

The Impact of Variability of Soil Properties on Characteristic Values for Geotechnical Design

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Abstract. Modern geotechnical codes of practice such as Eurocode 7 acknowledge that soil properties are variable and require “characteristic” values which should allow not more than a small (typically 5%) probability of failure due to the property under consideration. Factors are applied to characteristic values to give design values which should have very little probability of failure. A probability density function is required for a realistic estimate of a characteristic value, but this would require so many tests that it is generally considered impractical. It is therefore assumed that variability follows a distribution which is convenient for calculation purposes. This study evaluates the probable validity of this assumption. Results indicate that the assumption may be very unrealistic in some cases and could lead to designs which do not meet the intended safety criteria.

Keywords: Characteristic values, variability of soil properties, probability density functions, Eurocode 7

1 Introduction

Geotechnical engineering deals with materials more variable than those used in most branches of engineering. This variability has been noted by many observers, e.g. Singh and Lee [1]. For many years there appears to have been relatively little heed paid to this by many practising engineers. Little attention has been drawn to it in tertiary level geotechnical engineering courses. Little attention is given to it in many major soil mechanics text books.

Variability of properties results in uncertainties. Uncertainties are best dealt with by statistical methods. Reliability based design (RBD) has been developed over many years to be a powerful statistical tool to enable a reasonable estimate of a design’s probability against failure (Phoon [2]). RBD procedures tend to be mathematically intensive, and not popular with many practicing engineers. The standard method currently used in many countries (Limit States Design) is an extreme simplification, but nevertheless it still relies on the same statistical parameters as more rigorous and complex RBD analyses. Any kind of reliability-based design method requires probability density functions (PDFs) for action and resistance parameters involved in a design. General disregard for variability has been reinforced for many years by codes of testing practice. For example, British Standard BS 1377 [3] calls for individual clods and lumps to be broken down with mortar and pestle and then recombined and mixed thoroughly until representative samples are obtained. South African Standard

3001 [4] calls for exactly the same procedure. This quest for “representative”, or average values deliberately and specifically hides any variability which may be present. This is consistent with working state design, where the expected working state is analysed and a safety factor is applied to the working load. It does not seem to be well suited to any of kind of RBD.

2 The Nature of Variability

Variability in soils, and particularly the fact that variability tends to show fractal distribution patterns, was recognised by soil scientists well before engineers began to realise the importance of variability. As Patchepski et al. [5] pointed out, soil properties display variability on fractal scales ranging “from the microscopic to the landscape”. That being the case, it would appear to be of great value to use testing procedures which highlight the variability of soil properties rather than hide it. The belief in the reality of one “representative value” for a stratum of soil has led to many attempts to find out why different laboratories may give widely different values of properties for samples of the same soil. Minty et al. [6] suggested that operator bias and differences in testing procedures might explain the discrepancies. Others have suggested that carelessness and taking short-cuts could be the explanation. Personal visits to several commercial laboratories have generally led to the conclusion that testing operatives are skilled practitioners who take pride in their work, and that laboratory managers are concerned about maintaining standards, and jealous for the reputation of their laboratory. It therefore appears likely that the discrepancies of results from different laboratories may be showing the extent of variability on the sample-size fractal scale and this has been mistaken for faulty testing.

3 Limit States Design

The aim of Reliability based design (RBD) is to give designs with realistic, and acceptably small probabilities of failure. Eurocode 7 has been a leading example of the move towards the simplified version of RBD known as limit states design. Many other countries are adopting Eurocode 7 or adapting it. Limit states design attempts to quantify the variability or uncertainty in the various aspects of loading (“actions”), and stabilising influences (“resistances”). Figure 1 gives a schematic illustration of the method of implementing this aim in practice. Estimates of the probable values of action are compared with probable values of resistance and arranged such that there is only a small probability of them overlapping. Safety factors are then applied to actions and/or resistances. These “partial factors” apply increases to actions and reductions to resistances. The design should then have only a very small probability of reaching a limit state.

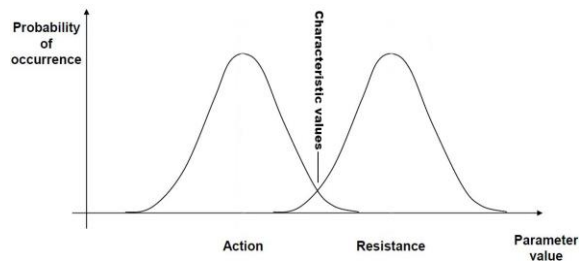


Fig. 1. Schematic arrangement of probable values of actions and resistances giving characteristic values with small probability of failure. Factors are applied to these values.

