Effect of Variability and Disturbance in the Measurement of Undrained Shear Strength

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Summary: Natural soil variability and sample disturbance are issues to be accounted for in any site investigation. While standards help reduce the inconsistency in determination of soil parameters, there is still some variability from soil disturbance, as the procedures and interpretation carried out by various supervising geotechnical engineers do differ considerably.

The undrained shear strength is one of the more variable soil parameters. Many quick and easy tests such as the Standard Penetration Test (SPT), Pocket Penetrometer (PP), and Vane Shear (VS) are routinely used in the measurement of this strength parameter. There seems to be divided opinions in various geotechnical reports on the use of the PP on a sample obtained from a SPT sample. The rational that the PP on SPT sample provides additional information, and therefore is better than no PP tests. This paper provides the theoretical evidence that sample disturbance distorts the PP value obtained in this manner. Case studies are then shown where PP values were obtained from undisturbed 50mm samples (U50) and SPT samples and the variability inherent in such values.

INTRODUCTION

Natural soil variability occurs even in uniform sites. This random variability can be further clouded with the equipment and procedures used in the testing. Sample disturbance can have a significant effect in the numerical values obtained from the test results.

While standards supposedly reduce the errors inherent in the above variability, the procedures and interpretation carried out by various supervising geotechnical engineers do vary considerably. This paper examines a few of the quick and easy tests that are typically used in a site investigation and the variability that is currently occurring in practice.

The Pocket Penetrometer (PP) and Standard Penetration Tests (SPT) are routinely used to determine soil undrained strength. The SPT on clays can have some variability in its results and interpretation, and ideally undisturbed samples should preferably be obtained in clays. This paper discusses the case where SPTs are carried out in clays to obtain the undrained strength. In addition, some supervising engineers carry out PP testing on SPT samples. The variability associated with PP tests on undisturbed 50mm samples (U50) and SPT samples are shown by a case study.

CHARACTERISTICS OF GEOTECHNICAL VARIABILITY

All tests have measurement errors associated with them. These errors are due to:

- Random variability.
- Equipment / Test type; and
- Procedure used

Random and test error types are discussed in this section, while the procedural errors are discussed in the section that follows. This discussion shows that the undrained shear strength is one of the more variable soil parameters and that the SPT has one of the largest measurement errors.

Random Variability

Random variability of natural soil deposits is significantly more then manufactured materials. Concrete and steel, for example, have a coefficient of variation of 11% (Harr, 1996). This can be compared with the inherent soil variability properties given in Table 1 (Kulhawy et al., 1991).

Table 1. Coefficient of variation for available data (Kulhawy et al., 1991)

Parameter	Number of Observations	Mean Coefficient of Variation (without outliers) %
Unit Weight	12	7
Liquid Limit	28	11
Plastic Limit	27	11
Friction Angle, ϕ	20	13
Natural Water Content	18	18
Initial Void Ratio, e_0	14	20
Rock Uniaxial Compressive Strength, q_u	14	23
Undrained Shear Strength, S_u	38	34
Compression Index, C_c	8	37

This shows that the least variation can be expected in the unit weight measurement and the index properties. The largest variation can be expected in measurement of the undrained shear strength and the compression index. These values are approximately comparable with those quoted in Harr (1996). Table 2 shows this comparison together with variation associated with other material parameters.

Table 2. Coefficient of Variation (Harr, 1996)

Parameter	Coefficient of Variation %
Unit Weight	3
Friction Angle (Sand), ϕ	12
Natural Water Content (Silty Clay)	20
Undrained Shear Strength, S_u	40
Compression Index (Clay), C_c	30
Standard Penetration Test	26
Structural Steel – Tension Members	11
Flexure of Reinforced Concrete – Grade 60	11
Flexure of Reinforced Concrete – Grade 40	14
Flexure Strength of Wood	19

Test Variability

Table 3 summarizes the measurement errors associated with some common in situ tests. The measurement error for the SPT is the largest while the electric cone penetration and the dilatometer tests are the smallest.

Table 3: Summary of Measurement Error of Common In-situ Tests (Phoon and Kulhawy, 1999)

Test	Coefficient of Variation, COV (%)				
	Equipment	Procedure	Random	Total [a]	Range [b]
Standard Penetration Test	5 – 75[c]	5 – 75[c]	12 – 15	14 – 100[c]	15 – 45
Electric Cone Penetration Test	3	5	5 – 10	7 – 12	5 – 15
Vane Shear Test	5	8	10	14	10 – 20
Dilatometer Test	5	5	8	11	5 – 15

[a] *$COV(Total) = [COV(Equipment)^2 + COV(Procedure)^2 + COV(Random)^2]^{0.5}$*

[b] Because of limited data and judgement involved in estimating COVs, ranges represent probable magnitudes of field test measurement error.

