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An update of the SPT-c_u relationship proposed by M. Stroud in 1974

Une mise à jour de la relation SPT- c_u proposée par M. Stroud en 1974

F. White
Ove Arup & Partners Ltd, London, United Kingdom

P. Ingram, D. Nicholson, M. Stroud
Ove Arup & Partners Ltd, London, United Kingdom

M. Betru
Network Rail, London, United Kingdom

ABSTRACT: The interpretation of in situ mass undrained shear strength (c_u) data from SPT Blow Count (*N*) results and the influence of the Plasticity Index (*PI*) was reported by Stroud (1974) "The Standard Penetration Test in Insensitive Clays and Soft Rocks", and subsequently in (1975) and (1989). The f_1 factor was defined as the ratio of c_u /SPT *N*. For a clay with a *PI* of about 50%, such as London Clay, a typical f_1 value of 4.0-5.0 was identified. The correlation has been used routinely in engineering practice since. In recent years it has been noticed that the relationship established by Stroud has under-predicted c_u results obtained from triaxial tests significantly. The apparent increase in f_1 values can be attributed to changes in the way the SPT is now carried out. This paper describes the processing of recent ground investigation data (triaxial, SPT, and *PI*) to update the f_1 correlation. An additional interpretation process is also suggested to improve possibilities for future automation.

RÉSUMÉ: L'interprétation des données de masse in-situ de résistance au cisaillement non drainée (c_u) à partir de résultats d'essais SPT (*N*) en fonction de l'indice de plasticité (*PI*) a été rapporté par Stroud (1974) "Le test de pénétration standard – Test d'argile non-sensible et de rock tendre", puis en (1975) et (1989). Le facteur f_1 a été définit par le rapport entre c_u/SPT *N*. Pour une argile dont le *PI* est d'environ 50% (argile de Londres), une valeur f_1 typique égale à 4.0-5.0 a été était identifiée. Cette corrélation fait depuis partie des règles de l'art dans la pratique du génie civil. Récemment, on a constaté que la relation établie par Stroud a considérablement sous-estimée les résultats d'essais triaxiaux c_u. L'apparente augmentation de la valeur f_1 peut être attribuée à la méthode d'exécution de l'essai SPT, qui a maintenant changée. Cet article décrit l'interprétation de données géotechniques récentes (essais triaxiaux, essais SPT, *PI*) pour mettre à jour la corrélation f_1. De plus, une autre méthode d'interprétation est proposer pour améliorer les futures possibilités d'automatisation.

Keywords: design parameters; interpretation; testing.

1 INTRODUCTION

This paper describes work carried out to update the relationship between undrained shear strength and Standard Penetration Test (SPT) *N* values which was first described by Stroud (1974) in a paper "The Standard Penetration Test in Insensitive Clays and Soft Rocks". At that time, the SPT was commonly used to estimate the in situ properties of coarse grained soils, but was not commonly used for fine grained soils.

The relationship is now used routinely in engineering practice and provides a very useful method of interpreting undrained shear strength data from quick undrained tests on U102 samples which typically exhibit scatter. This scatter can be for a variety of reasons, including sample disturbance, and scale effects caused, for example, by local discontinuities in the sample. SPT data generally exhibit far less scatter, and therefore this correlation is particularly useful for deriving design lines and discarding unrepresentative test data for calculations where c_u is the key input parameter, e.g. LDSA (2017).

In recent years, it has been noticed that the relationship established by Stroud has significantly under-predicted c_u compared with the results obtained from triaxial tests. Having plotted the new data together with depth in a similar way to Figure 2 in Stroud (1974) it was evident that the trend and spread of triaxial data was almost identical to that in 1974 data plot, whereas there was a significant shift in the SPT data. The apparent increase in f_1 values can therefore be attributed to changes in the way the SPT is now done.

As the f_1 values derived by Stroud are so widely used, it can be problematic agreeing higher site specific values for use in design with design checkers etc. even though these are often apparent from the data.

This paper therefore reviews more recent test data, to consider whether it is appropriate to use higher values of f_1 compared to those originally proposed by Stroud. An alternative correlation method is also described, devised to improve the possibilities of automation.