4 Statistical Considerations

Many common statistical analyses assume (and are only valid for) normal distributions. Some distributions, e.g. the log-normal, can be transformed to normal for statistical analysis. The widely used Student's *t* test is valid only if the underlying distribution is normal to a high confidence level. The *t* test makes comparisons between the tails of the *t* distribution and the tails of the normal distribution, and it is the tails of the distribution which are therefore critical. To render some popular statistical analyses (including the *t* test) meaningful, a confidence level of 99.5% in the normality of the PDF is appropriate. To establish this theoretically requires 636 tests. Most soils tests require considerable time for preparation of samples and for testing. Many require a considerable quantity of soil which needs significant effort to extract and transport to a testing facility. Consequently, PDFs for individual soils have rarely actually been measured, they are typically estimated by data-base mining or from a few test results and some apparently reasonable assumptions. One such assumption is that soil properties follow a log-normal distribution. As pointed out by Low [7] this is because a log-normal is convenient for analysis. It cannot give negative values, which would be problematic, and it is convenient for statistical analysis since it can be transformed into a normal distribution. Eurocode 7 specifies a log-normal distribution for soil properties providing resistance against structural failure. A Gumbel distribution is specified for action components, which could apply to soils in some circumstances. The lack of measured probability density functions for soils has led to Eurocode making a concession by allowing a cautious estimate of the value affecting the occurrence of the limit state instead of the fifth percentile specified for other disciplines regulated by Eurocode. A report by Spear and Selemetas [8] covering information requested on Eurocode 7 by geotechnical practitioners indicates that 94% of these geotechnical experts requested guidance on how to arrive at the required cautious estimate. Phoon and Ching [9] suggested ways to reduce the cautious estimates typically used for COVs (which they suspected to be uneconomically conservative). Eurocode itself gives very little guidance. It seems, however, self-evident that there is no way to estimate the value of a property allowing only 5% chance of failure except from a meaningful probability density function.

5 Tests to determine probability density functions

A procedure for assessing shrink-swell potential by measuring suction potential of small, relatively undisturbed samples has been suggested by Stott and Theron [10]. The samples are brought to equilibrium water retention at a predetermined suction in a controlled temperature and humidity environment. Preparation is minimal, samples can be broken from larger peds at apparent lines of weakness or simply picked out from the sample bag. Small samples enable stabilisation of water retention in a reasonably short time; multiple samples can be tested together. Suction is a common factor in many aspects of soil behaviour. The suction versus water content curve (SWCC) is considered the key indicator of many soil properties and is used to derive property functions unifying saturated and unsaturated soil mechanics. Variability in suction potential may therefore be expected to be echoed in other properties. Codes of practice based on Eurocode 7 assume a lognormal distribution for all soil properties from the resistance standpoint. Suction potential may give an indication of how valid this assumption may be.

The rationale behind expecting small scale suction tests to deliver an indication of variability is the observation that peds of soil often show distinct lines of weakness - one of the most noticeable of which are slickensides. Larger peds tend to break into smaller peds along these lines of weakness. This observation suggests the possibility that the lines of weakness mark regions of different properties. Change of moisture content may lead to differences in volume change between the regions and weakness at the boundaries. If this is the case, then the natural ped size may be one of the fractal scales on which variability manifests itself. Unsaturated southern African clayey soils typically break into peds from about 1g to 8g. Such small samples necessitate an analytical balance to give moisture retention to better than 0.1%. Samples are placed in glass sample jars with ground-in glass lids, weighed and placed with lids open in a controlled suction environment. When moisture equilibrium has been achieved the samples are re-weighed and the moisture content determined.

Samples of ten soils, from various South African construction sites, were tested by Stott and Theron [11]. Sufficient tests (between 600 and 800) were performed on each soil to give at least 99.5% confidence in the normality or lognormality of the suction potential. The results are reproduced in Figure 2.

