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Effect of cone penetrometer type on CPTU results at a soft clay test site in Norway

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ABSTRACT: Seven different cone penetrometers from 5 manufacturers have been used in a comparative testing program at the Norwegian GeoTest Site (NGTS) on soft clay in Onsøy, Norway. Tests with all cone types give very repeatable penetration pore pressure, u_2. When comparing tests with different cone types, six of the cones give very similar u_2 values. One cone type give consistently higher u_2 values. Measured cone resistance, q_c, generally varies somewhat more, both regarding tests with the same cone, and when comparing results of one cone type with another. Some of the cone types give good repeatability for sleeve friction, f_s, readings, while some show relatively large variation. When comparing f_s from different cone types the variation is quite large, which is in line with previous experience. An attempt has been made to understand the reasons for the large f_s variations.

1 INTRODUCTION

It is a well-known fact that even if cone penetrometers adhere to the international standards (e.g. ISO 22476–1:2012), results of tests using equipment from different manufacturers can give different results (e.g. Lunne et al.1986, Gauer et al. 2002, Powell & Lunne 2005, Tigglemann & Beukema 2008, Lunne 2010, Cabal & Robertson 2014). This is particularly a problem when soil investigation contractors using different cones operate in the same area, and especially on the same project. Lunne et al. (1986) carried out a comprehensive laboratory and field study comparing tests results from cone penetrometers from 8 different manufacturers. In that study it was shown that all three parameters q_c, f_s and u_2 could vary significantly, depending on the equipment used.

A later study by NGI (Gauer et al. 2002) based on a number of different cone penetrometers tested in Onsøy clay showed that the situation had improved. The cone resistance showed relatively small scatter, and the penetration pore pressure was even more repeatable from one cone type to another. However, the scatter in the measured sleeve friction, and hence the friction ratio, was very significant.

Powell & Lunne (2005) showed that if calibration of all cone penetrometers used was done in a consistent manner by one organization who also carried out all tests, then the variation in results will be reduced.

Over the last few years further improvements in cone design and electronics have occurred by some cone manufactures. The establishment of 5 new national test sites in Norway (L'Heureux et al. 2017) has given the opportunity to revisit the problem of uncertainties in CPTU test results by inviting several companies to do testing at 4 of the sites.

This paper includes only results of tests from the soft clay site at Onsøy, a later paper will include test results from all 4 test sites.

For the tests reported herein the calibrations were carried out by each cone manufacturer. It is thought that the test results will then be more representative for general practice in the soil investigation industry. Each cone manufacturer has tried to follow requirements and recommendations in international standards and guidelines.

2 ONSØY TEST SITE

The Onsøy test site is located about 100 km south of Oslo. It consists of a 25–35 m thick marine deposit which has never been subjected to higher vertical stresses than today, but it has an over consolidated ratio due to ageing. The Onsøy test site has been used by NGI for more than 40 years, including testing out of *in situ* tools and testing many types of samplers (Lunne et al. 2003). Due to development of the area for industrial purposes several locations at Onsøy have been used over the years. The present site appears to be slightly less uniform compared to the previous locations (L'Heureux et al. 2017). A soil profile is shown in Figure 1.

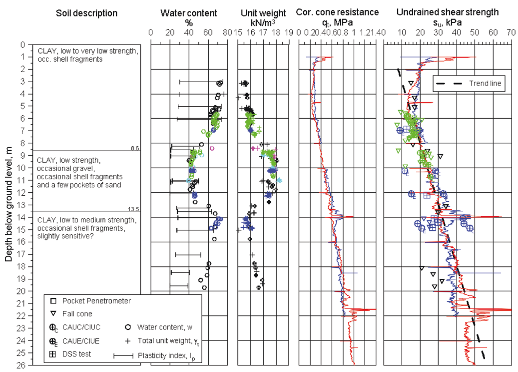

Figure 1. Soil profile at Onsøy.

3 DESCRIPTION OF CONE PENETROMETERS USED

Seven different cone penetrometers from five manufacturers were used in the present study. Some key dimensions and other information about the cone penetrometer is given in Table 1.