2 BACKGROUND

2.1 *Relationship proposed by Stroud (1974)*

In his 1974 paper Stroud recognised that for engineering design what is required is the mass strength of the ground in-situ that takes into account the weakening effect of discontinuities. He proposed a simple correlation between mass undrained shear strength c_u (kPa) and SPT *'N'* blowcount:

$$c_u = f_1 \,.\, N \qquad (1)$$

where f_1 (kPa) is a constant dependent on Plasticity Index, *PI*.

Stroud showed that for a large number of sites on London Clay the pattern of *N* value data with depth below ground level could be correlated closely with evaluations of mass undrained shear strengths made by Marsland (1971, 1972) using deep in-situ plate loading tests.

Figure 1 is reproduced from Stroud's original work and shows two graphs of undrained shear strength data with depth below ground level. On the left hand side are shown the 102mm triaxial test data for all the sites taken together, plotted with depth below ground level. On the right hand side are the corresponding SPT data (small dots) correlated against the triaxial test results for each site and plotted together (having an average correlation of about f_1 = 4.4). Also plotted on the right hand graph are the undrained strengths derived from the plate load tests (large dots).

The SPT results show good agreement with the plate test data suggesting that the SPT could be used to estimate mass undrained shear strength to depths of at least 30m, and probably more.

The SPT plot also showed far less scatter than the triaxial data, particularly at depth. These factors indicate that the SPT might provide a more dependable measure of mass in-situ undrained shear strength than triaxial tests, but at the least can be used to help evaluate triaxial data often beset with large scatter.

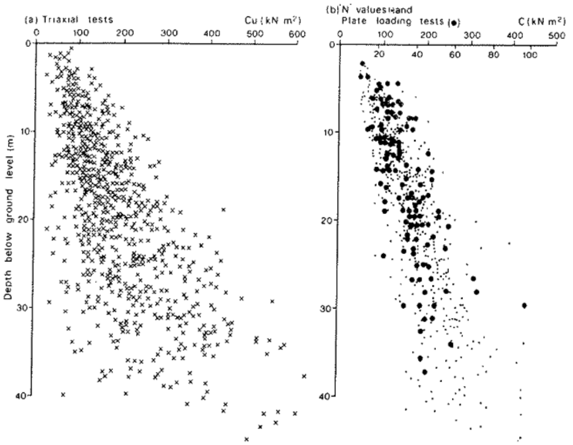

Figure 1. Comparison for London Clay of all N values with all undrained triaxial shear strength results and with mass shear strengths estimated from deep plate loading tests. After Figure 2 of Stroud (1974)

A series of graphs of undrained shear strength against depth were presented by Stroud (1974) on a site by site basis. On these graphs, the corresponding SPT *N* data for the site were plotted on the same axis as the c_u data, with the scale adjusted to give a best fit to the triaxial data down to depths of 30m or so, but more particularly down to a depth below which the clay strength exceeded about 350kPa. Below this level the wide scatter of triaxial data made evaluation uncertain.

In these harder materials the discontinuity spacing is often of the same order as the size of the triaxial sample. Some samples will contain few or no discontinuities and will survive the sampling and sample preparation better. They will be much stronger than average. Such an effect is consistent with the trend noted by Marsland (1971, 1972) for the plate loading tests. He found that in the upper strata plate test results correlated well with the mean of the 102mm triaxial data. At depth, however, he concluded that the averaged triaxial test data may over-estimate the mass in-situ strength of the clay. In these deeper strata undrained strength based on *N* values and the f_1 value derived from the strata above, often lie below the mean of the triaxial results. This suggests that estimates of the mass strength of these lower, harder materials can be made using the SPT and an f_1 value derived in the upper materials.

A typical London Clay site from the paper is reproduced in Figure 2 showing the derived f_1 = 4.5 for a *PI* = 57.

Data from numerous sites were plotted in a similar manner to enable a relationship over a range of values of Plasticity Index to be developed. The dataset was added to in further papers: Stroud and Butler (1975), and Stroud (1989).