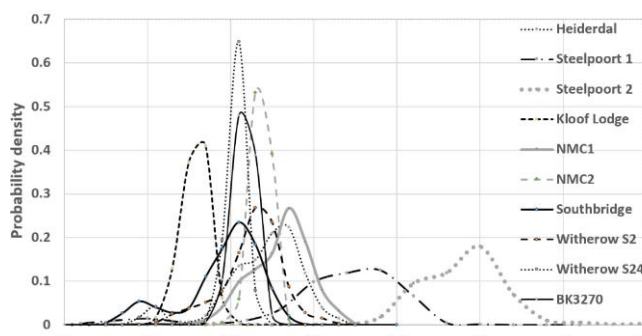


Fig. 2 Measured probability density functions of 10 South African Soils

None of the PDFs show a close correlation with either a lognormal or a normal curve. The rise towards the peak of a lognormal curve is more rapid than the fall beyond the peak. Most of the curves show the opposite. Analysis of the data used to produce these PDFs suggests that a smaller number of tests can give a reasonable indication of the general form of the likely PDF. Further suction tests have been performed on samples from construction sites in South Africa and Lesotho using a smaller number of samples (100-300). These test have confirmed the findings that PDFs tend to fall into three patterns, namely: approximately symmetrical, bulging, and bimodal. The approximately symmetrical distributions are not good approximations to normal or lognormal distributions, the bulging distributions are even less so and bimodal distributions are unlike any standard probability curve.

6 Estimating characteristic values

The procedure described in Eurocode 7 is straightforward and should give very low probability of failure if the probability density functions of soils are comparable to normal or lognormal. As an example consider a distribution measured for a stiff dark olive clayey soil from a shopping centre in central South Africa shown in Figure 3. For the characteristic value of an action one looks for the point below which only 5% of the area of the curve is to its left – approximately 10.5 in this case. Dividing by the material factor, 1.28, one gets the design value 8.2, which appears to have a very small probability of leading to failure, as the code requires. However, some probability density functions for soils are very far from the normal pattern. Figure 4 shows a fairly typical bimodal distribution from a soil at a housing development in central South Africa. The first point to note about this distribution (which was the result of 760 tests) is that no normal statistical procedures will be of help in deciding on a characteristic value. Only a PDF appears to give a basis for a reasonable estimate for a value giving no more than a 5% chance of failure. A characteristic value of about 7 appears to be reasonable. Dividing by 1.28 gives the design value of about 5.5. But this still leaves a probability of failure of at least 2%, which is far from negligible. The problem of unusual distributions is again highlighted by a soil from a housing project in Maseru, Lesotho illustrated in Figure 5. Perhaps the way to deal confidently with this soil could be to remove the layer entirely and replace with fill or use piles to a competent layer below.

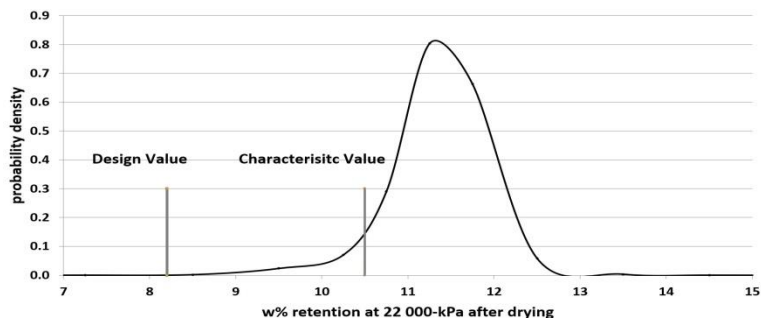


Fig. 3. Characteristic and design values from shopping centre, central South Africa

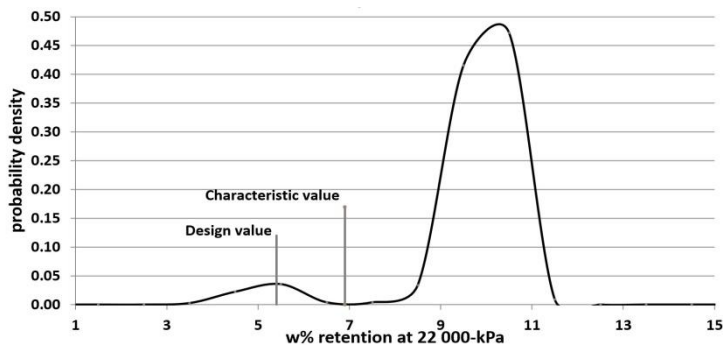


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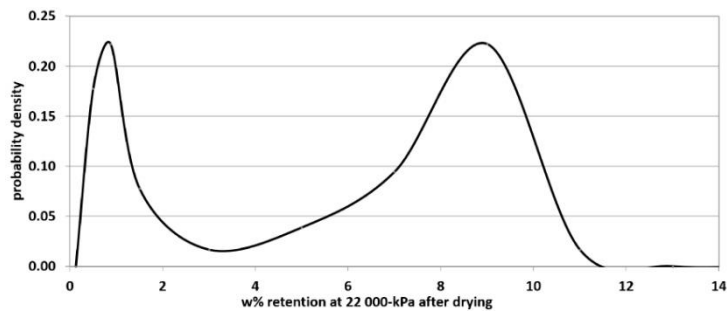