[c] Best to worst case scenarios, respectively, for SPT.

SAMPLING AND SAMPLE DISTURBANCE

Soil disturbance can occur during:

- drilling;

- sampling;
- transportation and storage; and
- preparation for testing.

Any sample taken from the ground has already experienced some disturbance. The supervisor's role is to minimize such disturbance to provide confidence in the quality of the end result.

Hvorslev (1949) defined one of the critical parameters affecting the disturbance of soil during tube sampling as the area ratio, defined by:

$$Area\,ratio = \frac{D_e^2 - D_i^2}{D_i^2} x100\%$$

where:

D_e = external diameter of the sampler cutting edge
D_i = internal diameter of the sampler cutting edge

The smaller the area ratio the less likely the sample is to be disturbed. Thin walled samples for undisturbed samples generally have an area ratio of 10%. This is to be used in combination with a suitable cutting edge taper (Clayton et. al, 1995). Table 4 provides the usually specified area ratios.

Table 4. Area Ratios

Reference	Area Ratio	Comments
NAVFAC (1986)	≤ 15%	Defines (in part) where a sample can be considered undisturbed.
Queensland Main Roads (1977)	≤ 10%	For undisturbed soil sampling.
Smith GN and Smith IGN (1998)	≤ 25% ≤ 20%	For good undisturbed 100mm samples. For good undisturbed 38mm samples.

Rowe (1972) shows that the size of the sample should be appropriate to the fabric and data required. Rowe (1972) outlines various Quality classes of samples, and states that site work should commence with the taking of samples with an optimum diameter of samples of 76mm. Larger size sampling may then be required depending on the soil fabric observed. Thus sample size can affect the amount of disturbance of the soil.

The type of driving method also influences the disturbance of the soil. Table 5 provides the usual driving methods and its effect on sample quality.

Table 5. Driving Methods (Hvorslev, 1949)

Method	Motion	Sample Quality
Hammering: repeated blows of a drop hammer. Jacking: levers of short commercial jacks. Pushing: steady force – no interruptions.	Intermittent fast motion. Intermittent slow motion. Continuous uniform motion.	Worst
Single blow: blow of a heavy drop hammer. Shooting: force supplied by explosives.	Continuous fast motion. Continuous very fast motion.	Best

SPT SAMPLES

The question of whether an SPT sample is considered disturbed, may seem self-evident to some engineers. However the fact that there are many geotechnical reports which show a PP on a SPT sample means that there may be some uncertainty to some geotechnical engineers on the amount of the disturbance.

Tables 4 and 5 show the area ratios for good undisturbed samples, and the effect of driving methods on the quality of samples. The SPT sample is considered disturbed as:

- The SPT Area Ratio is greater than 100%, if the split tube sampler conforms to the Australian Standards A.S 1289. This is significantly above the 20% maximum value advocated for an undisturbed sample (Table 4). Therefore by definition, samples obtained from SPT sampling are considered highly disturbed as it has been subjected to remoulding.

- The sample size assumes that soil fabric has no influence.
- The hammering method of driving provides the worst sampling quality as shown in Table 5.

When an SPT sample is being driven 450mm with 1 blow should not be equated to the second "best" condition in Table 5. Such a sample suggests a soft / very soft deposit, which will be disturbed even more because of its sensitive soil structure. Where soil fabric is required and sensitivity greater than 5 then even a U50 (50mm undisturbed) sample is brought in question. Rowe (1972) describes the minimum sizes of specimens, and considers even a 50mm tube sample as destroying the structure of sensitive soils. A 35mm (inner diameter) SPT sampler would destroy the fabric even more.

Australian Standards 1289 (1993), British Standards 1377 (1990) and ASTM American Standards (1992) consider the SPT as producing disturbed samples for identification purposes. Further discussion can be obtained from Clayton (1986) on sample disturbance. The SPT is classed as a quality sample 3 or 4, where 1 is the best and 5 is the worst sample quality.

Despite the convincing evidence presented above, the popular text of Bowles (1996) shows a picture of a PP being carried out on an SPT sample (Pg 161). Some engineers use this as evidence that Bowles (1996) is advocating using the PP on an SPT.