As can be seen from Table 1 six of the cone penetrometers are of the compression type with both cone resistance, q_c, and sleeve friction, f_s, being measured by separate compression load cells. One of the cones is of the subtraction type where one compression load cell measures q_c, and another load cell measures $q_c + f_s$. Then f_s can be calculated by subtraction.

The penetration pore pressure is measured at the location just above the conical part, u_2.The pore pressure measurement systems vary as shown in Table 2 where the filter type and saturation fluid are summarized. Six of the cones use filter made of bronze, brass or stainless steel. Five of these use silicon oil as saturation fluid and one uses glycerin. One of the cone penetrometers use a so-called slot filter. As described in ISO 22476–1:2012, in this system the pore pressure is measured by an open system with a 0.3 mm slot immediately behind the conical part. The slot communicates with the pressure chamber through several channels. De-aired water, antifreeze (glycol) or other liquids can be used to saturate the pressure chamber, whereas the channels are saturated with gelatin or a similar liquid.

Table 1. Dimensions and other relevant information regarding the cone penetrometer used in this study.

Cone type	D1	D2	h	L1	Ac	Asb	Ast	As	a-nom	b-nom	Cone type	Capacity qc	fs	ua
1	35.76	35.78	10	134	1003.84	200	200	15014	0.80	0.0	Comp	50	1.6	2.5
2	35.90	36.00	10	135	1012.23	163	163	15155	0.85	0.0	Comp	25	0.5	2
3	36.00	36.10	10	135	1017.36	279	279	15000	0.80	0.0	Subtr	100	1	2
4	36.00	36.10	10	135	1017.36	279	279	15000	0.80	0.0	Comp	100	1	2
5	36.00	36.10	10	135	1017.36	279	279	15000	0.80	0.0	Comp	50	0.5	2
6	36.00	36.00	10	135	1017.36	297	168	15268	0.69	0.008	Comp	50	1	2
7	35.70	35.90	10	133.8	1006.6	208	208	15090	0.75	0.0	Comp	75	1	2

Table 2. Pore pressure measurement systems for the various cone penetrometer used in this study.

Cone type	Filter type	Saturation fluid	Date performed	Number of tests
1	Bronze	Silicone ISOVG 100	04092017	4
2	Bronze	Glycerine	17112017	3
3	Brass 38 micron (SIKA B-20)	Silicone oil 200 fluid 50 cSt	18092017	2
4	Brass 38 micron (SIKA B-20)	Silicone oil 200 fluid 50 cSt	18092017	4
5	Brass 38 micron (SIKA B-20)	Silicone oil 200 fluid 50 cSt	18092017	4
6	Slot	Grease/oil	13112017	3
7	Stainless steel, S/S 10 micron	Silicone oil, DC200, 50 cSt	14112017	2

4 TEST PROGRAM AND MEASURED PARAMETERS

The tests included in this paper were carried out between 4th September and 17th November 2017 within an area of 5 m by 12 m. All tests were carried out to a depth of 25 m below ground level except for cone 1 which was stopped at 21 m. Pore pressure measurements show that the water table has been at about 0.5 m throughout the testing period. Due to various circumstances a various amount of soundings (2–4) were carried out with each of the cone penetrometers. Predrilling to 1 or 2 m was used for the tests with cones 2, 6 and 7.

Figure 2 shows the results of all tests from the seven cone penetrometer types, in terms of measured q_c, u_2 and f_s. The following immediate observations can be made from visual inspection:

- For all cone penetrometers except cone 3, u_2 show very good repeatability. The two profiles with cone 3 are deviating 10–60 kPa from each other in the depth interval 5–20 m. The large deviation between 21 and 25 m is possibly caused by the sounding being influenced by a neighbor CPT hole.
- For all cones the measured q_c exhibit reasonably good repeatability, but not as good as u_2
- Most variations occur for f_s; especially for cones 1, 2, 3 and 7.

