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Impact of a spacing reduction in a fall cone test

Technique d'essai répétée du cone de chute

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ABSTRACT: The paper investigates an adjustment to the fall cone test, where the same soil sample is reused for four extra tests. The analysis shows that the fall cone test inaccuracies are much higher than the effect of reusing the sample. Therefore, the proposed procedure may help to establish the soil properties more accurately without much extra effort and reduce the number of samples needed for testing.

RÉSUMÉ: L'article étudie un ajustement au test du cône de chute, où le même échantillon de sol est réutilisé pour quatre tests supplémentaires. L'analyse montre que les imprécisions du test du cône de chute sont bien supérieures à l'effet de la réutilisation de l'échantillon. Par conséquent, la procédure proposée peut aider à établir les propriétés du sol avec plus de précision sans trop d'effort supplémentaire et à réduire le nombre d'échantillons nécessaires aux tests.

Keywords: Fall cone test; statistical analysis; marine clay; sensitive clay.

1 INTRODUCTION

The fall cone test was initially devised by the Swedish state railways during the period from 1914 to 1922 and subsequently gained widespread adoption in Scandinavian countries (Hansbo, 1957). Currently, the ISO 17892-6:2017 standard contains the details of the procedure.

In general, the fall cone test requires that before its release the metallic cone is in direct contact with the surface sample. After the release, the cone penetrates the specimen. The undrained shear strength is correlated with the measured depth of penetration. The test relies on the lack of friction in the apparatus, hence the apparatus should be lubricated to minimise friction. The test accuracy is related to a number of factors, the interested reader may see Llano-Serna & Contreras (2020) for discussion on cone roughness influence and further references.

2 RESEARCH HYPOTHESIS

The ISO 17892-6:2017 standard requires that the test points should be distributed so that the distance between the outer boundaries of the cone penetration in two tests is at least 14mm, and the cone penetration closest to the perimeter is at least 7mm. For soft marine clays, for 60 deg 60g cone the penetration can reach 9mm, leading to the spacing requirement of 24,4 mm between centres of penetration and 12,2 mm from the sample perimeter. For common core diameters 50, 54 and – used in this study – 58 mm, these limitations lead to 3 sampling points on the single cross-section of the sample. Three points are the minimum required by ISO 17892-6:2017. However, ISO 17892-6:2017 requires that any test result deviating from the mean penetration by more than 0.5mm should be excluded. This means that often an extra point is needed, however, due to distance restriction, no more sampling points are allowed on the sample and another sample for testing should be taken. This may be difficult and affects the testing programme.

Recent research (e.g Mohapatra *et al.*, 2023a; Mohapatra *et al.*, 2023b; Tran & Sołowski, 2019), has indicated that the impact of the fall cone penetration into a soft sensitive clay is contained to approximately double the radius of the 60-degree fall cone penetration mark, see Figure 1. Furthermore, the results have shown little sensitivity to lateral support, with no changes for full lateral support or lack of it. Based on those results we decided to check the hypothesis that a reduction of the spacing of the sampling points to double the radius of the penetration mark may have no influence on the results, while it allows for the increase of the number of sampling points on a standard 50 to 58mm sample cross-section, potentially increasing the accuracy of the findings. Additionally, the work aims to evaluate whether the results of the test are statistically influenced by removing the lateral support. If the denser spacing or lack of lateral support has an effect, the depth of the penetrations closer to the sides of the sample should be higher compared to the first penetration in the middle of the sample.

