An improved statistical analysis of field soil testing methods for design purposes

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ABSTRACT: Traditionally, geotechnical designs have relied on the Workload Design approach, which uses subjective global factors of safety to address uncertainties and ensure reliability. However, this method often results in designs that are either overly conservative or insufficiently safe. The Limit State Design approach offers an alternative by using partial safety factors tailored to specific uncertainties, aiming to reduce the probability of failure. Characteristic values for design are derived using judgement, experience, and statistical methods, with the latter being the most effective in addressing uncertainty and variability. Statistical methods require selecting characteristic values to ensure a failure probability of no more than 5%, theoretically necessitating over 600 tests, which is impractical due to costs and time constraints. A large dataset is essential for improving confidence in parameter values and statistical reliability. Therefore, frequent economical tests may yield more accurate results than infrequent sophisticated tests. The research evaluates three soil shear testing methods-field vane shear, pocket penetrometer, and fall cone test-to obtain reliable data analysis and establish less conservative characteristic values for design input. Difference between these methods is noted, along with potential improvements in test interpretation and equipment.

1 INTRODUCTION

Geomaterials are more variable in nature compared to manufactured materials with variability in geotechnical design resulting from a variety of different sources of uncertainty. According to Kulhaway et al. (1992) the main sources of uncertainty can be attributed to measurement error, transformation uncertainty, and inherent soil variability, with the latter receiving little attention from both industry and in tertiary-level education (Stott & Theron 2016). Statistical uncertainty may also be present when estimating material properties (Ehnbom & Kumlin 2011, Schneider & Schneider 2013). To gain a comprehensive understanding of soil property variability, site investigations and testing must be both accurate and thorough. By using statistical analysis to quantify variability and incorporating probabilistic design, inherent soil variability can be addressed (Phoon & Kulhaway 1999, Cortellazzo 2000). Accurate and dependable statistical analysis requires a substantial number of reliable measurements. Stott (2020a, b) suggests that over 600 measurements are necessary for reliable statistical analysis of inherent soil variability. Harr (1987) highlighted the effectiveness of statistical measures, such as the mean, variance, and coefficient of variance (COV), in quantifying soil property variability. COV is commonly used to assess data dispersion. Harr (1987) further classified variability into three categories based on COV. This paper aims to assess cost-effective shear strength testing methods that efficiently produce a large dataset within a reasonable timeframe, leading to more accurate measurement of the inherent variability in soil shear strength.

2 METHODOLOGY

2.1 *In-field testing*

Field testing and sampling for this study were carried out by the researcher along with an industry partner. Various test pits were excavated across the Mangaung Metro Municipality, Free State. A field kit, including a pocket penetrometer (PP) and vane shear (VS) device with interchangeable heads and vanes, was used for in-situ testing. Stainless steel sampling rings for extracting undisturbed soil samples were manufactured by the university's mechanical department for fall-cone (FC) testing in the laboratory. Soil shear strength measurements were taken with both devices (PP & VS) on the same soil layer along the sidewall of each excavated test pit. The PP involved pressing the retracting head into the soil, and the force was measured on a calibrated scale in MPa. The VS device, using a spring-loaded vane blade, was pushed and rotated into the soil to obtain readings. The vane blades were cleaned after each measurement to remove soil residues. Different penetrometer heads and vane shear blades were selected based on the soil's stiffness or softness. A larger head was used for softer soils, and a smaller one for stiffer soils. Test results for both devices were recorded by an assistant in a field book. Extracted soil samples were protected against moisture loss and disintegration during transport.

2.2 *Sample preparation for FC testing*

Sample preparation involved removing disturbed material from the top of the sample ring and placing the sample on a flat surface beneath the FC apparatus. The cone was locked in an elevated position and lowered to just touch the soil sample's surface. The undisturbed samples, following ISO 17892-6 (2017), were tested using a standard FC device. Excess material was carefully cut away, and a portion was taken for moisture content analysis. The sample was positioned under the cone, which was then released to penetrate the soil for 5 seconds, with the penetration depth measured using a digital depth gauge. After each measurement, the cone was cleaned and re-positioned for the next test. The type of cone and weight used were also recorded. While prior studies suggested using an oil layer on the cones, this was not done, as these claims were disproved by Llano-Serna and Contreras (2020). The ISO standard also makes no mention of this. A minimum of three measurements per sample was required by ISO 17892-6 (2017), but the researcher aimed to obtain more readings for more accurate and reliable data analysis. The cone factor value suggested by ISO 17892-6 (2017) is slightly lower (0.8) compared to the factor values recommended by numerous scholars (Karlsson 1961, Houlsby 1982, Wood 1985 & Zreik et al. 1995) when using the 30° cone.