All dimensions in mm; All areas mm^2; Capacity q_c, f_s and u_2 sensors in MPa; nominal means average values given by manufacturer, D_1 = diameter of cylindrical part of cone tip; D_2 = diameter of sleeve; h = height of cylindrical part of cone tip, L_1 = length of friction sleeve, A_c = cross-sectional

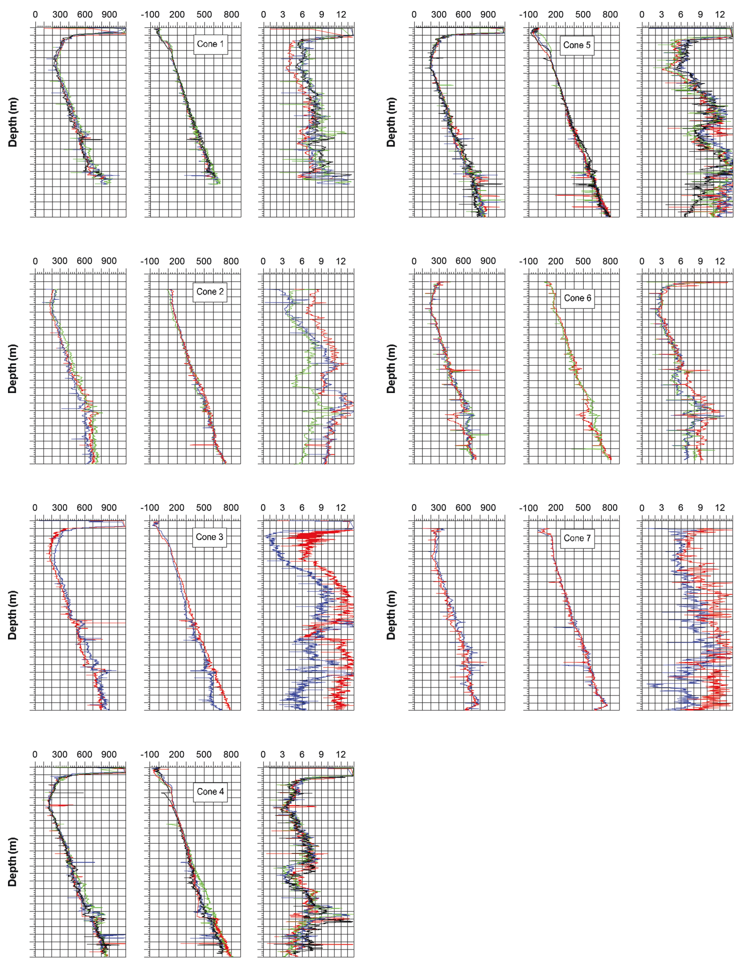

Figure 2. Measured q_c, u_2 and f_s vs depth for all CPTU profiles included in study.

area of cone tip, A_{sb} = area where pore water pressure can act at bottom of friction sleeve; A_{st} = area where pore water pressure can act at top of friction sleeve; A_s = area of sleeve; a = area ratio of cone; b = are ratio of sleeve

5 COMPARISON BETWEEN THE DIFFERENT CONE TYPES

5.1 *Measured parameters*

For all types of cones used a representative profile has been chosen. Average values have been worked out for all three basic measurements. Obvious erroneous results caused by poor saturation, like for cones 4 and 5 have been excluded as well as some other anomalies. One test with cone 7 was not included due to large zero shift observed at test completion. As mentioned in the introduction, details in calibration of CPTU sensors can potentially vary between different cone manufacturers, especially in the lower range of values as in soft clay. At 10 m for instance a u_2 value of 300 kPa is typically measured and the nominal capacity of the pore pressure sensor is 2000 kPa, this means that about 15% of the capacity is utilized. q_c with capacity of 100 MPa about 0.3% is typically utilized at same depth. And for f_s with a typical load cell capacity of 1 MPa about 0.8% is utilized. It can be expected that the u_2 reading may be more accurate and consistent since a larger part of the capacity of the measurement sensor is utilized compared to q_c and even more so f_s.

In addition to the general calibration which is normally carried out at room temperature sensitivity of zero readings to change in temperature can also be important.

Figure 3a compares the representative profiles of the measured parameters (q_c, u_2 and f_s), without any corrections for the 7 cone types.

