Evaluation of different soil shear strength testing procedures taking inherent soil variability into account

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ABSTRACT: Historically, the Workload design method has served as the foundation for geotechnical designs. This approach relies on global safety factors which does not guarantee a sufficient margin of safety against every uncertainty involved in design. Limit states design accounts for probable failure by using partial safety factors for characteristic values to obtain a design value. Characteristic values are determined based on probability theory and statistical distributions. To obtain reliable probability density functions a large dataset of measurements is required to increase confidence in parameter values and statistical reliability. It is unfeasible to establish the 5th percentile of a soil parameter for most shear strength tests due to time and expense. This research evaluates three testing methods to obtain reliable probability density functions for more reliable data analysis and a less conservative characteristic value.

1 INTRODUCTION

Geotechnical designs have conventionally relied on the Workload design (WLD) approach which relies on average values of soil parameters and subjective global safety factors to account for various uncertainties to ensure sufficient reliability. This approach does not account for variability and has resulted in overly conservative or unconservative designs (Allen, 2007) with safety factors being a poor measure of reliability. The alternative Limit States design (LSD) approach was later introduced to geotechnical engineering in the early 1990s with the introduction of Eurocode standards and more specifically Eurocode 7 for geotechnical design. Several countries, including South Africa, has adopted the Eurocode in one form or another. The LSD reduces the likelihood of design failure through the use of partial safety factors for each associated uncertainty. The selection of characteristic values is a fundamental aspect of this approach which is determined by various methods. Figure 1 summarizes the various ways in which a characteristic value is selected according to Eurocodes. Characteristic values are determined based on past experience, statistical methods, making a cautious estimate or selecting values from standard tables. This has led to some debate with experts being hesitant on selecting a characteristic based on a "cautious estimate". Eurocodes provides little guidance in this regard and the only apparent way to determine the characteristic value of a soil parameter would be by means of statistical methods. Eurocode specifies a 95% confidence level in the dataset if statistical methods are used. A variety of statistical procedures are available for choosing and fitting of probability distributions. Essentially, the coefficient of variance and probability density functions are used to quantify inherent soil variability (Phoon & Kulhaway, 1999; Cortellazzo, 2000). Detailed and reliable statistical analysis necessitates a large number of reliable measurements. According to Stott (2020a, b,) more than 600 measurements are required to establish reliable a probability density function. Because of this, many if not most soil shear strength tests cannot determine the 5th percentile of a soil property without incurring significant time and financial costs. Due to time and budgetary constraints, it is rarely possible to perform more than a minimum of number of tests, typically 3, which decreases our knowledge and comprehension of soil variability (Blight, 2013). Eurocodes assume soil properties to have a lognormal distribution, however, research done by Galeandro et al (2017), Stott & Theron (2018) indicated that this might not always be the case due to variability in some (cohesive) soils. Three testing methods are used in such a way that allows for a large of measurements that may allow for more reliable variability analysis. These tests can be used to evaluate the PDFs for soil shear strength which may lead to procedures that actually accounts for soil variability.

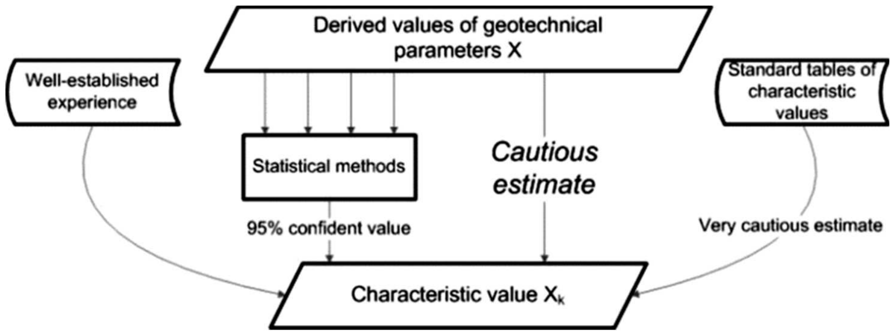

Figure 1. characterizing geotechnical parameters (Bond & Harris, 2008)