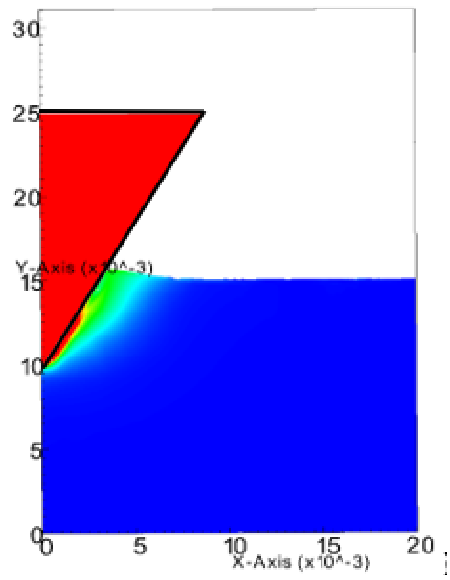

Figure 1. Numerical replication of a fall cone test in soft marine clay showing localised deformations around the cone, Mohapatra et al. (2023b).

3 CLAY SAMPLES

In this research, tested soil samples had a diameter of 58 mm and a height of 10 cm. The penetration test was conducted using a cone with a 60° angle and a mass of 60 grams. The observed penetration depths across all samples range approximately from four to 12 mm.

In this study, a total of 39 normally consolidated marine clay samples were tested with a fall cone. The samples came from four locations at the offshore Kytö site: KU2 (with depths ranging from 0.1 to 3.87 meters), KU3 (with depths ranging from 0 to 3.48 meters), KU1 (with depths ranging from 0 to 3.1 meters), and KU4 (with depths ranging from 0.15 to 3.75 meters). For a more detailed site description see Saresma *et al.* (2023), while for more details on properties and tests see Li *et al.* (2023).

The composition of these marine sediments exhibits some variations primarily attributed to the different stages of the Baltic Sea's evolutionary history. However, the stratification of these sediments is relatively weak and the samples were very similar. The clays are structured and sensitive. Their intact undrained shear strength varies, mainly due to differences in depth from which the samples originate.

4 METHODS

4.1 Fall cone test procedure

Figure 2 shows the position of each penetration for each sample in the testing programme, with numbers indicating the penetration sequence, leading to the spacing between the sampling points smaller than required by ISO 17892-6:2017. The sample used had a 58 mm diameter and the points 2-5 were positioned at least 10 mm from the side of the sample, with the impact point approximately in the middle of the line connecting the edge of the penetration 1 mark and sample perimeter, i.e. around 10-14mm from the sample perimeter. This means that the distance between the edge of the penetration mark was around 5-8mm to the sample perimeter, but there could be only about 8 mm between the edges of the penetration mark at test 1 and the subsequent test, instead of the required 14mm. Nonetheless, the spacing always was approximately 2 penetration radii, complying with the condition identified in numerical analyses. Besides the spacing, the testing procedure followed ISO 17892-6:2017, with tests done on thick 10cm extruded from plastic tubes. There was no lateral support at the sides.

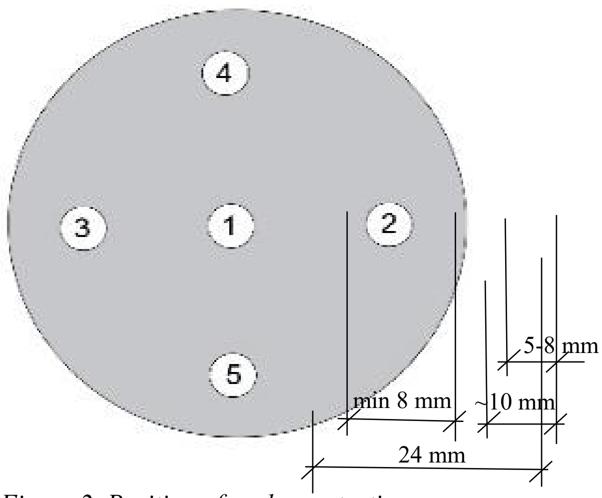

Figure 2. Position of each penetration.

4.2 Discussion of the testing procedure

An alternative would be to perform 3 tests according to ISO 17892-6:2017 and then one extra test in the middle with smaller distances to the other tests. However, that would lead to a distance between the middle test mark and any other test as low as 5mm, in which case the penetration distortion zones would likely overlap.