3 FINDINGS

3.1 *Problematic vane shear*

The VS test, though widely used for measuring the undrained shear strength of cohesive soils, was unsuitable for this research project due to its limitations in testing duration, procedure, and shear strength capacity. Most of the investigated soils were very stiff or hard, making it difficult to insert the vane blades. The device's maximum measurable shear strength is 280 kPa, which was exceed by most soils tested. Additionally, cleaning the blades after testing was challenging and could affect subsequent results. Due to the limited number of readings, no comparison could be made with other testing methods. The test is more effective for very soft clays, making it unsuitable for this research area. Smaller vane blade could potentially address these issues but were beyond the project's scope.

3.2 *FC challenges*

The FC method is commonly used to determine liquid limits and estimate the shear strength of fine-grained soils. However, it may not always be suitable for assessing the shear strength of soil, particularly in undisturbed samples. This is due to low shear strength readings and the empirical formula used to convert penetration data into shear strength values. The k factor value plays a significant role in correlating the FC results with the undrained shear strength of soils. Factor values can range from 0.8 to 1.2 depending on the soil type and cone surface roughness. Most standard practices use a value of 0.8. With varying calibration methods and standards, the cone factor values differ, affecting the consistency and comparability of results across different regions, countries, and testing protocols. The main challenges of using the FC method on undisturbed soil samples are discussed in the following sections.

3.3 *Low penetration readings*

Using the recommended 80 g cone for FC testing resulted in very low shear strength readings for testing on extruded undisturbed samples. The smaller the penetration, the higher the shear strength. To obtain higher penetration readings, the cone mass was increased to of 400 g. Despite this, increasing the cone mass did not significantly improve penetration readings across sites. The sites Bloemdal 1 and Somerton exhibited the lowest penetration readings and highest shear strength, but there were not analysed further due to unrealistically low penetration values (<1 mm). The relationship between penetration and shear shows a slight increase after a 10 mm penetration and a greater increase after 4 mm, with the greatest increase occurring below a 2 mm penetration reading. Even a small difference in penetration (0.1 mm) can have a significant impact on shear strength results for very low penetration values, potentially leading to inaccurate and variable data. Figure 1 below shows the shear strength values at different penetration readings using a 30º 80 g cone.

3.4 *Transformation uncertainty*

The fall-cone method relies on an empirical formula to convert penetration readings into shear strength values, which introduces transformation uncertainty. This uncertainty is reflected in the COV of both penetration data and the converted shear strength values as shown in table 1 below.

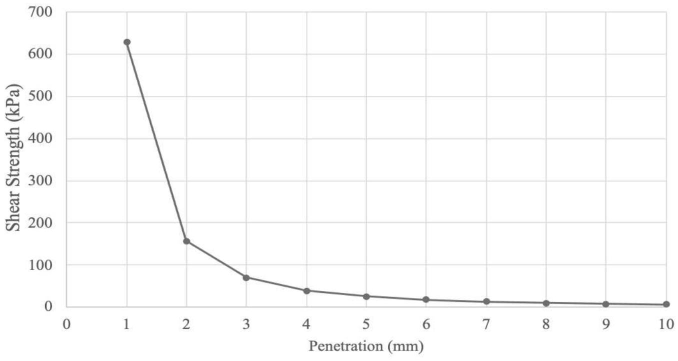

Figure 1. Penetration & shear strength relationship (30° 80 g cone)

Table 1. COV % for FC penetration & shear strength values

Site name	COV %	
	mm	kPa
Tempe	28	52
CUT Agri TP2	39	65
CUT Agri TP4	36	66
Somerton	44	65
Bloemspruit	21	40
Estoire	20	43
Bloemdal 2	12	26

Since the fall cone is not a direct shear measurement and the formula is logarithmic, the conversion leads to scattered data, increasing the COV almost twofold. This transformation causes unrealistic variability in the data, and the cone factor may further contribute to the scatter and increased COV.

3.5 *Sample disturbance*

During FC testing, the quality of the soil sample and its composition can impact the results. Stone fragments or organic material can reduce penetration readings and artificially increase the shear strength values of the soils tested. Silty or dry samples may not remain intact during testing, affecting the accuracy. Additionally, using a wire cutter to smooth the sample, before testing, can cause shearing, compromising the sample's integrity.