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7 Extension to other kinds of soil tests

While large numbers of test results can be obtained economically and conveniently by small scale suction tests, most other soils tests require much more time and expense. This raises the question of whether the results of these suctions test have any relationship to soil properties like shear strength, compressibility, etc. A start has been made to answering this question by a series of tests at a construction site in central South Africa. In an excavation for a mass-concrete anchor block, field vane shear tests were performed to assess shear strength. Undisturbed samples were collected for laboratory testing of shear strength using a fall cone. Samples for suction tests were collected from areas adjacent to the location of vane shear tests and undisturbed sample extraction. Fall cone tests on undisturbed samples were performed in the laboratory using a 30° 400g cone. The adjustment of fall cone factor for penetration depth and shear strength detailed by Feng[12] was extended to somewhat higher shear strengths than covered in his paper. In all, 90 vane shear tests, 150 fall cone tests and 240 suction tests were performed on this soil. To see if a relationship exists between the suction measurements and the shear measurements each group of measurements was divided into 12 quantiles (corresponding to $n \times 8.333$ percentiles). The values in each of these 12 quantile ranges were averaged; shear values were plotted against suction values (Figure 6).

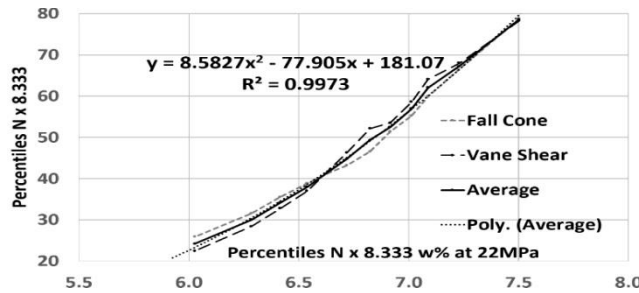


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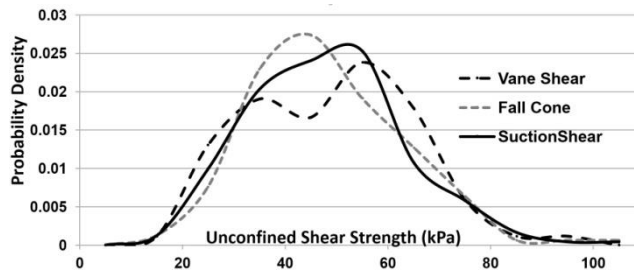


Fig. 7. Combined shear PDFs for field vane, fall cone and scaled suction

A trendline can be fitted ($R^2=0.9973$), giving a relation enabling shear values to be derived from the suction values. The resulting PDFs for vane shear, fall cone shear and suction shear correspond well despite there being relatively few vane shear test results (Figure7).

8 Conclusions

Variability in many soils does not appear to be well described by the usual assumption of a lognormal distribution. This may give over-conservative design values in some cases and unsafe values in others. Probability density functions can be determined for suction potential in a feasible amount of time and at reasonable cost. There may be simple ways of correlating suction values to other engineering properties of soils, as suggested by Figure 7. If this proves to be generally the case, then this may provide a reasonable way of estimating characteristic values which will conform to Eurocode 7 standards.

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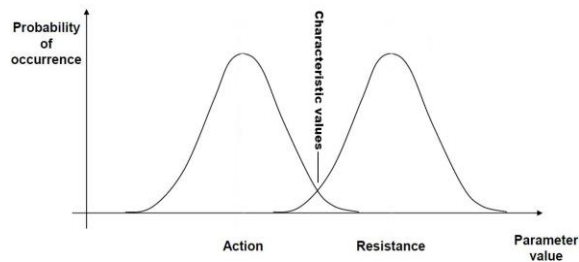


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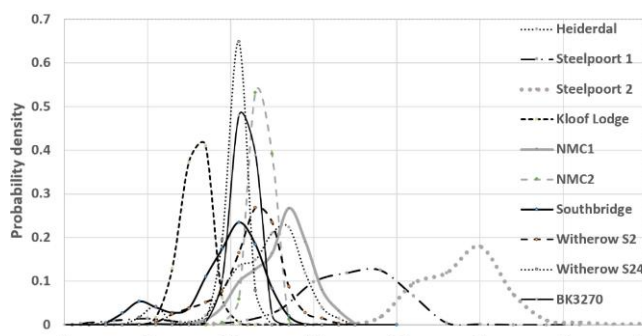