4.3 Statistical analysis

In case the spacing of the points was too close, the subsequent penetrations should be affected due to the disturbance of soil and the associated reduction in the undrained shear strength. Hence, in case the soil is disturbed, we expect that there will be a statistically significant difference between the results obtained in the first penetration (middle point) and the subsequent 4 penetrations. Similarly, in case the lack of lateral constraint affects the penetration depth, the statistical analysis should reveal that.

Even though ISO 17892-6:2017 decides on the acceptance or rejection of the test based on penetration, in this contribution we decided to concentrate on the statistical analysis of the undrained shear strength. This is because the undrained shear strength is the key value obtained in the test and the important value for engineering. The results of the analysis performed based on the penetration depths are similar, but not included in this paper.

To analyse the data, first, all the undrained shear strengths were normalised with respect to the 'correct' penetration in the middle of the sample.

$$s_{n,i} = \frac{s_i}{s_1} \qquad i = 2,3,4,5 \tag{1}$$

where $s_{n,i}$ is the normalised value of the undrained shear strength obtained from the i-th penetration with respect to the value s_1 obtained from the first penetration. This assumes the middle point is the correct one, with the four subsequent penetrations possibly deviating from it. First, we tried analysing the data for each penetration. Then, as the number of tests was small, we decided to pool the data together.

In this case, all the tests besides the first one are treated the same, leading to 39 sets of 4 deviating data points. Then, we first assessed whether the obtained data follows a normal distribution. Later, we checked whether the undrained shear strengths from the subsequent 4 penetrations deviated from the undrained shear strength obtained from the test done at the centre of the sample using the Student's t-test. The null hypothesis for the test is that the differences in the averages obtained from the other penetrations are not statistically significant when compared to the first penetration.

Finally, we also assessed whether the data with outliers removed (defined as data points with undrained shear strength deviating from the value obtained in the middle point by a certain percentage) would lead to any statistically significant result. The outlier cut-offs were 250% and 40% (marked 2.5), 200% and 50% (marked 2), 150% and 66.7% (marked 1.5) and 125% and 80% (marked 1.25).

We also assessed the data with tests following the acceptance/rejection strategy similar to that in ISO 17892-6:2017. In this case, if in the first three penetrations, there was a value deviating by more than 0.5mm, the value most deviating from the average was discarded (excluding the test from the middle of the sample) and another value was taken to compute the average.

5 RESULTS

5.1 Statistical distribution of the normalised data and testing of the hypothesis

The data is first normalized with respect to the data from the first penetration. Assuming a normal distribution for data, data obtained for each penetration has a very high standard deviation, see Table 1. The difference in mean value, vs the middle penetration, is between 0,68% to 7.84%, while the standard deviation is between 30,76% to 78.08%. These are very high values, indicating much scatter in the data. In this case, for each penetration point, we had 39 tests. The results of the Student's t-test show that the differences in obtained undrained shear strengths for each test point location are not statistically significant. The t-test suggests that the mean values differences are not statistically meaningful and cannot be taken as evidence that the adjusted test procedure leads to differences in the obtained values of undrained shear strength. Unfortunately, the amount of data points for each penetration location is not sufficiently large to make a meaningful discussion about whether the assumption of normal distribution is correct.

Table 1. Mean value, standard deviation and t-test result for each penetration location.

Location	Mean	Standard deviation	T-test	Significant?
2	1,0186	0,3869	0,3005	NO
3	1,0784	0,7808	0,6267	NO
4	0,9932	0,3076	0,1389	NO
5	1,0730	0,4614	0,9874	NO

To increase the amount of data, we decided to pool the data from all the points together, leading to 155 data points, due to cutting one outlier (see Figure 3). This full data, as well as data with cut outliers, is assessed for the normal distribution based on histograms and QQ plots, see Figures 4 and 5. The plots are similar and suggest that the normal distribution is an acceptable assumption. The results of a statistical analysis based on the assumption that the data follows normal distribution are in Table 2. The same table contains also mean and standard deviation values, as well as the Student's t-test values.