3.6 *Fall-cone vs pocketed penetrometer*

The FC and PP test provided significantly more test results in a shorter timeframe than the VS and potentially more than any other shear strength test (e.g. shear box and triaxial testing). The number of results from the FC depends on the number of undisturbed samples collected using the sample rings, sometimes producing fewer or more results than the PP. While a substantial amount of data could be collected for each soil sample, it falls short of the 600+ results needed for a fully reliable PDF analysis. The FC test generally underestimates shear strength readings compared to the PP test for most sites, likely due to the cone factor (0.8) used in the FC formula. For two of the sites the FC overestimated the shear strength due to low very penetration readings (<1 mm). Increasing the cone factor to 0.9 or 1.0 makes FC shear strength results more comparable to PP readings for some soils. Further research is needed, as a higher cone factor may not be suitable for all soil types.

Figure 2 compares the COV % for shear strength between the FC and PP across sites. FC testing generally has a higher COV % than the PP, except at Bloemdal 2, where fewer tests and higher penetration values influenced results. The FC COV values exceed those reported by Bond and Harris (2008) for undrained shear strength, which is notable given the apparent homogeneity of the soil layers tested.

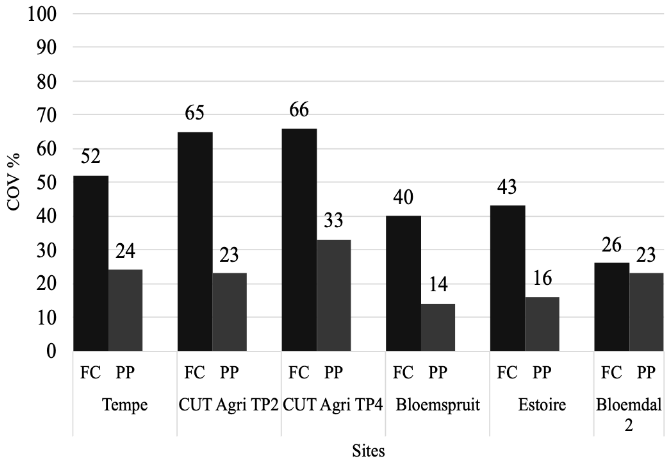

Figure 2. COV % for FC & PP shear strength values

Harr (1987) categorises variability into three groups based on COV %, as shown in Table 2. According to this classification, PP results indicate that all site samples are moderately variable, except for Bloemspruit, which exhibits low variability. In contrast, FC results show that most site samples are highly variable, primarily due to transformation uncertainty when converting penetration readings to shear strength values. Bloemdal 2 is classified as moderately variable for both FC and PP testing.

Table 2. Degree of variability (Harr 1987)

Degree of variability	COV %
Low	< 15
Moderate	15 < COV < 30
High	COV > 30

Measured probability density functions (PDF) and lognormal distribution fits for each soil sample indicate that FC PDFs are skewed to the left, exhibiting broader distributions with positive skewness. In contrast, PP PDFs are narrower, suggesting more concentrated values around the mean. The skewness in FC results arises from methodological challenges in converting penetration depth to shear strength, which could be mitigated by increasing the cone factor (de Villiers et al. 2024). Combined PDFs across sites highlight methodological differences, with FC generally underestimating compared to PP. Figures 3 and 4 on the following page illustrate the combined PDFs for FC and PP testing at the specific sites.

