Variability of suction in expansive clays

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ABSTRACT: One of the problems which led to the modern discipline of unsaturated soil mechanics was the founding of light structures on expansive clay; yet relatively little success has been achieved in solving this problem. One of the reasons may be variability of suction potential. Variability among active clays is very different from one soil to another, with coefficient of variation ranging from less than 5 for some soils to more than 25 for others. Variability appears to be characteristic for a particular soil and shows similarities to a fractal distribution over a considerable range of scales. A wide range of values for properties, such as the SWCC and swell potential, may therefore be expected for some expansive soils. Values may vary over scales from a few millimetres to tens of metres throughout what appears to be one consistent soil stratum. Framing the problem of heave in terms of differential equations with soil-property functions as input may be inadequate for soils with high variability. It may be necessary to consider statistical aspects to design for an acceptable probability of failure. Variability is examined from perspectives ranging from suction to X-ray diffraction and possible application to the problem of heaving foundations is considered.

1 INTRODUCTION

Expansive clays present serious problems for light structures founded on them in many parts of the world. Central South Africa is one such area. The South African government's attempts to provide millions of subsidized houses for its poorest citizens have been hampered by an alarming proportion of such houses having to be demolished as unfit for habitation within a few years of construction. South African insurance companies routinely include a clause in their home-owners' policies excluding liability for damage due to expansive clays.

The problem of expansive clays was a key factor in the development of the modern discipline of unsaturated soil mechanics. Yet despite great advances and notable successes in a number of aspects of geotechnical engineering, relatively little success has been achieved in solving this problem. This was forcefully brought home in the question time of the 8th C.W. Lovel lecture at Perdue, when Fredlund said *"I started in unsaturated soil mechanics by looking at swelling clay problems, where if you get involved you usually lose money, it is not a good problem"* (Fredlund 2009).

The authors began examining the question of why expansive clay foundation problems are difficult solve in 2012 and have concluded that variability of properties of expansive clays may be a key factor.

2 BACKGROUND TO THE TESTING METHOD

The procedure for assessment of suction potential used in this investigation, as well as evaluation of its accuracy and reliability, are detailed in Stott and Theron (2017). The method arose from tests to assess the suitability of locally available filter-papers for the filter-paper method of measuring suction in soils. The calibration procedure involves allowing samples of filter-paper to come to moisture equilibrium over salt solutions whose suction potentials have been established to a high degree of accuracy. The procedure leads to a Filter-paper Water Characteristic Curve to which a mathematical description is fitted. This is used to deduce the suction in soil which has been brought to moisture equilibrium with the filter paper. In the tests to calibrate the filter-papers, soil samples were also brought to equilibrium alongside the filer-papers to enable direct comparison of test results. This procedure leads to a Soil Water Characteristic Curve (SWCC) for each soil sample, to the same accuracy as filter paper calibration. The procedure has been adopted as a superior method of assessing soil suction and the CUT laboratory no-longer uses filter-paper but instead assess suction potential of soils directly by the filter-paper calibration procedure.

Suction potential can be set in a climate chamber by adjusting temperature and relative humidity.

While the suction cannot be maintained with the same accuracy as over salt solutions, consistency is nevertheless very good. Temperature can be maintained to +/- 0.1^{0}C; relative humidity can be maintained to +/- 0.3%. Results were compared by bringing both filter-papers and soil samples to equilibrium over saturated solutions of NaCl and KCl and then in a climate chamber set for the same suction potentials. Water retention values were practically the same. The climate chamber has the advantage of more rapid equilibration of moisture content because of forced circulation. It also has greater space for accommodating multiple samples; many samples can be tested very conveniently at the same time. This allows the suction potential of a large number of specimens to be investigated in an acceptable space of time. The climate chamber has the disadvantage of a somewhat smaller range of suctions due to the possibility of condensation at high relative humidity.

Samples for testing are extracted from the sample container with as little disturbance to structure as possible. Fabric of the samples is largely preserved and they are not subjected to destructive preparation procedures such as drying, crushing or slurrying; they are simply put into weighing bottles. This should provide less operator-induced variation than most test preparation methods. Since all samples were prepared in the same way, little of the observed difference in variabilities between soils assessed by this method should be attributable to sample preparation.