2 LIERTAURE

2.1 *Soil variability*

Soil variability is a complex attribute that results from various sources of uncertainty. The main sources of uncertainty being inherent soil variability, measurement error and transformation uncertainty (Kulhawy et al, 1992) along with statistical uncertainty when estimating soil properties (Ehnbom & Kumlin, 2011; Schneider & Schneider, 2013). The cause of inherent soil variability is due to natural geological processes which continue to modify soil, whereas the tools and techniques used in soil testing leads to measurement error. When measurements are converted into design attributes through the use of correlation models and empirical formulas, transformation uncertainty is introduced. Measurement error frequently includes statistical uncertainty which can be minimized by performing an adequate number of objective tests. It is fundamentally challenging to determine the mechanical and chemical properties of many geomaterials due to their highly variable nature (Bond & Harris, 2008). The multiple spatial scales also contribute to the soil variability of samples, and it is therefore important to evaluate the effects of soil variability. The shear strength of soil is a very important property of soil and engineers rely on shear strength values for a wide range of applications within the geotechnical and civil engineering fields. The primary factors that determine a soil's strength are the moisture content, clay size and quantity of clay particles (Dolinar, 2004).

2.2 *Shortcomings of common shear strength testing procedures*

Various tests and testing procedures have been developed and used over the decades to estimate the shear strength parameters of soil by means of in-field or laboratory testing. The direct shear test is one of the most commonly used methods due to relative operational simplicity. Testing accuracy is directly impacted by proper sample preparation. Some limitations need to be considered when using the direct shear method. Sample size can be difficult to obtain particularly of cohesive soils where small samples exhibit anisotropy. Information is provided on the shear strength in one plane whereas in the field the sample is subjected to stresses in multiple planes. According to Das (2008) since the sample is not allowed to shear along the weakest plane the reliability of such results may be requested. Furthermore, drainage conditions cannot be controlled with pore pressure assumed to be zero which may not be true in-field (Craig, 2004). Research by Bro et al. (2013) confirms that the shear displacement rate has a significant impact on drainage conditions within clay samples. Therefore, by conducting direct shear tests too rapidly, practicing engineers might be inadvertently measuring partially drained response. For consolidated or lightly consolidated materials, the drained shear strength would be underestimated, whereas the drained soil strength would be overestimated for severely over-consolidated materials that show dilatant behaviors under shear. Three conventional triaxial test types exist with the unconsolidated undrained test method being used more commonly on cohesive soils. Limitations of triaxial testing include small sample sizes (36 mm in diameter) which may not represent the behavior of larger soil masses accurately (McCarthy, 2006). Sample disturbance can also exhibit considerable scattering which influences test results. Typically, there is only one loading path and a high loading rate, which may not fully represent the complex loading conditions and paths that exist in the field (Murthy, 2002). Both testing methods can be very expensive and relatively complicated to perform on cohesive soils which may take anything from a couple of days to weeks for a single test measurement. Common field testing includes the use of pocket penetrometer and handheld vane shear devices. Both methods are simple and quick to use with relatively good accuracy. Accurate results may not be obtained if the failure envelope is not horizontal, and testing may not be suitable on cohesive soils due to sand lenses and seams and silt laminations. Application on stiff clay samples is also limited. For cohesive soils the pocket penetrometer may be a better alternative than vane shear testing. Scholars observed the pressuremeter tests generally overestimate strength values compared to vane shear, triaxial and static cone testing. Testing devices have improved over the years, but shear strength reading remains higher than other tests. This is due to the different modes of failure and the presence of a disturbed zone around probes (Isik et al, 2014). Consolidation also affects the undrained analysis of soil which leads to this overestimation on clay soils. The static cone penetrometer has very limited accuracy when it comes to soft soils and typically refuses in stiff soils. Testing remains very labor intensive with testing rigs not commonly used for everyday investigation. There are benefits and drawbacks to each of the shear strength tests mentioned. Test apparatuses can be costly and using them requires a thorough understanding of how they work. Most of the testing procedures can only obtain a few readings which are averaged to obtain a representative value of the soil under testing disregarding the range of inherent variability. A large number of test values are needed for reliable probability density functions in order to produce a 5% or 95% fractile value for design input. To do this, test methods that are easier to use, more affordable, and faster can be employed. Studies indicate that the distribution type of undrained shear strength may differ from that of other engineering materials, such as manufactured goods. Design values that could be used with a fair amount of confidence can be obtained by following (LSD). But to do so would mean giving up on current testing methods, which are restricted by the load factor design approach. This will necessitate updating a number of testing protocols and techniques.