It should be noted that the a-factor has been measured in a calibration vessel for each cone used and may deviate slightly from the nominal values given in Table 1. The q_c profiles in Figure 3 for cones 1, 3 and 4 showed much lower values than the other tests. The a values for these cones were not much lower than the others so this effect cannot explain the differences in q_c. Based on previous experience it was suspected that zero shift caused by different temperature at ground level (generally about 15 °C, but in a few cases as low as 0 °C) and soil temperature (7 °C) could occur. Laboratory calibration tests by two of the manufacturers (cones 1, 3, 4 and 5) showed that zero shifts due to change in temperature from 15 to 7°C could cause measured q_c to be too low by 50–100 kPa. For f_s temperature zero shifts were 1–4 kPa for the same cones. For u_2 the temperature zero shifts were not significant. Cone 7 gives

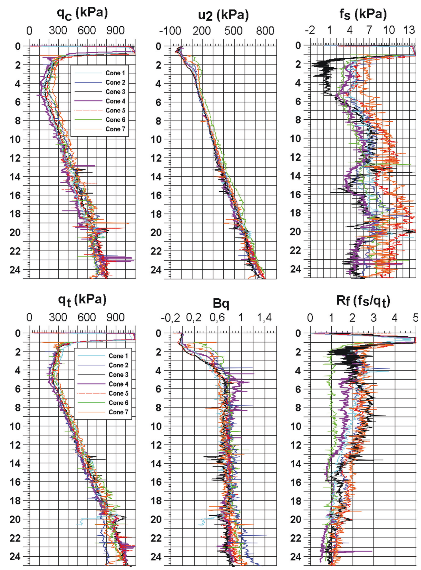

Figure 3. Comparison of representative values of q_c, u_2, f_s, q_t, B_q and R_f for all cones.

higher q_c, even though the two profiles carried out with this cone gave very similar q_c as shown in Figure 2. This can only partly be explained by an observed zero shift, which is 21 kPa for the average profile for cone 7.

For cones 1, 3, 4 and 5 corrections for temperature zero shifts have been made before computing the derived parameters. For cone 2 zeroing before tests was done in a bucket with temperature as in ground. For cone 7 the air temperature was quite close to ground temperature, No corrections were required for the tests with these two cones.

Except for cone 6, u_2 shows remarkably good comparison among the cone types. Cone 6 is the only cone using a slot (filter) instead of a filter. This may be an explanation why u_2 is higher (20–80 kPa in depth interval 5–15 m) compared to the other cones. However, neither NGI nor NPRA, who have many years of experience with using slot filters have observed such deviations earlier.

5.2 *Derived parameters*

Derived parameters q_t, R_f and F_r are also shown in Figure 3b. The derived parameters are defined as follows:

$$q_t = q_c + (1 - a) * u_2;\ R_f = f_s/q_t, \% \tag{1}$$

Considering q_t the range has narrowed down considerably when compared to the measured q_c values. Computed B_q values are as expected for a soft clay and generally within a range of 0.65–0.80.

The range for R_f is larger, indicating that for soft clay B_q can be a more reliable classification parameter compared to R_f. Lunne & Andersen (2007) summarised the potential main reasons for lack of accuracy in f_s:

1. Pore pressure effects on ends of the sleeve.
2. Tolerance in dimensions between the cone and the sleeve.
3. Surface roughness of the sleeve.
4. Load cell design and calibration.

Due to limited space, only factors 1 and 2 will be discussed in the following. To correct sleeve friction for pore pressure effects it is necessary to know the pore pressure in the u_3 position (behind the sleeve). Sleeve friction corrected for pore pressure effects:

$$f_t = f_s - (u_2 * A_{sb} - u_3 * A_{st})/A_s \quad (2)$$

NGI has previously carried out triple element CPTU at Onsøy which showed that on average $u_3 = 0.77 \cdot u_2$. This has been used here for calculating f_t. Previous studies, e.g. Gauer et al. (2002) and Powell & Lunne (2005) have shown that the pore pressure correction has resulted in lower variation in f_t compared to f_s.