An alternative is to use lognormal distribution, with the QQ plots, see Figure 6. Both distributions are visually confirmed based on histograms, see Figure 7, with perhaps lognormal distribution being a slightly better assumption.

The full data, as well as data prepared according to ISO 17892-6:2017, and data with outliers cut, were tested against the null hypothesis using Student's t-test. We checked both normal and lognormal distributions for statistical significance for the hypothesis that the undrained shear strength results obtained from tests done at the sides of the sample are statistically meaningfully different to the undrained shear strength values obtained from the tests done in the middle of the sample, Tables 1-3 contain the analysis results.

Table 2. Mean value, standard deviation and t-test values for the combined data, normal distribution assumption.

Cut-off	**Data points**	**Mean**	**Stand-ard de-viation**	**T-test**	**Sig-nifi-cant?**
No	155*	1.041	0.5127	0.3221	No
ISO	77	1.033	0.2349	0.2150	No
2.5	153	1.001	0.3389	0.0505	(No)
2	146	0.979	0.2713	0.0114	No
1.5	121	1.007	0.1881	0.5530	No
1.25	88	1.006	0.1153	0.6464	No

*Cutoff – preparation of the data, with the cut-off indicating cut-off values – 2.5- values below 40% and above 250% of the average value cut, 2 – 50% and 200%, 1.5 – 150% and 66,7%, ISO – according to ISO standard/ N- assumed normal distribution, L – lognormal. T-test confirms the hypothesis when p<0.05. *one point cut out, see Figure 3 for an explanation.*

5.2 Analysis of the results

The results confirm that there is no statistically meaningful effect indicating that the undrained shear strength obtained for the samples at the sides is different from those in the middle. The confirmation of the hypothesis for the cut-off value of 2.0 is due to the different number of points cut from both sides of the distribution. The results for this case, see Figure 5, indicate that the penetration depths at the sides are smaller than in the middle, which has no physical sense. This perhaps shows how tricky it is to cut the outliers in the data and that such action should be avoided, as it may lead to incorrect results.

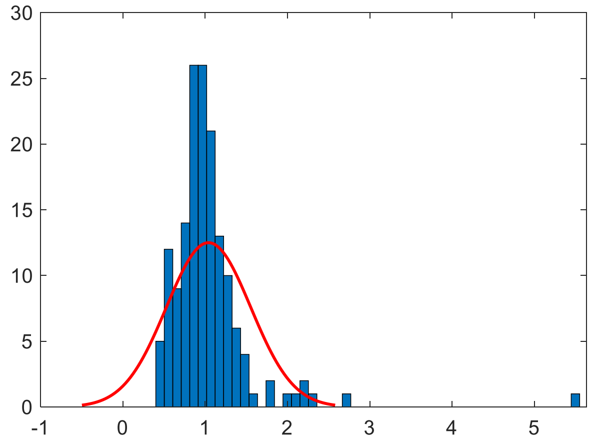

Figure 3. Histogram of all the data. The outlier pointed out by the arrow is cut off for analysis, as it is a clear testing error (insufficient penetration due to excessive friction in the apparatus).