3 CONSIDERATIONS FOR TESTS OF VARIABILITY

Investigation of variability in soil properties requires a large number of test results to establish the relevant parameters – mean, standard deviation, probability density function etc. Many soils properties, including expansive potential, are dependent on soil suction, and therefore on the soil water characteristic curve. Unfortunately producing a full SWCC may be a time-consuming process for the highly plastic clays associated with heave problems. Tests on a large number of samples of clayey soils have shown, however, that many high shrink/swell soils retain a reasonably predictable relationship with each other over a large range of suctions (Stott and Theron 2015). A single point on the SWCC at a standard suction may therefore give a good indication of the general pattern. The use of small samples and a high precision balance allows very accurate assessment of water retention under an applied suction to be achieved for sizable batches of samples within a few days, even for soils of high plasticity. Tests on multiple samples have shown that different clayey soils show a wide range of variability, and that this variability appears to be an intrinsic property of the individual soil (Stott and Theron 2016). Convenient suction values for these multiple, small scale suction tests are 22 000 kPa and 35 000 kPa. A limited number of such tests on spatial scales up to about 100m suggest that the measured variabilities show fractal distribution.

4 EXAMPLES OF VARIABILITY

Three expansive South African soils have been selected from a large number tested to illustrate the question of variability in these soils. Two of the soils come from electricity sub-station sites, the third from a shopping centre.

4.1 *Electricity sub-station in Limpopo Province*

Foundations for a major electricity substation at Steelpoort were designed following the standard procedure of taking samples from test pits for analysis by a certified engineering soils laboratory. The material was described as red alluvium. Standard tests indicated little expansive potential and foundations were designed accordingly. Shortly after completion the substation began to exhibit severe heave damage. Repair and modifications to the structure were required. Duplicate samples of the underlying soil were sent to four reputable laboratories. Results varied significantly, some suggesting only moderate expansive potential, others suggesting high expansive potential. The engineers concerned concluded that soils laboratories are unreliable in their execution of standard tests and a report to this effect was published (Jacobsz and Day 2008).

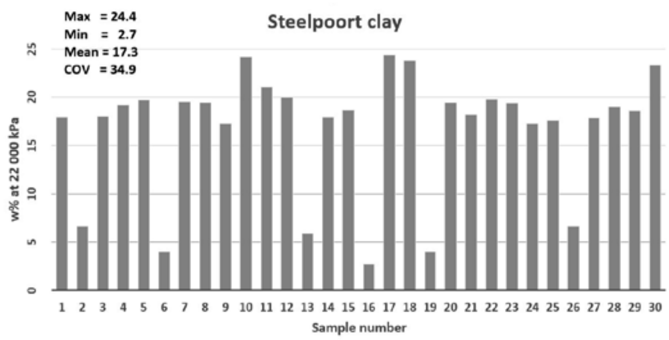

Figure 1. Water retention at 22 000 kPa suction for 30 samples of Steelpoort clay.

As part of the authors' broad-based investigations into variability in soils, multiple samples of this soil were tested by the procedures of section 2 above. Typical results are shown in Figure 1. Repeated testing of individual samples gives consistency of the order 0.1%. It is therefore not feasible to show error bars in the figures.

Samples were sent for parallel testing to certified soils laboratories of good reputation, to determine Atterberg limits and particle size distribution (Jakobsz and Day 2008, Badenhorst et al. 2015). Values of PI ranged from 30 to 49, hydrometer values for clay fraction varied from 12% to 56%.

Samples were sent for X-ray diffraction (XRD) analysis. The resulting plots of diffraction against 2xTheta angles are shown in Figure 2. Although all of the samples were taken from the same sample bag and appear to be almost identical to each other, the XRD results show limited similarity.