However, Bowles (1996) does refer to the SPT as providing a **disturbed** sample, and in a classification ranking of A, B, and C where A is the most applicable and C the least applicable, the SPT is classified as a "C" – least applicable for determining the undrained shear strength.

COMPARISON OF TEST RESULTS

Pocket Penetrometer Test on Undisturbed 50mm samples

The pocket penetrometer (PP) while a useful and simple tool should be used with its limitations in mind. The PP value is halved to give the undrained shear strength (C_u). Due to its limited size of sample area, the PP value does not account for any structure in the clay sample. In addition, the PP test is carried out at a much faster rate than the Unconfined Compressive Strength (Q_u) in the laboratory. Therefore the results of the PP should not be used directly in design calculations. Figure 1 shows the relationship of the Q_u as tested in the laboratory and the PP value on the same U50 sample.

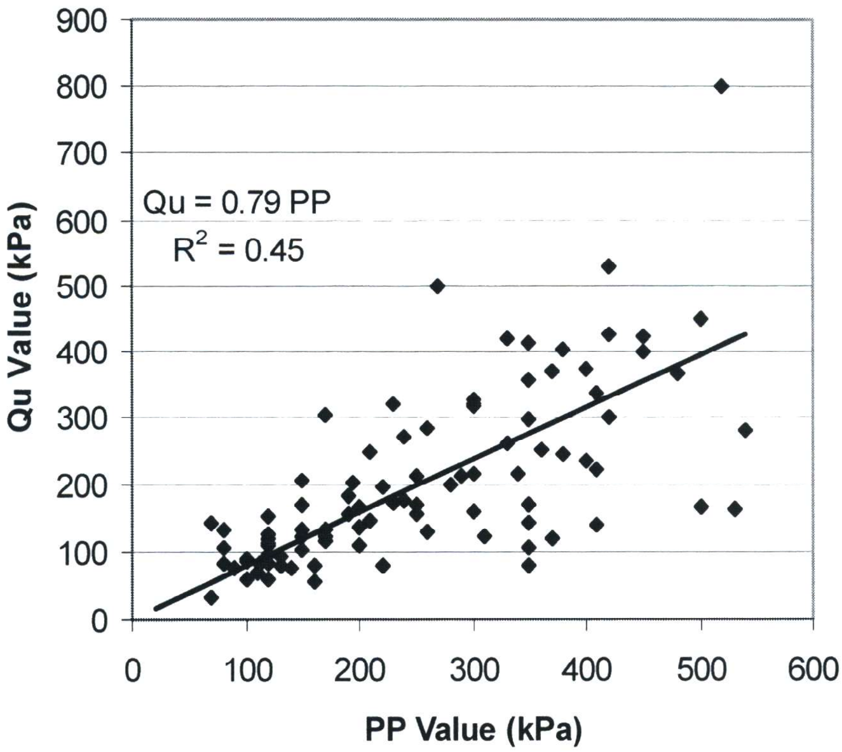

Figure 1. Relationship of Unconfined Compressive Strength with Pocket Penetrometer Values.

The 93 data points (n) plotted were obtained from 35 Queensland sites. As the maximum PP value is 600kPa, then all PP values greater than or equal to that value was neglected in the analysis. There is an improved regression correlation ($R^2 = 0.53$) for a power trend line. However, the simple linear trend line with the $R^2 = 0.45$ has been adopted for discussion purposes, and in general the Q_u value is 80% the PP value.

If the data is sorted and the obvious outliers are removed than, then the improved linear relationships calculated are shown in Figure 2. These Trend lines can be summarized as follows:

Q_u = 0.8 PP for all data (n = 93: $R^2 = 0.45$)
Q_u = 0.85 PP for natural material and non fissured material (n = 53: $R^2 = 0.76$)
Q_u = 0.6 PP for Fissured material (n = 21: $R^2 = 0.57$)
Q_u = 1.15 PP for Fill material (n = 7: $R^2 = 0.66$)