Fig. 2 Measured probability density functions of 10 South African Soils

None of the PDFs show a close correlation with either a lognormal or a normal curve. The rise towards the peak of a lognormal curve is more rapid than the fall beyond the peak. Most of the curves show the opposite. Analysis of the data used to produce these PDFs suggests that a smaller number of tests can give a reasonable indication of the general form of the likely PDF. Further suction tests have been performed on samples from construction sites in South Africa and Lesotho using a smaller number of samples (100-300). These test have confirmed the findings that PDFs tend to fall into three patterns, namely: approximately symmetrical, bulging, and bimodal. The approximately symmetrical distributions are not good approximations to normal or lognormal distributions, the bulging distributions are even less so and bimodal distributions are unlike any standard probability curve.

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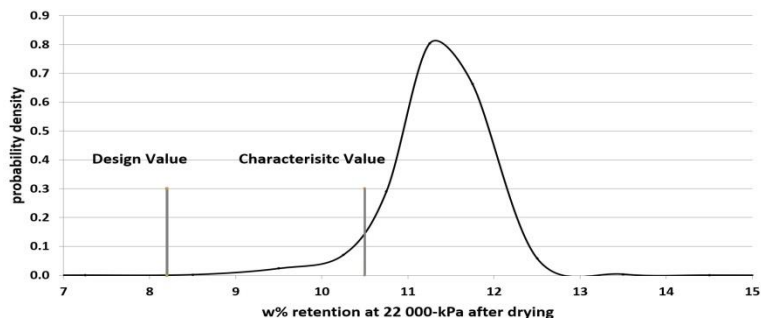


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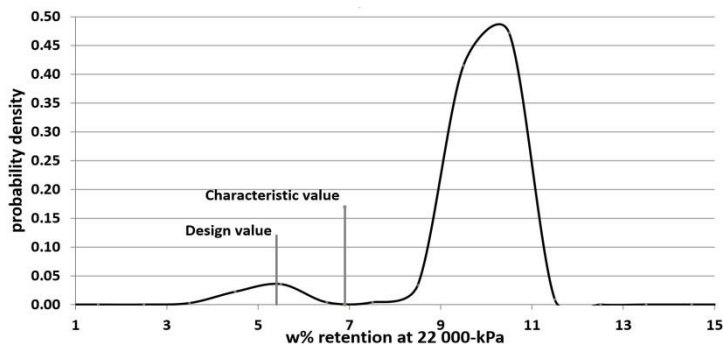


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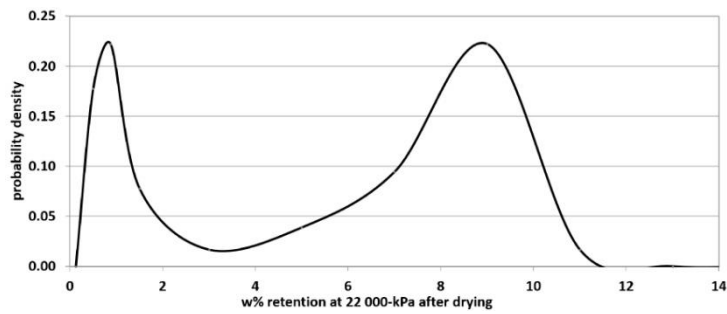


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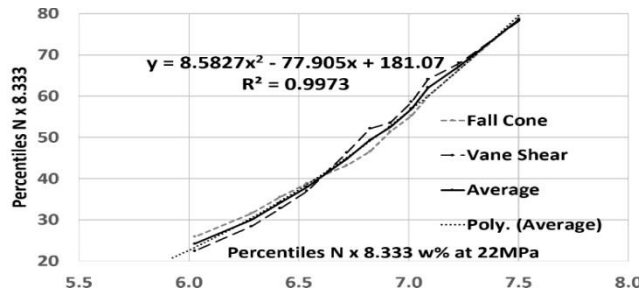


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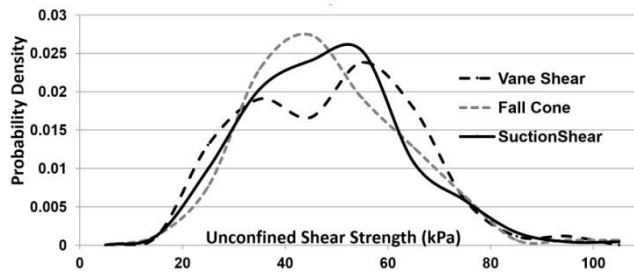


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References

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