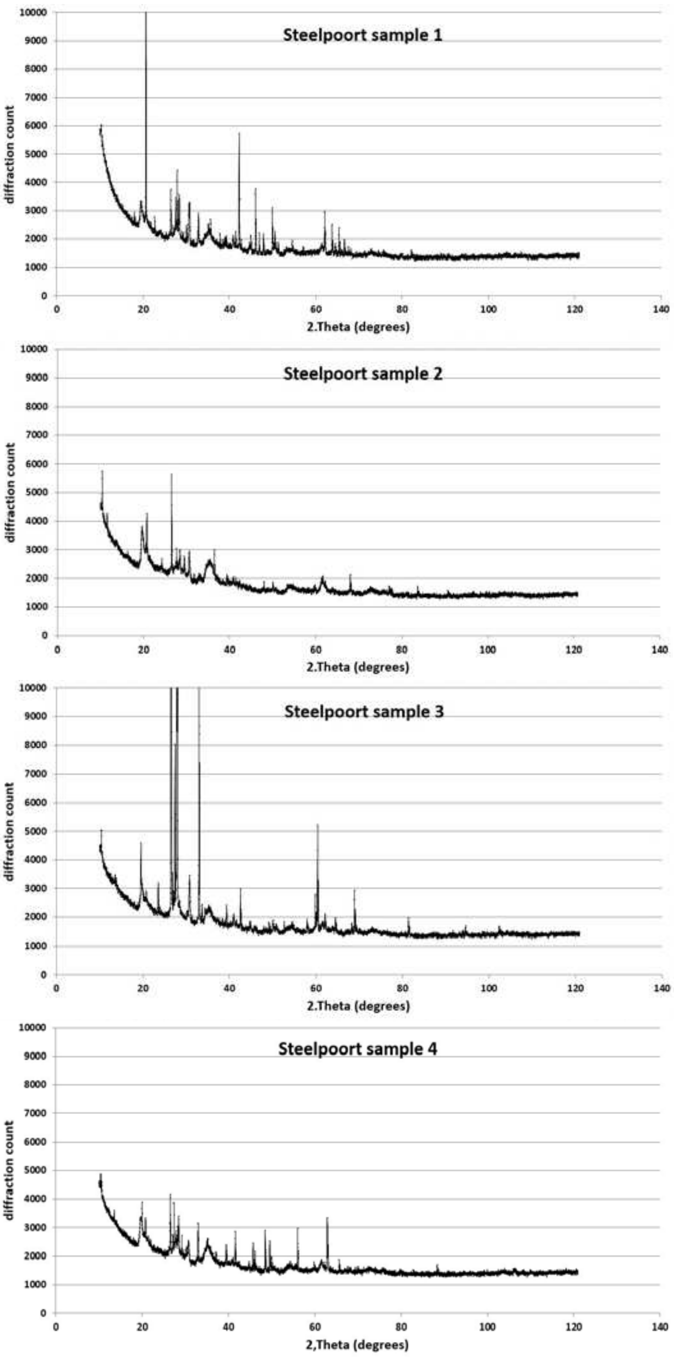

Figure 2. Plots of X-ray diffraction from four samples of Steelpoort clay.

The XRD graphs show variability in both position and intensity of features, and therefore in the composition of the soil even though all of the samples were taken within a short distance of each other and appear to be identical. There does not appear to be an obvious way to allocate a numerical value to the XRD variability. Numerical values can, however, be applied to the values of PIs and clay fractions found by the certified soils testing laboratories mentioned above. Their results are shown in Figure 3. The variabilities, particularly of clay fraction, are high.

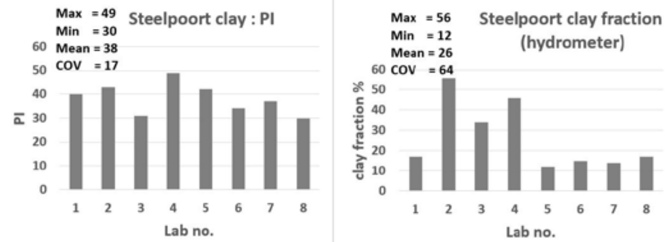

Figure 3. PI and clay fraction from 8 laboratories

4.2 *Electricity sub-station in Free State Province*

Samples of a very plastic, black, transported clay were recovered from four test pits at a proposed site for an electricity sub-station at Botshabelo in the central Free State of South Africa. Standard tests from several laboratories all indicated high swelling potential; the foundations were designed accordingly and no significant heave problems were encountered.