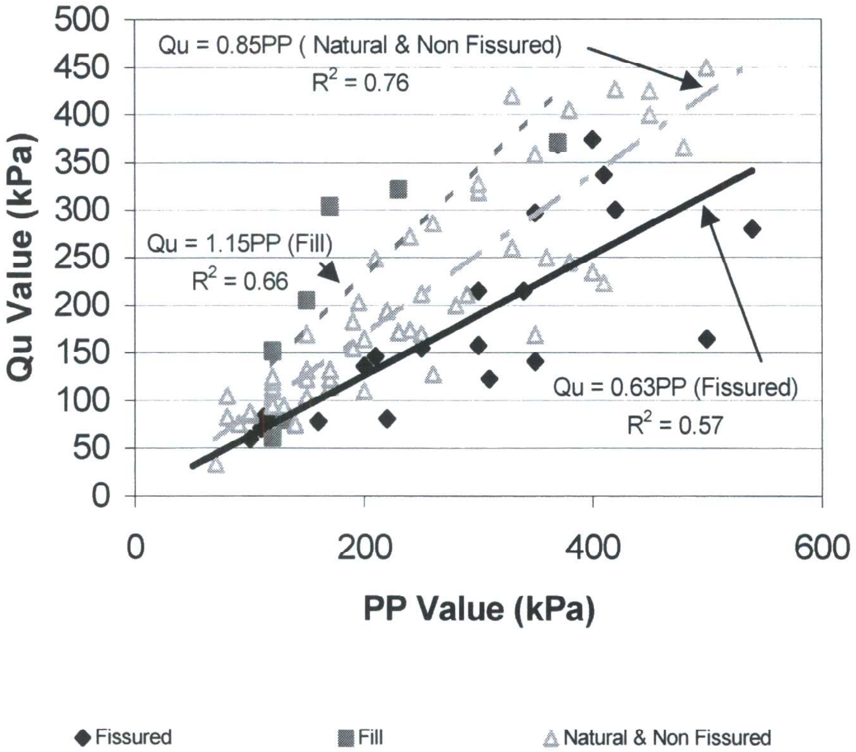

Figure 2. Relationship of Q_u with PP values for different clay structures.

Some Geotechnical Engineers do prefer the less subjective PP numerical value in classification of the clay strength (Soft, Firm, Stiff, etc) as against only the tactile feel of the sample (moulded by light finger pressure, strong finger pressure, cannot be moulded by finger pressure, etc). However, the numerical values from the PP if used in natural materials may overestimate the field strength of a clay.

Pocket Penetrometer Test on Disturbed SPT samples

The following case study illustrates the effect of carrying out PP tests on SPT and U50 samples. This was at a site in South Brisbane, where the geotechnical consultant carried out PP tests on both SPT and U50 samples. Figure 3 shows the data from this site. The PP on the actual SPT sample was tabulated and compared with the PP on the U50 samples on either side the SPT value. Therefore one would expect greater variability for the PP on the U50 samples because of the U50 tabulation using "nearby" data.

Yet, the results show a nominally better correlation for the PP on the U50 samples, and the U50 samples would also provide a strength value 12% lower then the PP on the SPT. However, for all practical purposes, there is not a lot of difference. The trend line shows:

PP	= 27.4 N (on SPT samples)	= 24.2 N (on U50 samples)
R^2	= 0.51	= 0.59

The C_u/N correlation in both cases however seems high, as a value of 5 is typical but within the range of 4 to 7. In soft sensitive clays the values can vary from 0.4 to 20 (Clayton, 1995). This soil was an insensitive over consolidated clay.

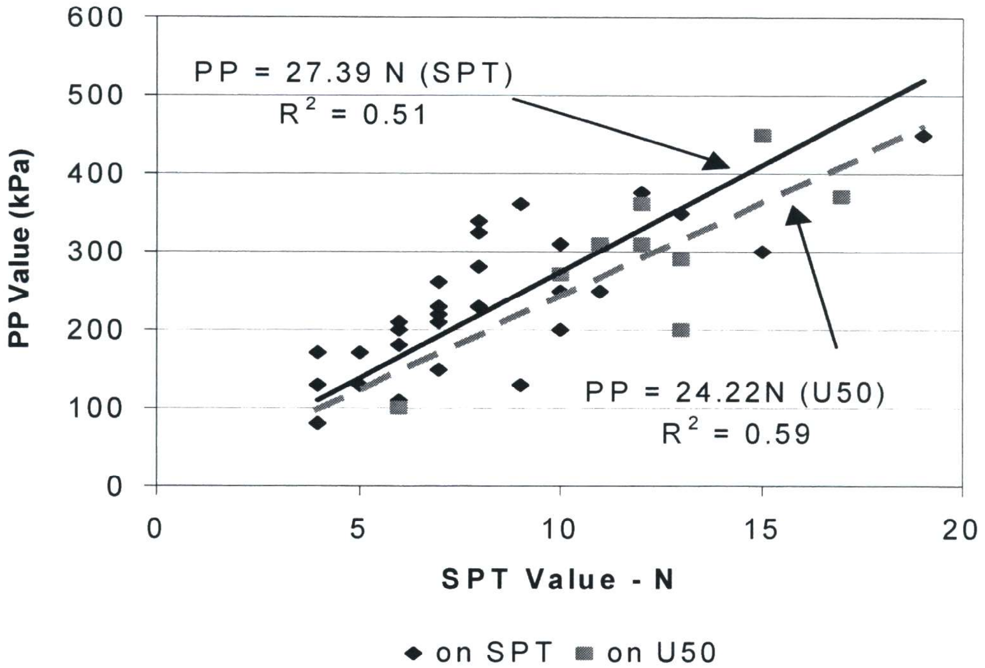

Figure 3. Relationship of PP Value with SPT.