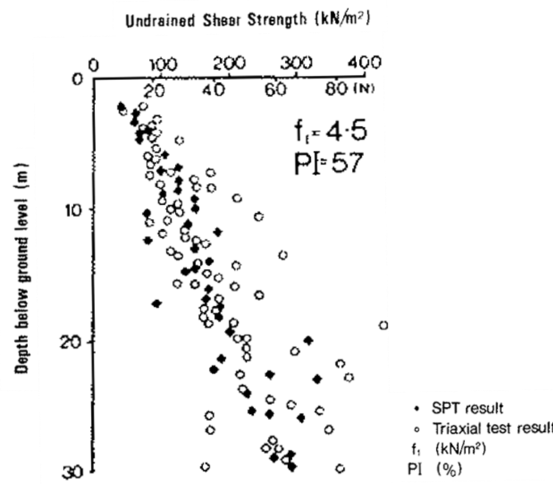

Figure 2. Plot of c_u vs SPT N with depth for 'London Clay Site 6' after Figure 1 of Stroud (1974).

2.2 Variation of f_1 factor with Plasticity Index

Stroud and Butler (1975) plotted f_1 values against Plasticity Index, *PI*, for a series of glacial deposits, insensitive clays and soft rocks. They showed that an average relationship for f_1 varied between 4.4 and 7.0 kPa (with London Clay varying between around 3.7 and 4.8) and proposed a curve through the data shown in Figure 3**Error! Reference source not found.**.

Based on this, a value of f_1 of between 4.4 and 5.0 is typically used to correlate with undrained shear strength data for the London Clay, which is of high plasticity, with Plasticity Index, *PI* ranging from about 25 to 60%.

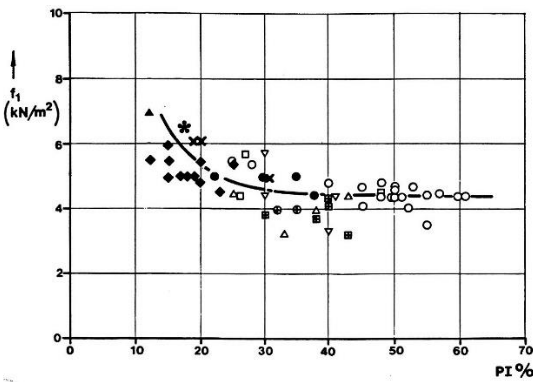

Figure 3. The variation of $f_1 = c_u/N$ with Plasticity Index after Figure 3 Stroud and Butler (1975).

3 SPT EQUIPMENT CHANGES SINCE STROUD'S WORK

The evidence suggests that the magnitude and spread of data from triaxial tests on U102 samples has not changed significantly over the years. (Conventional U102 sampling was used, as for the 1974 study) SPT *N* values, however, appear on average about 20% lower in magnitude than previously. This is most likely due to changes in the way the SPT has been performed in recent years.

Clayton (1995) describes the historical development of the SPT. The test involves driving a sampler into a soil at the base of a borehole by dropping a 63.5kg hammer with a fall of 760mm for each blow and recording the number of blows required to achieve a penetration of 300mm after an initial 150mm seating drive.

The test procedure was first introduced into the British Standard in 1967.

A revised British Standard BS1377-9:1990 was introduced in 1990, with changes to the methodology. While the basic specification of the SPT sampler was unchanged, important changes were introduced specifying how the sampler at depth was to be connected to the hammer mechanism at the surface.

The current standard, BS EN 22476-3 (in common with the previous BS 1377-9) requires a connecting rod stiffness of at least an AW rod for tests less than 20m depth, and of a BW rod for greater depth (for definitions of AW and BW rods, see ISO 22475-1:2006, Table C.1).

The data that were used in developing Stroud's curve were based on traditional solid square boring rods, which are nominally 1.25 x 1.25 inches (i.e. 31.75mm) in cross section. These are smaller than the current standard equipment and may therefore have transmitted less energy to the sampler resulting in a higher SPT (and consequently a lower f_1) for a given strength of soil.

Square SPT rods started to be phased out in the mid to late 80s, although some drillers still used them until the late 90s, so through this time the type of rod used may be unclear.

Nine sites on London Clay investigated in recent years, using SPT methodology according to either BS1377-9:1990, or BS EN 22476-3 have been identified and the value of f_1 obtained for each using the method followed by Stroud (1974). The results are presented in Section 6.