Multiple samples of this soil were subjected to suction tests. Figure 4 shows typical results.

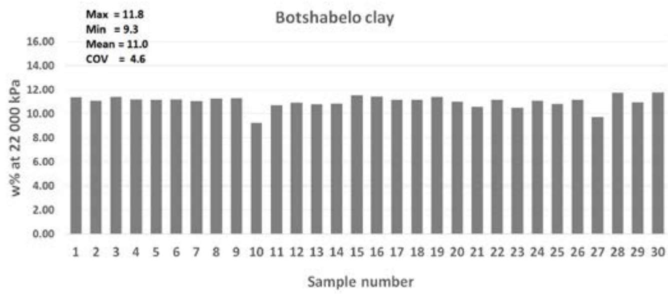

Figure 4. Water retention at 22 000 kPa suction for 30 samples of clayey soil from central Free State sub-station.

The difference between Figures 1 and 4 is striking. In the case of the soil from the first power station, where the COV (for 30 samples) is more than 30, it would be possible to choose samples at random which show very low suction potential - and therefore low heave potential. This appears to be what actually happened, and the design accordingly took no account of the extremely high heave potential of the majority of the soil. The situation is very different for the second power station, where the COV for 30 samples is less than 5. There appears to be very little chance of taking a sample which would significantly underestimate the general potential of the soil. It is perhaps not surprising that the sub-station foundations performed satisfactorily.

Samples of this soil were also examined by XRD. Results of four tests are shown in Figure 5.

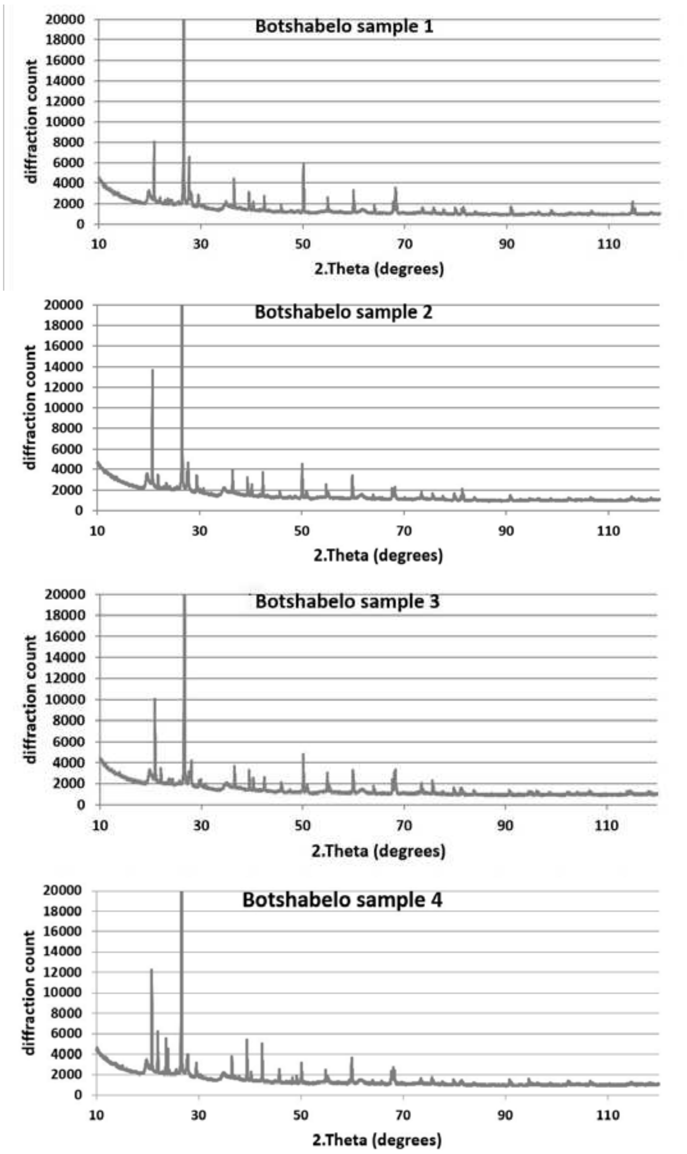

Figure 5. Plots of X-ray diffraction from four samples of Botshabelo clay.