Figure 4 compares the same numerical PP values on U50 and SPT samples with the tactile field assessment. A field description of firm (25kPa to 50kPa) to stiff (50kPa to 100kPa) can be expected to have maximum and minimum values of 25kPa to 100kPa, respectively. This is shown in Figure 4 as Max and Min. Only 8 of the 30 PP values on the SPT samples matched the range as expected by the tactile value, while 8 of the 10 PP values on the U50 samples matched. However the U50 samples are biased towards the very stiff classification, while the SPT samples are of lower strengths.

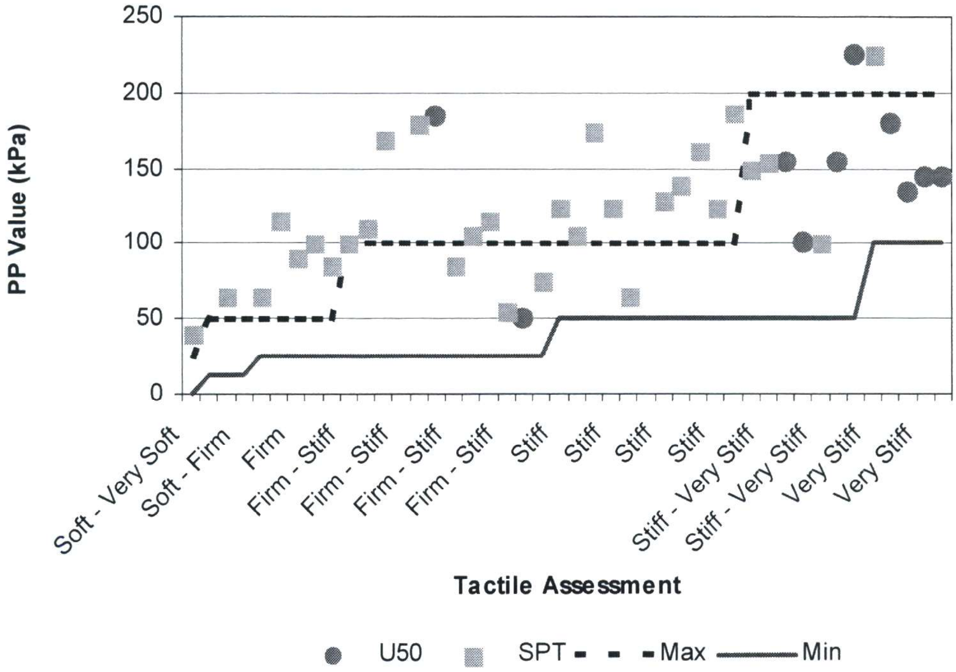

Figure 4. Comparison of PP Values obtained on U50 and SPT samples with tactile assessment.

The conclusion from these test results at this site are:

- Expect greater variability from PP tests on SPT samples.
- PP tests on SPT samples would produce significantly higher values than the tactile strength classification, while PP tests on U50 samples would more closely mirror the tactile strength classification.
- PP tests on SPT samples with strengths below 50 kPa (firm/soft/very soft) have been sufficiently remoulded to produce values 2 to 3 times higher.

CONCLUSION

Even with the best intent, variability is inherent within test results. Efforts should therefore be made to minimize such disturbance where possible. The undrained shear strength is one of the more variable parameters. Some Geotechnical Engineers prefer the less subjective PP numerical value in the classification of the clay strength rather than a subjective tactile strength classification. Because of its simplicity and low cost the PP can be routinely used on undisturbed samples for soil strength classification. However this should not tempt us into its over use.

The case study shows that using the pocket penetrometer on an SPT sample would generally produce a higher strength result than from an undisturbed U50 sample. The SPT sample is highly disturbed due to its area ratio, sample size and method of driving. Even the PP on a U50 sample does not account for the structure of the clay and should be suitably factored for design purposes. The PP should therefore be used with caution in all cases and should not be used on SPT samples.

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