4 PROPOSED f_1 DERIVATION

A key aim of the present review was to look at ways to automate the f_1 derivation process. To this end, the following section describes the process proposed by the authors to enable automation. The method is described for a typical London Clay site.

In Section 5 of this paper, this process is compared to the method described in Stroud (1974), to consider whether there is sufficient equivalence such that either method can be used to evaluate f_1.

4.1 Data collection

To effectively carry out this process, appropriately comprehensive sets of ground investigation data were required. As a minimum, the following was sought:

- Conventional U102 (consistent with the recommendations of LDSA (2017));
- Atterberg limit test results including moisture content from wax sealed samples (preferably not bulk bags unless the boreholes are shallow);
- undrained triaxial test results (U102);
- SPT *N* test results; and
- a complete Final Factual Report.

To ensure that, for a given dataset, each point can be directly related to the other parameters, c_u tests were paired with the appropriate SPT performed from the base of the hole created by the open tube sampler. Similarly, Atterberg limit test results were taken from sub-samples cut from the same open tube sample.

For the ease of data collection, data were also sought in Association of Geotechnical & Geoenvironmental Specialists (AGS) standard format with the factual report in PDF, complete with figures and appendices.

The importance of sourcing good quality data cannot be emphasised enough, as this allowed the refinement and checking of anomalies within the datasets, allowing the most accurate determination of the SPT-c_u relationship. The site where data were obtained in this way to demonstrate the revised methodology is located in central London (Site 1), and the in situ and laboratory tests presented are from samples of London Clay.

4.2 Discounting outliers

A process of identifying anomalies and discounting outliers was developed to ensure that the most reliable determination of f_1 was made for each dataset. In particular, unusually high and low SPT *N* and triaxial tests results were identified and investigated to determine whether they could be discounted.

Figure 4 shows an example of where an SPT *N* point (and its corresponding c_u test) was discounted. For this example. The high *N* value was first identified from the plot, and then the same point identified in the appropriate borehole log.

In this instance, it was determined that the SPT was carried out at the location of a claystone (which are common in the London Clay stratum), and therefore the high observed value was discounted.

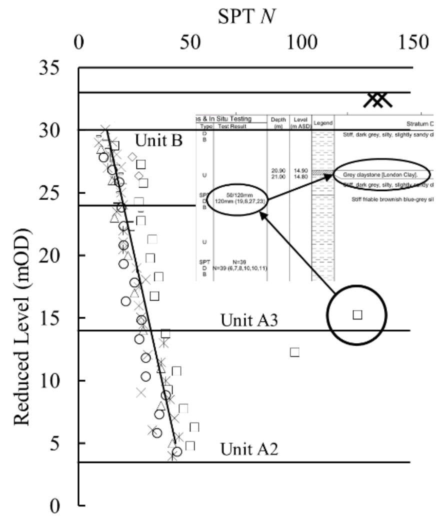

Figure 4. Site 1 - Discounting outliers from SPT data (solid line is the mean, referred to in Section 4.3)

4.3 Calculating the f_1 factor

After the rules for discounting outliers were applied to all samples in the dataset, calculation of the f_1 factor was carried out for each pair of c_u and SPT data.

For the example site used for this section, an additional stage was carried out to identify the different lithological units of the London Clay by using the step changes in water content with depth as described by King (1981). Layers B, A3 and A2 were identified for this site.

This was carried out for the example site (and Site 2) to identify whether there was a strong influence of the different London Clay units on f_1. For the other sites described in the paper, this was not carried out.

Once the f_1 value for each pair of points was found, an arithmetic average was taken for each London Clay unit, and for the full dataset (Table

1). Average *PI* values were also calculated for each unit. The value of f_1 was largely the same in the upper units but increased dramatically in Unit A2. When the lithological units were ignored, and the dataset taken as a whole, the process yielded a value of f_1 = 5.7. Given the small change in PI between A1 and A2, it is assumed that the elevated value of f_1 at depth in the lowest Unit is due to the higher triaxial test results as the testing process is biased towards the more intact, and therefore stronger clay, as discussed previously.

Figure 5 shows a plot of triaxial test data for the site where only the paired data, as described above, are shown.