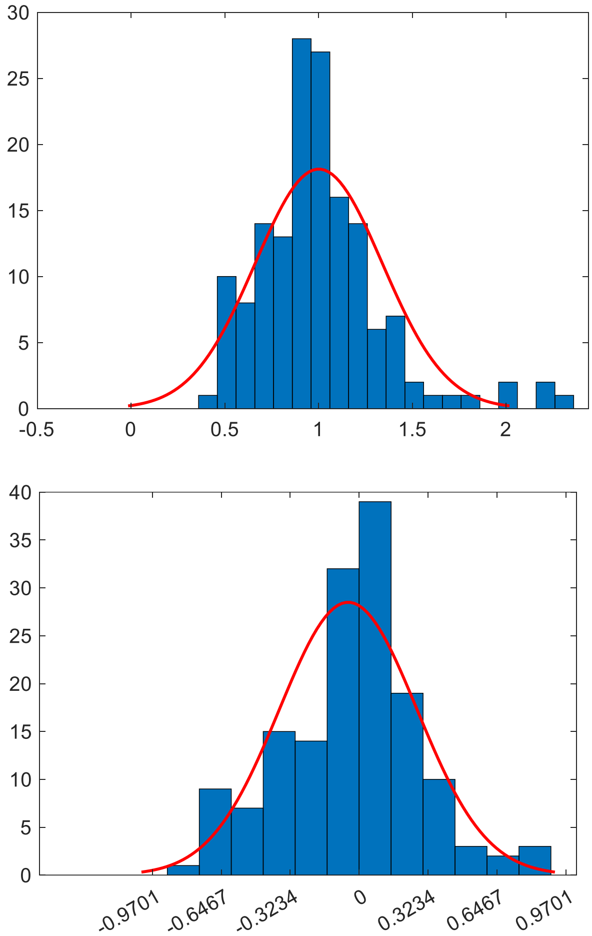

Figure 4. Histogram of data with outliers cut off (cut of value 40% and 250% of the average value), shown vs normal distribution (top) and lognormal distribution (bottom) In lognormal distribution numbers correspond to standard deviations.

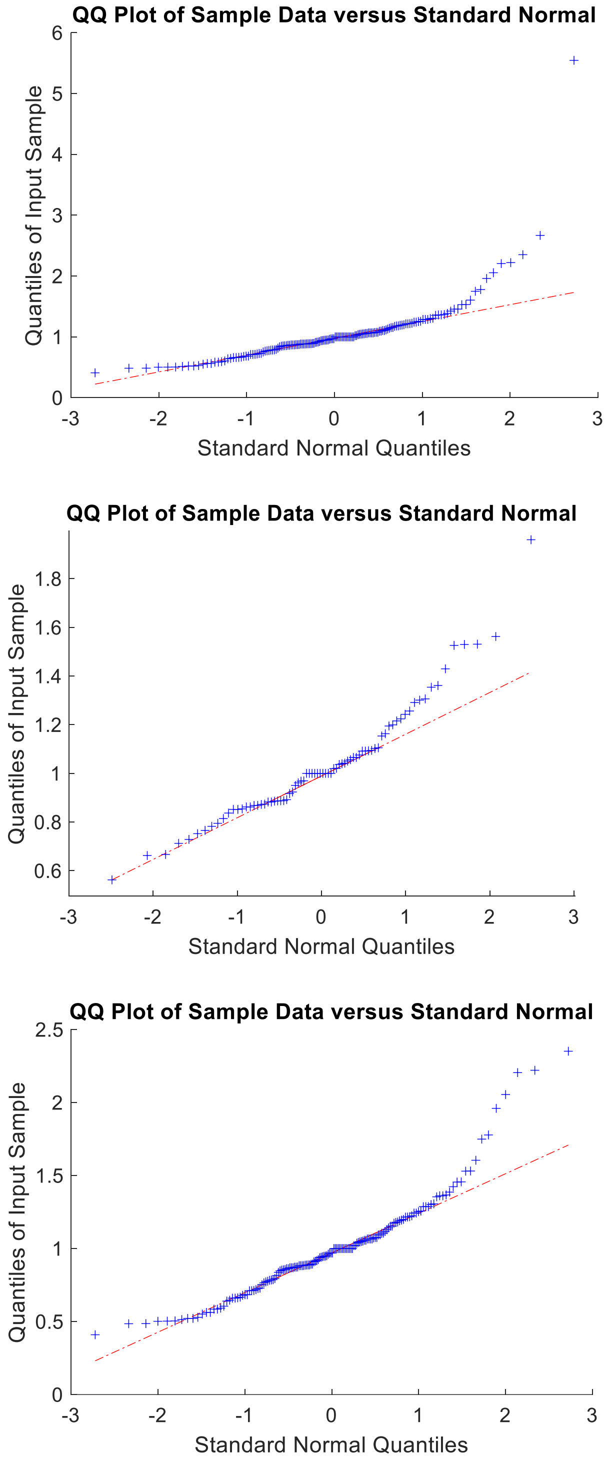

Figure 5. QQ plots of data assuming normal distribution: full data (top), data prepared according to ISO 17892-6:2017 (middle) and with outliers cut off (cut of value 40% and 250% of the average value)(bottom).