Results are not identical, but are quite similar and in spite of a lack of an obvious way to allocate a numerical value to variability, the general impression is of low variability.

4.3 *Southbridge Shopping Centre in Bloemfontein*

Part of a shopping centre in the Free State, South Africa became unsafe for occupancy when roof trusses pulled apart in two separate areas. The first area suffered major damage to trusses over a considerable distance, the foundations had been designed to cope with only moderate heave potential. One of the walls carrying the roof trusses was found to be leaning away from the rest of the building. Measurements showed that where many trusses were broken, the wall was leaning several centimetres from the vertical. Where no trusses were broken the wall was not far from vertical, and where few trusses were broken the wall showed an intermediate degree of leaning. Suction test results for the clayey soil directly under the foundation are shown in Figure 6.

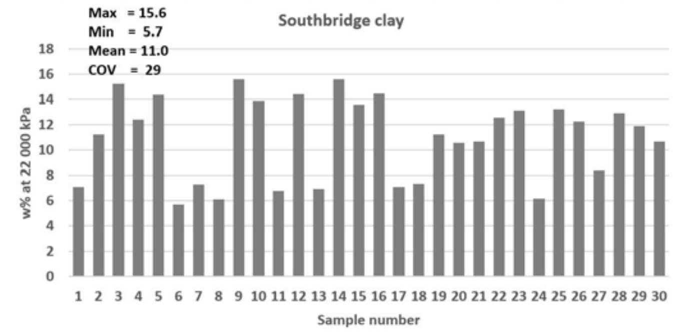

Figure 6. Water retention at 22 000 kPa suction for 30 samples of clayey soil from Free State shopping centre.

The results are similar to Figure 1 in showing a distinctly bi-modal distribution. In this case the difference between the higher and lower values is smaller, but the number of low values is greater. There would appear to be a very substantial possibility of taking a sample for testing which has a heave potential significantly lower than a representative value. This may explain why a reinforced concrete strip footing was chosen, while the majority of the values would indicate the need for a much more substantial foundation. The variation in distortion of the wall is compatible with different degrees of expansion at different locations along the wall. This would corroborate a number of observations at other sites which suggest that variability of soils has a fractal distribution, and reveals itself at different scales, from centimetres to many metres. Pachepski et al (2000) note that fractal distributions in soil science generally may range in scales *"from micrometres to the landscape."*

5 IMPLICATIONS FOR DESIGN

A partial SWCC for the Botshabelo clay is shown in Figure 7. Ten individual samples, assessed with the procedure detailed in section 2 above, show almost identical curves over the measured range of suctions. It would appear that it would be reasonable to consider an SWCC to be a useful design concept for this soil.

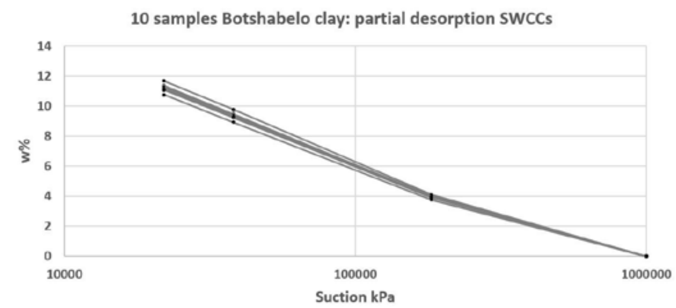

Figure 7. Ten partial SWCCs (desorption) for undisturbed samples of Botshabelo clay.

Figure 8 shows a partial SWCC for the Southbridge soil. Ten individual samples show such a wide range of moisture content for any particular suction that the concept of one SWCC for this soil appears to be far less reasonable. For such a soil it might be more realistic to consider statistical, rather than analytical methods for design.