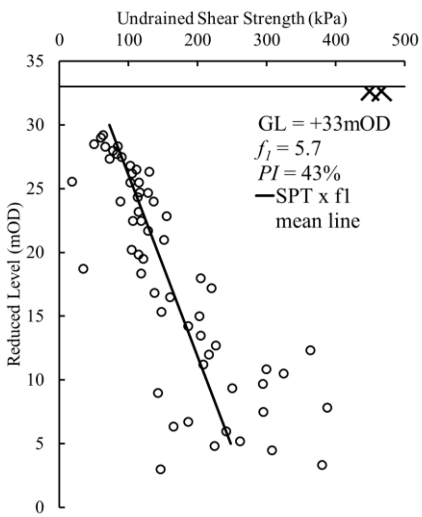

Figure 5. Site 1 - SPT mean design line using calculated f_1 value.

A mean line, drawn by eye through a separate plot of the SPT data (solid line on Figure 4) has been converted to c_u using the calculated average f_1 value of 5.7 and shown on the graph. The SPT data mean line provides a reasonable average trend line for the triaxial data without being over influenced by the elevated triaxial strength at depth. Such a line is in keeping with the approach generally taken by engineers when choosing design lines through the wide scatter of triaxial results.

Table 1. Summary of f_1 and PI (%) for the site.

Value	**London Clay Units**			**Average**
	B	**A3**	**A2**	
f_1	5.4	5.1	6.6	5.7
PI (%)	45	43	42	43

5 COMPARISON OF METHODOLOGY WITH THAT USED BY STROUD

In order to verify that the proposed methodology is consistent with the derivation of f_1 used in Stroud's original work, Figure 6 shows the data for the site re-plotted in a similar manner to which he used, with the f_1 factor adjusted by eye until the best fit was achieved.

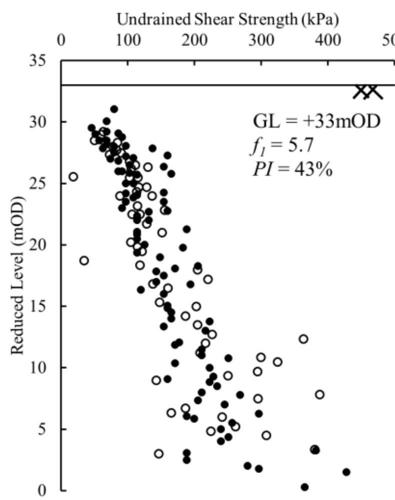

Figure 6. Site 1 - Plot of c_u vs SPT N with depth for the example site. f_1 = 5.7, PI = 43 (SPT shown as solid dots).

As can be seen from the figure, the method used by Stroud identifies the same f_1 value for the data for Site 1 as the method described in Section 4. The same comparison has been carried out for all of the datasets considered in this review and is shown in Table 2 below.

The table shows that the f_1 values determined using the two methods are close, but not in complete agreement. The average for all sites is also very similar.

Table 2. Summary of f_1 and PI (%) for all sites.

Site*	f_1 (by eye)	f_1 (proposed method)	PI	Location
Site 1 (B)	5.7	5.4	45	Finsbury
Site 1 (A3)		5.1	43	Park
Site 1 (A2)		6.6	42	
Site 2 (B)	5.5	5.3	51	Pimlico
Site 2 (A3)		5.5	44	
Site 2 (A2)		5.6	42	
Site 3	5.0	4.5	41	Victoria
Site 4	5.5	6.0	45	W Brompton
Site 5	6.1	7.0	44	Soho
Site 6	5.6	6.4	46	Liverpool St
Site 7	5.8	6.4	46	White City
Site 8	6.5	7.2	46	Earls Court
Site 9	5.8	5.5	45	NWR
Average	5.7	5.9	45	All sites

*London Clay unit shown in brackets where assessed.

It should be noted, however, that the site investigations for Sites 3 to 9 (unlike those for Sites 1 and 2) were not designed to provide paired data. Paired points of proximity have had to be chosen for the analysis. This highlights a limitation of the proposed method to allow automation. Due to the need to use paired cu and SPT data at each horizon, the data set is reduced somewhat, where some boreholes for a site do not include cu tests, or SPTs.