2.3 *Testing devices used for the study*

Three testing methods, the vane shear pocket penetrometer and fall-cone test, were investigated for the study in order to obtain reliable probability density functions. Vane shears are simple and accurate to use with most site investigation manuals and codes including the description of the equipment and recommends its use. The pocket penetrometer is lightweight and approximates unconfined strengths in a fast and reliable way. The fall-cone device has become a popular alternative to the Casagrande cup in determining the Atterberg limits of remolded soil samples. The test can also be used to estimate the undrained shear strength of remolded and undisturbed samples collected infield. The cone tip angle and cone mass are the primary differences between the various international standards for the fall-cone test. Table 1 below summarizes the main differences between the standards.

Table 1. Fall-cone standards across the world (adapted from Feng, 2005).

Country	Standard	Cone Angel	Cone mass
Australia	AS 1289	30	80
Canada	CAN/BNQ 2501-092-M86	60	60
China	SD128-007-84	30	76
France	NF P94-052-1	30	80
India	IS 2720-5	30.5	148
Japan	JGS 0142	60	60
New Zealand	NZS 4402	30	80

Norway	NS 8002	60	60
Russia	GOST 5184-49	30	76
Sweden	SS 027120	60	60
UK	BS 1377-2	30	80

3 METHODOLOGY

For laboratory Fall-cone test, undisturbed samples were gathered from soil layers in a variety of test pits. Undisturbed samples were protected against drying before testing using perforated wrap. The same soil layers were tested infield using the pocket penetrometer and the hand vane shear device to compare the results with the fall-cone test. Soil testing and sampling was done at various locations in and around the metro municipality of Bloemfontein in the Free State, Sout Africa. The sites fall under the Adelaide Subgroup of the Beauford Group and Karoo supergroup which consist of mudrock and sandstone along with dolerite. Manufactured stainless steel sampling rings with a cutting edge on top that measured 5.5 cm in diameter and 2 cm in height were used for the undisturbed sampling for fall-cone testing in the laboratory. The rings were created and produced in accordance with a typical oedometer ring that is utilized for consolidation testing in laboratories. The sample rings were gently driven into the stiff soil layers using a mallet and a wooden block. Utilizing a geological pick, the sample ring's surrounding area was marked once it had fully penetrated the layer of soil. A section approximately 20 by 20 cm was marked out for removal and cutting. A sizable chunk of soil along with the ring was retrieved from the sidewall. Figure 2 below illustrates the typical sampling of the soil samples. The sample was prepared by carefully removing any material that had been disturbed from the top of the sample ring and placing it on a level surface before fall-cone testing could commence. Testing was done using a 30º cone with a standard weight of 80 g as recommended by the ISO 17892-6 standard used and most standards mentioned in table 1. Heavier weights were later added to obtain higher penetration readings. A cone factor value of 0.8 was also used to determine the shear strength.

Figure 2. Probability plot for fall-cone testing (Estoire site).