A probability distribution function forms an essential part of a statistical analysis. A log-normal distribution is widely assumed for engineering soil properties. The justification for this, as noted by Low (2008) "*since it excludes negative values and affords some convenience in mathematical derivations",* is attractive since negative values would be meaningless for many soil properties and potentially problematic for some analysis procedures. The necessity of a large number of tests (to give a level of confidence comparable to that desired for an acceptable probability against failure) has discouraged attempts to establish probability distribution functions experimentally. The time, expense and quantity of sample necessary would be unreasonably great since a minimum of about 650 tests would be required. It is therefore common to estimate probabilities for soils by examining variation across values of typical results across databases of various types of soil. Figures 1, 4 and 6 suggest that variability across databases of soil types may not be adequate, and variability of individual soils may be required. A series of tests were performed to establish probability density functions for the three expansive soils examined above.

6 PROBABILITY DENSITY FUNCTIONS FOR THREE EXPANSIVE SOILS

Multiple batches of 20 samples each of the three samples introduced above were brought to moisture content equilibrium at 20^0C and 85% relative humidity (RH), which corresponds to a suction of approximately 22 000 kPa. Samples were generally between 1g and 8g and were either individual small peds as found in the sample bags or broken from larger peds along lines of weakness. Seven hundred and forty samples of Southbridge clay yielded mean retention 11.42% and COV 20.65. Figure 9 shows plots of the lognormal curve corresponding to these values and the measured probability density function. The measured curve shows a bimodal form, as might be expected by reference to Figure 6. The difference from the widely assumed lognormal distribution is substantial.

Figure 10 shows corresponding plots for the Botshabelo clay, for which 660 samples gave mean 10.81 and COV 6.2. Tests on other low variability soils have yielded similarly shaped curves. The lognormal distribution corresponding to these values, while not precisely the same as the measured distribution, should give meaningful answers if used as the assumed distribution function in a statistical design approach like the first order reliability method.

This would probably not be the case for Steelpoort clay, as can be seen in Figure 11, where 660 samples give mean 16.40 and COV 25.32 the difference between lognormal and measured probability density functions is profound.

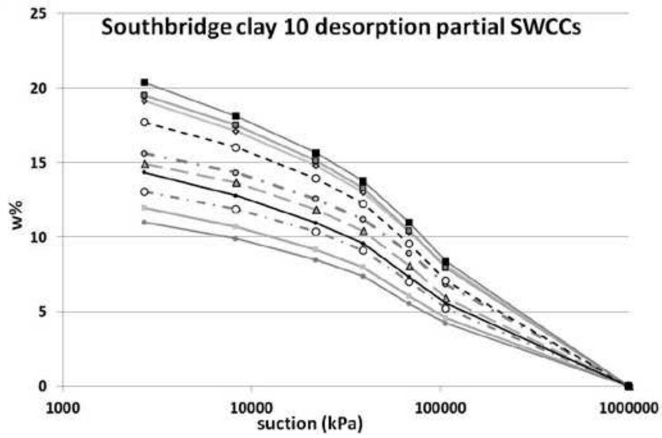

Figure 8. Ten partial SWCCs (desorption) for undisturbed samples of Southbridge clay.

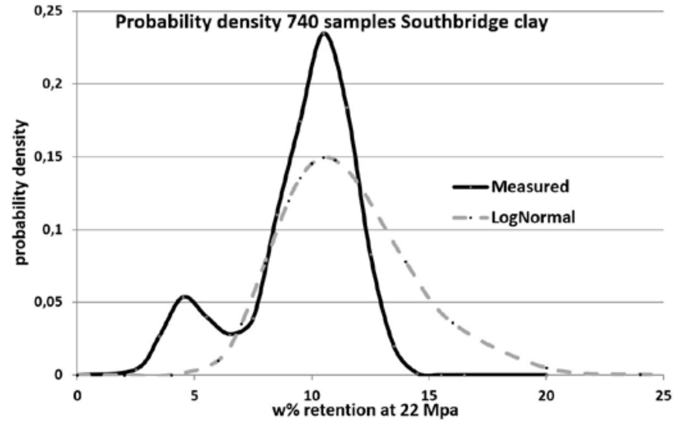

Figure 9. Measured and lognormal probability density functions for Southbridge clay.