The impact of this is to produce an inconsistency between the f_1 values determined in the same manner as Stroud (1974), and those by the proposed technique to assist with automation. This can be particularly marked where the difference between the paired tests and the overall number of tests is large.

This leads the authors to conclude that if the automated process is to be used, the dataset must contain a large number of alternate c_u and SPT data (which does not happen for all projects). If this is not the case, then using the automated process can lead to calculated f_1 values that do not fit the overall dataset well. This finding reinforces the need to continue to plot c_u and SPT on the same graph (as in Figure 6) and to check the correlation by eye to ensure a correct evaluation. However, it is anticipated that the automated process will allow more datasets to be evaluated quickly once coded which can then be plotted to speed up the overlay check by eye. This gives a good starting point for comparing approaches.

In addition, more work is required to refine the automated process to allow for the discrepancy between triaxial and SPT data at depth. The authors are currently looking at the influence of discarding data below a particular depth, although this has the obvious shortcoming of reducing the dataset further still.

At the present time, it is considered that the method proposed by Stroud, although reliant on human factors, is the most reliable method for determining f_1.

6 REVISED RELATIONSHIP BETWEEN f_1 AND *PI*

The data for all sites shown in Table 2 have been plotted against Stroud and Butler's data in Figure 7**Error! Reference source not found.**, showing the original proposed relationship between f_1 and *PI*. In accordance with the discussion in Section 5, the method proposed by Stroud has been used to derive the f_1 values shown.

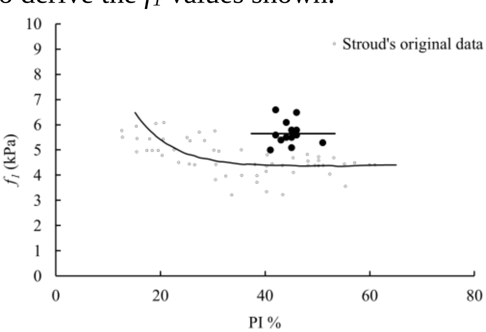

Figure 7. Data (by eye) from nine London Clay sites plotted against test data from Stroud and Butler (1975).

As can be seen from the figure, these new data points plot significantly higher than the best fit line presented in the original figure, and indeed significantly higher than the data points on which it is based.

An increase in f_1 of between 25-35% compared to a typically used value of 4.4 can be observed for the London Clay data presented here, with similar gains expected through the range of Plasticity Index, significant design savings may be possible. An f_1 value of around 5.5 to 6.0 would appear to be appropriate for London Clay (a line for 5.7 is shown on the figure).

7 FURTHER WORK

The authors are continuing to process data from a range of identified datasets and are identifying further datasets from Arup's project archives. Clearly, processing data from low and medium *PI* sites is a priority in order to identify an improved design line over the full range investigated by Stroud. In addition, CPT data for sites (where it is available in addition to the other data) will be considered to try to develop companion correlations. The SPT energy methods suggested in the Eurocodes will also be incorporated into the review of the SPT performance.

8 CONCLUSIONS

The correlation between mass undrained strength and SPT *N* value proposed by Stroud (1974), Stroud and Butler (1975), and Stroud (1989) has been revisited and it has been demonstrated that the f_1 value has increased in recent years, due, it is believed, to the introduction of different SPT practice since the introduction of BS 1377-9:1990. A value of f_1 for London Clay of about 5.7 kN/m^2 is indicated, rather than 4.4 kN/m^2 used previously.

A revised process for deriving the f_1 factor linking undrained shear strength, c_u from conventional U102 samples and SPT blowcount, *N*, has been developed in order to assist with future automation. Good agreement with the method proposed by Stroud (1974) has been determined. The revised relationship once developed across a full range of plasticity is expected to lead to improved confidence in c_u design lines where the data appear to indicate a higher f_1 than common practice. The data presented indicate improvements in mass in situ undrained shear strength design lines of 25-35%, and it is expected that similar gains will be made across a range of *PI*. This highlights the importance of assessing the SPT and c_u data on a site by site basis to determine the appropriate f_1 value, rather than simply adopting the historical f_1 values.

9 ACKNOWLEDGEMENTS

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