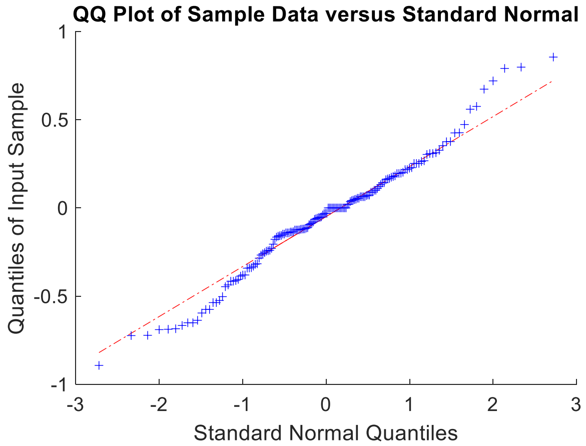

Figure 6. QQ plot of data vs lognormal distribution line with outliers cut off (cut of value 40% and 250% of the average value).

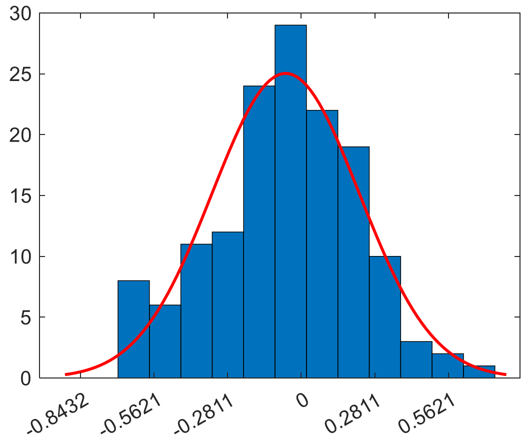

Figure 7. Histogram of data with outliers cut off at 50% and 200% of the average value, shown vs lognormal distribution, with numbers indicating standard deviations. Data is skewed towards lower values of undrained shear strength due to the cut-off value selected.

Table 3. Student's t-test values, lognormal distribution.

Cut-off	t-test p-value	Confirmed (Y/N)
No	0.2484	N
ISO	0.7120	N
2.5	0.0505	(N)
2	0.0114	**Y**
1.5	0.5530	N
1.25	0.9479	N

Cutoff – preparation of the data, with the cut-off indicating cut-off values – 2.5- values below 40% and above 250% of the average value cut, 2 – 50% and 200%, 1.5 – 150% and 66,7%, ISO – according to ISO standard/ N- assumed normal distribution, L – lognormal. T-test confirms the hypothesis when p<0.05.

6 CONCLUSIONS

The data we have does not support the hypothesis that the undrained shear strength values from tests on the sides of the sample are different to the undrained shear strength values obtained from the tests in the middle of the sample, even when the distances of the penetrations are smaller than those required by ISO 17892-6:2017. Instead, the statistical analysis of the data indicates that there is no meaningful difference between the results of the tests in the middle and on the sides of the samples. The data used is still small in the statistical sense (a total of 39 tests, with each test giving 5 data points), and the test results for each sample are quite scattered. As such, in the future, the analysis may be redone with a larger set of data, ideally with data which exhibits smaller variation. Such analysis may give a more definite answer to the posed hypothesis. Additionally, the tests may also be extended to plastic limit tests.

The proposed approach is very convenient and may improve the uncertainty of the testing results, due to the larger amount of obtained values of undrained shear strength. Further investigations and comparisons to other methods of obtaining undrained shear strength will give further arguments on whether the proposed approach is beneficial, and what is the best strategy to obtain the accurate undrained shear strength values based on fall cone tests.

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