4 FINDINGS AND RECOMMENDATIONS

The pocket penetrometer and fall-cone test produced significantly more test results than the vane shear and arguably considerably more than any other strength test (i.e. shear box and triaxial testing). The vane shear posed some challenges during testing and could not obtain results for most of the sites due to the over consolidated soil layers encountered with blades being difficult to clean and to penetrate the soil layers. The device was only capable of measuring a maximum of 280 kPa. Most of the samples were heavily over consolidated producing shear strength readings much higher than 280 kPa using the pocket penetrometer and fall-cone. Probability plots were obtained using MARTLAB to verify whether or not the test data was a good fit to a lognormal distribution or not as stipulated by Eurocodes. For both the fall-cone and pocket penetrometer testing, none of the soil samples taken from the site fit the theoretical distribution (lognormal). The majority of FC probability plots indicate that the curves resemble lognormality at values near the midrange but deviate from lognormality as one approaches the outer edges as indicated in figure 3 below. Therefore, it is unlikely that the curves' 5% and 95% fractile values have any significance. For comparison, the combined PDFs of the two testing techniques are also shown in figures 4 and 5. The combined PDF shows that different patterns are produced by the two testing devices for the same soil sample. The PDF data is left-skewed for fall-cone testing. Increasing the fall-cone factor slightly may correct this and provide results close to the pocket penetrometer. The pocket penetrometer produces slightly (50 kPa) higher readings than the fall-cone. Using the 80g cone weight is not sufficient to obtain penetration readings higher than the prescribed minimum 4 mm penetration. Increasing the weight to the maximum of 400 g as specified by ISO 17892-6 delivered relatively low penetration readings between 4 and 6 mm for some of the samples. Research indicates that the fall-cone apparatus needs to be adjusted to allow for heavier weights possible as heavy as 1kg when it comes to testing on undisturbed stiff soils.

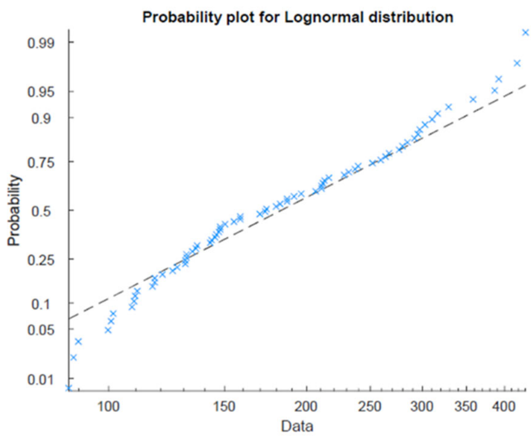

Figure 3. Probability plot for fall-cone testing (Estoire site).

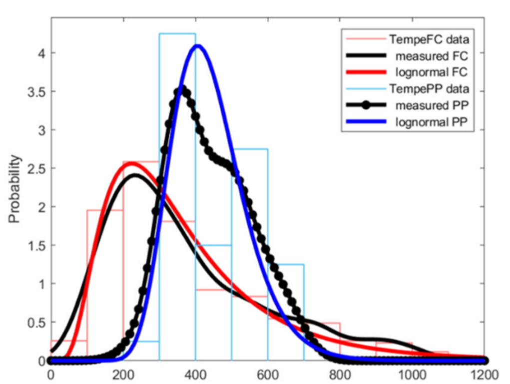

Figure 4. Combined probability density function (Tempe Site).

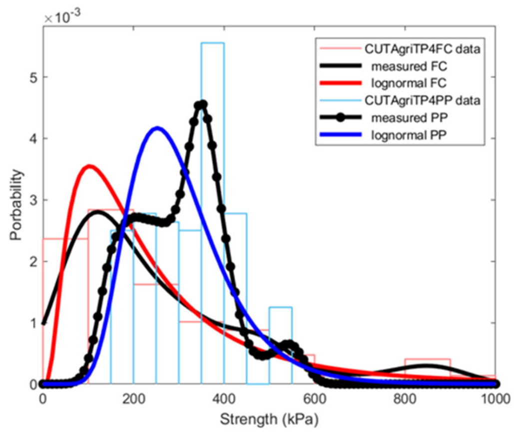

Figure 5. Combined probability density function (CUT Agri site).

5 CONCLUSION

The pocket penetrometer and fall-cone are both great tools to obtain large datasets in order to assess a soil's probability density functions in a quick and reliable way. Research indicates that measured shear strength probability density functions for cohesive soils may not always be a good approximation to lognormal curves due to inherent sample variation. A review on the fall-cone indicates that the empirical formula used to determine the shear strength of undisturbed stiff cohesive samples needs to be amended as opposed to using the same testing procedure and formula on remolded soil samples. A heavier cone weight (greater than 400 g) is recommended along with a slight adjustment of the cone factor, however more research is required in this regard. A correlation between the pocket penetrometer and fall-cone testing could also be investigated since similar strength readings were obtained.

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