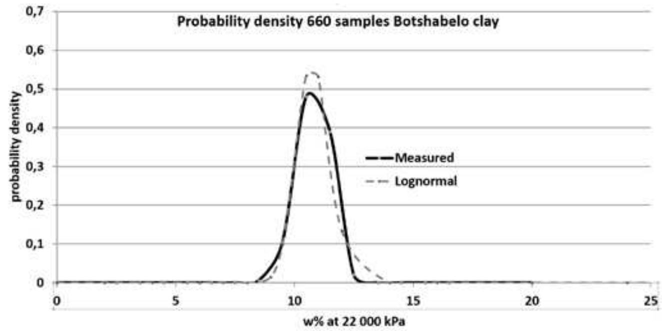

Figure 10. Measured and lognormal probability density functions for Botshabelo clay

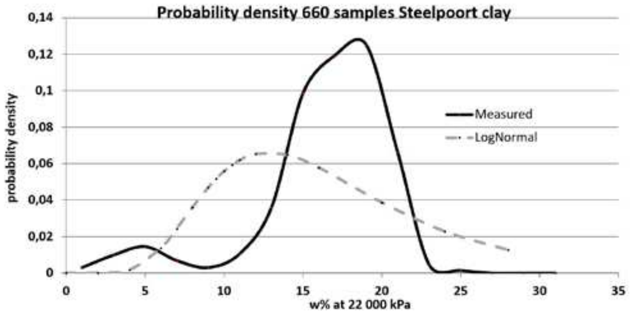

Figure 11. Measured and lognormal probability density functions for Steelpoort clay.

7 CONCLUSIONS

Variability in suction potential of expansive clays appears to be intrinsic to individual soils. Variability is often not measured, and if taken into account it is likely to be estimated by referring to variability across databases of similar soils. Where variability is low it would appear that the widely favoured practice of assigning one measured value to each design parameter in an analytical procedure should present no difficulty. Where variability is large this may be un-conservative, and cases have been encountered where problems have followed such design processes. Statistical procedures may be required for variable soils. Statistical design methods require probability density functions as standard input. For soil properties it is often assumed that a lognormal distribution is a realistic approximation. It appears that this is not always true. It is likely that for successful design to cope with expansive soils, an assessment of the variability of the individual soils concerned may be required. The method used here provides a way to produce a meaningful probability density function in a not-unreasonable amount of time. It should also be possible to get an indication of whether the usual assumption of a lognormal curve is likely to be acceptable from considerably fewer tests than the number required to give an accurate probability density function.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

Badenhorst, W.S., Stott, P.R. & Theron, E. 2015. Duplicate testing conducted on the input parameters for the estimation of potential expansiveness of clay *Proceedings of the 16th African Regional Conference on Soil Mechanics and Geotechnical Engineering. Tunisia 27-30 April 2015.* Tunis: ATMS.

Fredlund, D.G. 2009. Paradigm Shifts to Facilitate the Practice of Unsaturated Soil Mechanics. *8th C.W. Lovel Lecture.* Perdue Geotechnical Engineering. 26 October 2009.

Jacobsz, S.W. & Day, P.W. 2008. Are we getting what we pay for from geotechnical laboratories? *Civil Engineering,* 16(4): 8-11.

Low, B.K. 2008. Practical reliability approach. In Phoon K.K. (ed.) *Reliability Based Design in Geotechnical Engineering*, Tailor and Francis, Oxon and New York 2008.

Pachepsky, Y.A., Crawford, J.W. & Rawls, W.J. (eds), 2000. Fractals in Soil Science. Elsevier Science B.V. Amsterdam.

Stott, P.R. & Theron, E. 2015. Assessment of clays by small-scale suction tests. *Proceedings of the 16th African Regional Conference on Soil Mechanics and Geotechnical Engineering. Tunisia 27-30 April 2015.* Tunis: ATMS.

Stott, P.R. & Theron, E. 2016. Variability in soil properties and its consequence for design. *Proceedings of the 1st Southern African Conference on Geotechnical Engineering*. Sun City 5-6 May 2016. Rotterdam: Balkema.

Stott, P.R. & Theron, E. 2017. Estimation of Shrink/Swell Potential and Variability of Clays by Small-Scale Suction Tests. *Geotechnical Engineering Journal of the SEAGS & AGSSEA* 48(2): 115-125.