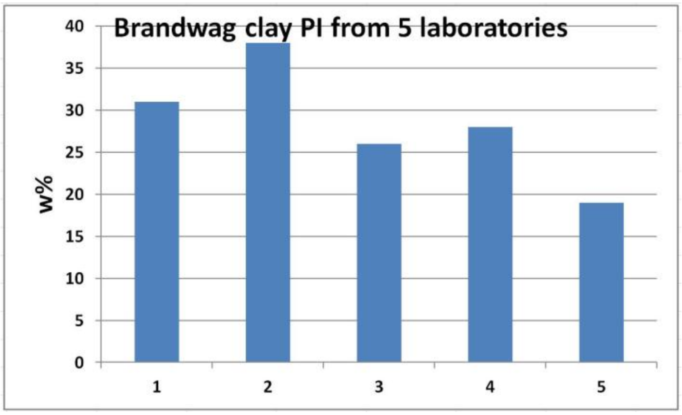

Figure 7. PI for Brandwag clay from 5 laboratories

PIs range from 19 to 38 with mean 28 and COV 17.1. The variability here also corresponds well with that of the suction values.

It should be noted that although PI is the most commonly used heave indicator in Southern Africa it is not a direct measure of heave. Sridharan and Prakash (2000) noted many instances of poor correlation between PI and heave potential. Suction is directly related to heave potential and may be a better indicator than PI.

4 SAMPLE PREPARATION AND VALUE OF SUCTION FOR CONSISTENT COMPARISON

If this testing procedure is to give consistent results and allow different soils to be compared meaningfully with each other, then two features need to be considered.

4.1 *Hysteresis*

Hysteresis plays a significant role in suction values in soils. Figure 8 shows the water retention of ten different clayey Free State soils from both wet and dry condition. The retention for the initially dry samples is on average 18% less than for the initially wet samples. This is due to hysteresis effects.

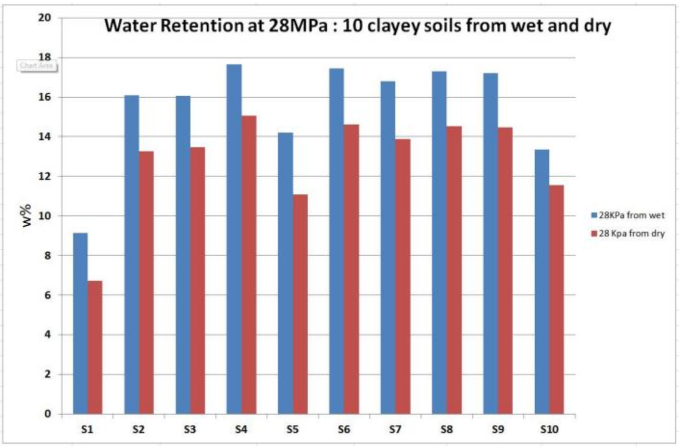

Figure 8. Differences in suction due to hysteresis

On the principle of preferring in situ conditions it might be logical to consider determining suction potential from natural moisture content. Unfortunately sample bags are often casually treated; they are often punctured, and stored and transported in the sun. Samples often reach the testing stage at well below their original moisture content. It appears that unless a concerted effort is made to improve sample treatment and storage, the most feasible consistent procedure would be to test dried samples. A reasonable procedure might be to dry at 40 degrees, since it is very unlikely that any South African soil will be dried at a temperature higher than this under field conditions. A commercially more attractive procedure would be to dry at 105^0C so that an additional drying step to establish water content would be eliminated.

4.2 *Suction value*

In general the higher the suction the quicker a soil stabilizes to its equilibrium water-content. But as can be seen in Figures 1 and 3, the lower the suction, the greater the equilibrium water-content and the less sensitive the weighing procedure required to differentiate between soils. Tests were performed on a number of clays to assess the effect of suction value on COV. Table 1 shows values for ten samples each of ten clayey soils at suctions at 22 MPa, 38 Mpa and 180 MPa. The COV for each soil at any of the suctions measured is not far from the average of all of the values.

Soil	22MPa	38MPa	180MPa	Average
Belcher 2	15.3	15.1	15.2	15.2
Lerato Park 1	10.5	10.9	10.7	10.7
Lerato Park 2	5.2	6.0	5.2	5.5
Fichardt Park	5.0	5.8	5.6	5.5
Botshabelo R	19.4	18.9	22.0	20.1
Botshabelo B	2.8	2.6	3.3	2.9
Dersley	7.1	7.0	7.1	7.1
BK 3270		2.3	2.3	2.3
Cecelia 5A		7.4	7.4	7.4
Cecelia 5B		14.0	14.2	14.1

Table 1: COV for 10 samples of 10 clayey soils

5 CONCLUSIONS

Some soils appear to show little intrinsic variability others show very large variability. Conducting one set of foundation indicator tests on some soils would therefore probably lead to reasonable values for use in design. In other cases this procedure could lead to very unsound design.

The investigation described here gives a reasonably quick, easy and inexpensive way of assessing soil variability. The question remains of how to proceed to design. The best way of dealing with such uncertainty is undoubtedly Reliability Based Design.

This is not likely to be an attractive solution for a large number of engineering practitioners since it requires time-consuming and skills-intensive procedures like Monte-Carlo analysis. But in view of the apparent variability of some soils it might be preferable to invest the time and effort required rather than risk expensive failures. It may also be worth noting Phoon's comment "*probabilistic techniques do exist to calculate the probability of failure efficiently. The chief drawback is that these techniques are difficult to understand for the non-specialist, but they are not necessarily difficult to implement computationally*." (Phoon 2008 p 27). If a decision were made that such an approach were advisable, then specialists would probably be prepared to develop the required software for non-specialists at an acceptable price.

Another possibility might be to accept the most unfavourable values as indicated by a variability assessment (or some statistically acceptable compromise). This would probably lead to simpler, but less economic designs then the first alternative.

To do nothing, and to continue to base designs on isolated test results, is likely to perpetuate the occurrence of expensive failures - which are not at all uncommon in certain fields, such as low cost housing.

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