Figure 4 shows f_s (corrected for temperature zero shifts for the cone types mentioned above) and f_t vs depth. For all cones except cone 6 the pore pressure correction is very small due to the following facts: i) equal end areas at both end of sleeves, ii) relatively small end areas and iii) u_3 is quite small compared to u_2. And when comparing f_s with f_t in Figure 4 the differences in the ranges for f_s and f_t are indeed small. For cone 6 the correction is larger due to difference in end areas at the upper and lower ends of the friction sleeve. Estimates of pore pressure effects do not explain the differences in f_s.

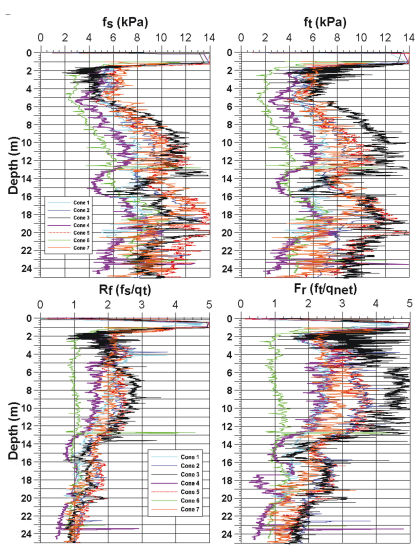

Figure 4. Comparison of f_s, f_t, R_f and F_r for all cones. f_s is corrected for temperature effects.

The effect of variations in sleeve diameter and cone diameter have been demonstrated by Holtrigter & Thorp (2016) and Cabal & Robertson (2014). Holtrigter & Thorp (2016) showed that if the friction sleeve diameter is larger than the cone diameter this can have a significant influence on f_s, even if the sleeve diameter is within the tolerances given in the international standards (ASTM 2012, ISO 2012). Figure 5 shows the results at the Huapai (clay) site. The cone diameter in Holtrigter & Thorp's work was 35.7 mm and sleeve diameters ranged from 35.7 to 36.15 mm. Based on the results shown in Figure 5 and results at 4 other sites, Holtrigter & Thorp suggested correction factors to take into account the effect of larger diameter of sleeve compared to cone. Assuming that Holtrigter & Thorp's correction factor for their Huapai clay can also be used for Onsøy clay, and using the diameters given in Table 1, the following corrections can be applied to the present f_s values: cones 1 and 6: 1.0; cones 2, 3, 4 and 5: 0.9; cone 7: 0.8.

The overall range for the measured f_s is 5.3 to 9.4; applying the correction factors suggested by Holtrigter & Thorp for Huapai clay the range reduces somewhat to 5.0 to 8.1.

The above indicate that for the present test series the variation in measured f_s values can only to some limited extent be explained by the effects of oversized friction sleeve diameter.

Figure 4 shows that R_f varies as expected for one type of cone to another. At 10 m R_f varies

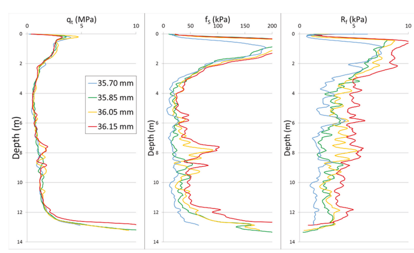

Figure 5. Results of tests with different sleeve diameters Huapai clay from Holtrigter & Thorp (2016).

Table 3. Average values at 10 m depth, kPa.

	Cone 1	Cone 2	Cone 3	Cone 4	Cone 5	Cone 6	Cone 7
fs mea.	6.8	9.0	7.1	5.6	9.3	5.3	9.4
fs corr.	6.8	8.1	6.4	5.0	8.4	5.3	7.5

from about 1.0 to 2.8%. If cone 6 is excluded this reduces to 1.7 to 2.8%.

5.3 *Final remarks*

The above discussion indicate that equipment related issues cannot explain all the variation in CPTU readings experiences in this study. A recent study by Kardan et al. (2016) showed that procedures and operator skill can have significant effects on the test results, in addition to the equipment. Thus uncertainties related to the test results can be caused by both the equipment and procedure details as well as operator skill.

In the present study, tests with cone types 3, 4 and 5 were carried out by the same personnel using one rig. Tests with all the other cone types were carried out by different personnel and rigs. It cannot be excluded that this also has had an influence on the results of tests with different cone types.