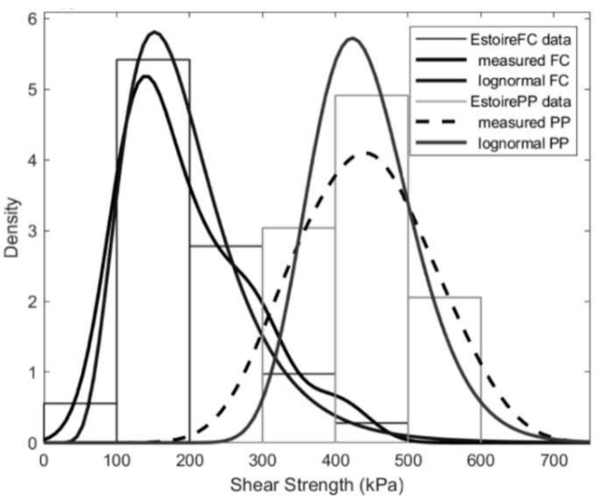

Figure 3. Estoire combined PDF

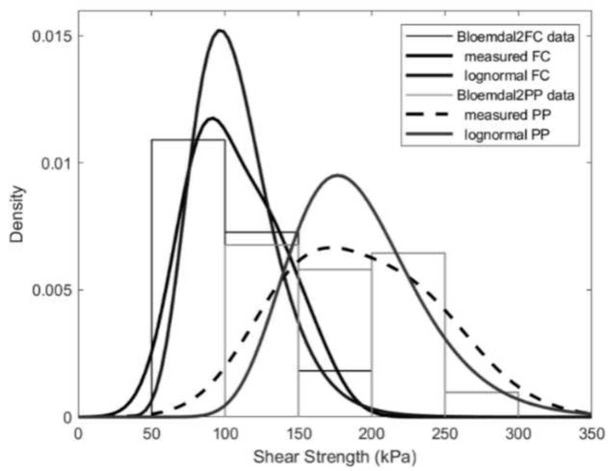

Figure 4. Bloemdal 2 combined PDF

The FC violin plots exhibit a consistent pattern/trend across all sites, with data predominantly concentrated in the first quartile, with a tail extending to the maximum, indicating positive skewness. In contrast, the PP plots display no clear trend or similarities between sites. Figures 5 to 8 illustrates the FC and PP violin plots side by side for specified sites.

MATLAB was further used to create probability plots to verify if the test data from various sites fit a lognormal distribution. PP testing shows poor lognormal fit for most samples, indicating higher-than-expected variance for a lognormal distribution. Most samples fit the theoretical lognormal distribution well for FC testing. The FC probability plots indicate similarity to a lognormal distribution near the midrange, but deviations occur towards the outer edges, as shown in Figure 9. Therefore, the 5% and 95% fractile values of the curves are unlikely to be meaningful (de Villiers et al. 2024).