The problems with the zero shifts caused by different air and ground temperature could have been avoided if the zero readings at the start of the tests had been carried out with the cone in a bucket with the same temperature as the ground. This procedure was followed for the tests with cone type 2.

6 SUMMARY AND CONCLUSIONS

Seven different cone penetrometers from 5 manufacturers have been used in comparative testing program at the Norwegian GeoTest Site (NGTS) on soft clay at Onsøy, Norway. Two to four tests were carried out with each cone type and the results have been systematically compared. The main findings are:

1. Tests with all cone types gave very repeatable penetration pore pressure, u_2. When comparing tests with different cone types, six of the cones give very similar u_2 values. One cone type using a slot filter gave consistently higher u_2 values.
2. Measured cone resistance, q_c, generally varies somewhat, regarding test with the same cone, and more when comparing one cone type with another. This is expected since the cones have different a-factors. Taking zero shifts for different air and ground temperatures into account, and correcting for pore pressure effects, improved significantly the comparison between the q_t values for the different cone types.
3. Some of the cone types give good repeatability for sleeve friction, f_s, readings, while some show relatively large variation. When comparing f_s from different cone types the variation is quite large, which is in line with previous experience. An attempt has been made to understand the reasons for the large f_s variations, but there are still unanswered questions.

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REFERENCES

ASTM D5778–12. 2012. Standard Test Method for Performing Electronic Friction Cone and Piezocone Penetration Testing of Soils, ASTM International. www.astm.org.

Cabal, K. & Robertson, P.K. 2014. Accuracy and Repeatability of CPT Sleeve Friction Measurements. Proc. CPT'14, Las Vegas, Nevada, USA.

Gauer, P., Lunne, T., Mlynarek, Z., Wolynski, W. & Croll, M. 2002. Quality of CPTu -Statistical analyses of CPTu data from Onsøy. NGI Report No.: 20001099–2, Oslo.

Holtrigter, M. & Thorp, A. 2016. Correction for CPT fs errors due to variation in sleeve diameter. .Proc. ISC'5, Gold Coast, Australia, Proc. Vol. 1, pp. 303–309.

ISO. 2012. Geotechnical investigation and testing – Field testing – Part 1: Electrical cone and piezocone penetration tests, International Standard ISO 22476-1:2012.

Kardan, C., Viking, K., Nik, L. & Larsson, S. 2016. Influence of operator performance on quality of CPTU results. Proc. Of 17th Nordic Geotechnical Meeting, Reykajvik May 2016.

L'Heureux, J.S., Lunne, T., Lacasse, S., Carrol, R., Strandvik, S.O. & Ozkul, Z. 2017. Norway's National Geo-Test Sites Research Infrastructure. Proc. 19th International Conference on Soil Mechanics and Geotechnical Engineering. Seoul 2017.

Lunne, T., Eidsmoen, T., Gillespie, D. & Howland, J.D. 1986. Laboratory and field evaluation on cone penetrometers. Proceedings of ASCE Specialty Conference In Situ'86: Use of In Situ Tests in Geotechnical Engineering. Blacksburg, ASCE, 714–729.

Lunne, T. & Andersen, K.H. 2007. Soft clay shear strength parameters for deepwater geotechnical design. Proceedings 6th International Conference, Society for Underwater Technology, Offshore Site Investigation and Geomechanics, London, 151–176.

Lunne, T., Long, M. & Forsberg, C.F. 2003. Characterization and engineering properties of Onsøy clay. Characterization and engineering properties of natural soils. Ed. by T.S. Tan et al. Balkema 2003. Proceedings of the International Workshop, Singapore 2002, Vol. 1, pp. 395–427.

Lunne, T. 2010. The CPT in Offshore Soil Investigation – a historic perspective. Proc. CPT'10, Los Angeles, May 2010, pp.71–113.

Powell, J.J.M. and Lunne, T. (2005). A comparison of different piezocones in UK clays. Proc. ISSMGE Conference, Osaka, 2005.

Tigglemann, L. & Beukema, H.J. 2008. Sounding Ring Investigation. Proc. ISC-3, Taiwan, pp. 757–762.