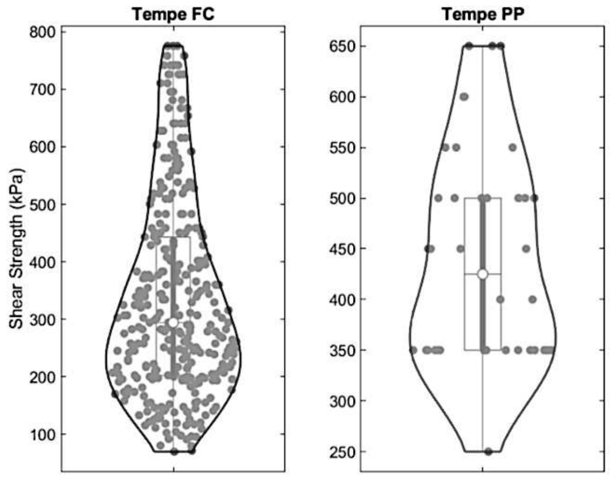

Figure 5. Tempe Violin plots

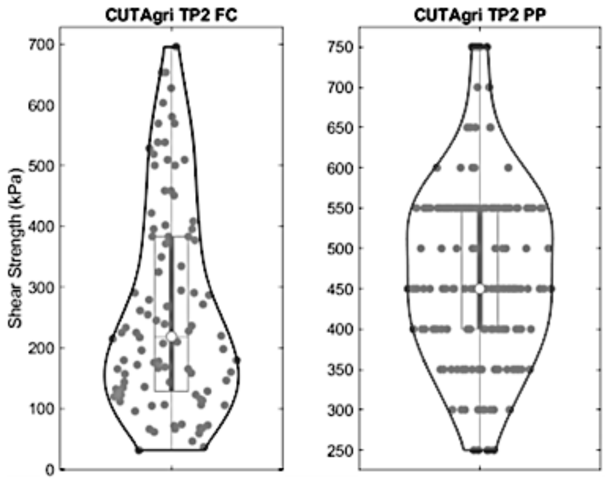

Figure 6. CUT Agri TP2 violin plots

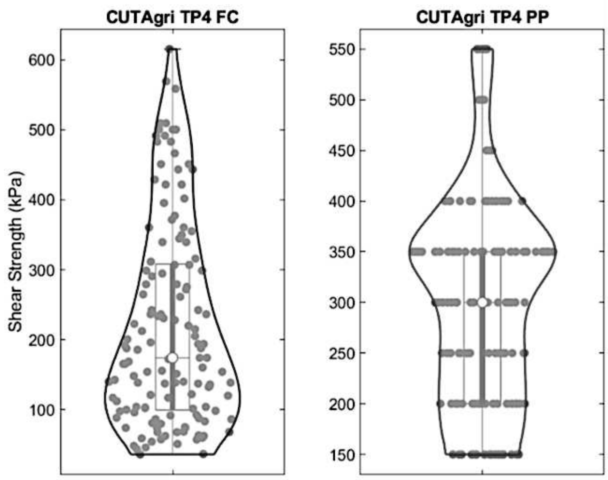

Figure 7. CUT Agri TP4 violin plots

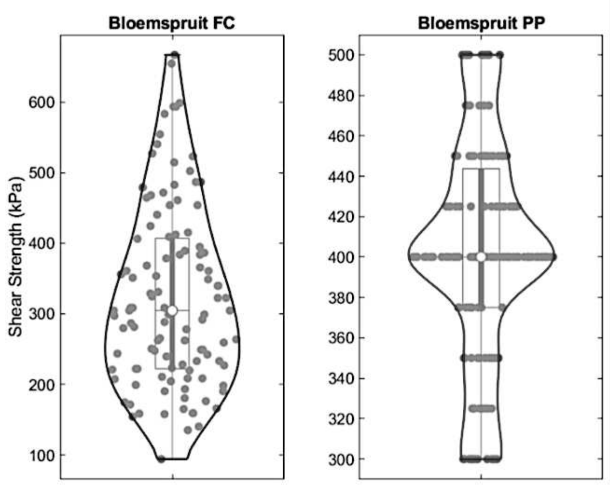

Figure 8. Bloemspruit violin plots

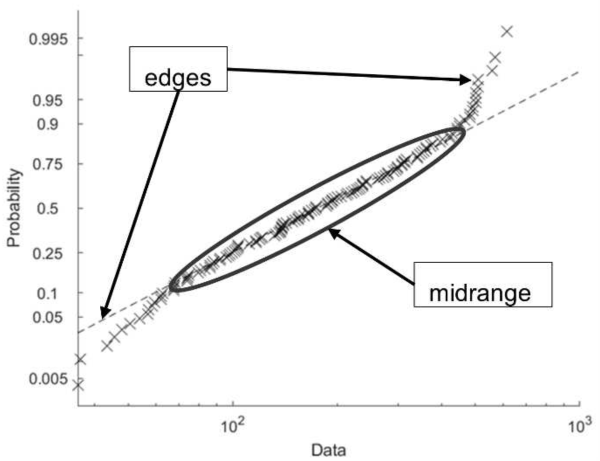

Figure 9. FC probability plot trend across sites

3.7 *Summary on findings*

Various tools and techniques were employed to visualise and analyse data from FC and PP tests. Converting penetration readings to shear strength increases data dispersion and variance. PDFs suggest that FC data aligns well with a lognormal distribution, as confirmed by probability plots, though minor deviations appear at the edges. Violin plots indicate a high concentration of FC data near the first quartile, highlighting positive skewness. FC testing also results in higher COVs, a broader range, and a wider IQR, indicating greater variability.

Conversely, PP PDFs show that PP data does not consistently fit a lognormal distribution. Violin plots reveal no clear patterns among samples, suggesting sample-specific variability. Probability plots further confirm that PP data deviates from a lognormal fit. Compared to FC, PP testing yields a smaller range and IQR, indicating more concentrated values around the midpoint and lower variance.

4 CONCLUSIONS

The FC is not ideal for assessing the inherent soil variability of undisturbed soils due to issues with the methodology, such as varying cone factor values used in different regions, low penetration depth, and sample condition. The conversion of penetration data to shear strength relies on the cone factor and a logarithmic equation, which can lead to inaccuracies and introduces transformation uncertainty. Using a higher cone factor may improve results and align FC readings more closely with PP readings. The PP, on the other hand, is effective for measuring soil variability, providing direct shear measurements without the need for conversions. It produces more consistent results and has fewer issues compared to FC. While the FC tends to underestimate shear strength and overestimate it for soils with penetration under 1 mm, the PP provides more reliable and consistent readings for undisturbed samples. Both PP and FC allow for quick, cost-effective data collection while the VS is unsuitable for soils in the studied are due to its inability to measure high shear strengths for stiffer soils. The PP provides the most realistic and consistent data across tests. It effectively indicates soil variability using Harr's (1987) classification method and the soil's COV.

5 RECOMMENDATIONS

Uncertainties persist in selecting the appropriate cone factor value, especially when comparing undisturbed and remoulded sample testing. The type of sampler used, and the degree of sample disturbance can influence the cone factor. Additionally, research is needed on using heavier weights (greater than 400 g) for increased penetration (6 mm to 10 mm) on stiff undisturbed soil samples. This would require modifications to the FC apparatus to accommodate larger size and/or heavier weights. The correlation between the FC test and the PP for could be further explored, as the study found somewhat similar undrained shear strength readings. Adjusting the cone factor for undisturbed FC testing may yield more comparable data between the two methods. Additionally, refining the empirical formula for undisturbed samples with low penetration values could reduce data scatter when converting penetration measurements to shear strength value. Exploring the relationship between soil suction measurements and shear measurements using FC and PP could also be compelling for inherent variability analysis.

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