CPTU results at a silt test site in Norway: effect of cone penetrometer type

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Abstract. Five different cone penetrometers from different manufacturers have been used in comparative testing program at the Norwegian GeoTest site (NGTS) on silt in Halden, Norway. The influence of cone type on the standard CPTU parameters is quantified. The corrected cone resistance shows approximately the same level of scatter as the penetration pore pressure, but far less scatter compared to the sleeve friction. Most of the tests show good repeatability within each series of tests. For the derived parameters of normalized friction ratio ($F_r$) and pore pressure parameter ($B_q$), the scatter is seen to be larger than the measured parameters which is expected from combining several parameters with scatter. The pore pressure parameter shows less scatter than the normalized friction ratio. An attempt has been made to understand the reasons for the large variations on the friction measurements and recommendations for future CPTU testing on silt are given.

1. Introduction

Using cone penetrometers from different manufacturers (e.g. [1], [2], [3], [4], [5] and [6]). may yield different results even if the equipment complies with international standards (e.g. ISO 22476-1:2012). 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. [1] carried out a comprehensive laboratory and field study comparing test results from cone penetrometers from 8 different manufacturers. That study included tests at Onsøy soft clay site and Holmen/Drammen sand sites and it was shown that all three parameters cone resistance $q_c$, friction sleeve $f_s$ and pore pressures $u_2$ could vary significantly, depending on the equipment used.

A later study by NGI [2], based on several different cone penetrometers tested in Onsøy clay, showed that the situation had to some extent 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 [3] showed that if calibration of all cone penetrometers used was done in a consistent manner by one organization which also carried out all tests, then the variation in results would 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 ([7], [8]) 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. The main objective of the testing program was to investigate if recent advancements in cone design and electronics have led to improved repeatability and less scatter in CPTU measurements for tests conducted in different types of soil. Lunne et al. [9] presented the results of tests
from the soft clay site at Onsøy. Lindgård et al. [10] presented similar results of tests at the quick clay site Tiller. The present paper includes test results from the silt site at Halden.

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. Halden Test Site

The silt deposit at Halden was first investigated by NGI in 2011 after a landslide in the area [11]. More recently, the deposit has been studied with the aim of developing a National GeoTest Site for silty soils as part of NGI’s internal strategic project 8 (SP8) and NGTS. A full overview of the geotechnical data available at Halden thorough site characterization is given in Blaker et al. [12].

The Halden Research Site is located in south-eastern Norway, approximately 120 km south of Oslo in the municipality of Halden. Here the marine silt deposit is up to 10 m thick and uniform in nature. Over the last two years a series of geophysical, geological and geotechnical investigations have been carried out in the field and in the laboratory to characterize the natural silt deposit. This information will provide a basis for understanding the main factors controlling the engineering properties and behavior for this silt. Figure 1 presents the borehole log for location HALB01.

![Figure 1](https://example.com/figure1.jpg)

**Figure 1.** Classification and CPTU data; (a) Soil units, (b) natural water content and Atterberg limits, (c) total unit weight, (d) clay particle and fines content, (e) corrected cone resistance, \(q_c\), (f) pore pressure, \(u_2\), and (g) sleeve friction, \(f_s\). Taken from [12].

3. Description of cone penetrometers used

Five cone penetrometers from different manufacturers were used in the present study. Some key dimensions and other information about the cone penetrometer are given in Table 1. All 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. 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.

Four types of the cones use filter made of bronze, brass or stainless steel. Three of them use silicon oil as saturation fluid and one uses glycerine. 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 gelatine or a similar liquid.

![Table 1](image)

| Cone type | D₁ | D₂ | h | L₁ | A_c | A_s | A_sb | A_st | a nominated | Capacity g | u₂ |
|-----------|----|----|---|----|-----|-----|------|------|-------------|------------|----|
| 1         | 35.8 | 35.8 | 10.0 | 134 | 1004 | 200 | 200 | 15015 | 0.80 | 0.000 | Comp 50 | 1.60 | 2.50 |
| 5         | 36.0 | 36.1 | 10.0 | 135 | 1000 | 219 | 219 | 15000 | 0.80 | 0.000 | Comp 50 | 0.50 | 2.00 |
| 6a        | 36.0 | 36.0 | 10.0 | 135 | 1017 | 297 | 168 | 15268 | 0.69 | 0.008 | Comp 50 | 1.00 | 2.00 |
| 6b        | 36.0 | 36.0 | 10.0 | 135 | 1017 | 297 | 168 | 15268 | 0.69 | 0.008 | Comp 50 | 1.00 | 2.00 |
| 7         | 35.7 | 35.9 | 7-10 | 134 | 1000 | 263 | 263 | 15000 | 0.75 | 0.000 | Comp 75 | 1.00 | 2.00 |
| 9         | 35.9 | 36.0 | 10.0 | 134 | 1012 | 163 | 163 | 15155 | 0.85 | 0.000 | Comp 100 | 0.50 | 2.50 |

*All dimensions in mm; *bAll areas mm²; *cCapacity qₙ, f_s, and u₂ sensors in MPa; *dnominal means average values given by manufacturer, D₁ = diameter of cylindrical part of cone tip; D₂ = diameter of sleeve; h = height of cylindrical part of cone tip, L₁ = length of friction sleeve, A_c = cross-sectional 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 = area ratio of sleeve

![Table 2](image)

| Cone type | Filter type | Saturation fluid | Date performed | Number of tests |
|-----------|-------------|------------------|----------------|----------------|
| 1         | Bronze      | Silicone ISOVG   | 05.06.2017     | 3              |
| 5         | Brass 38 micron (SIKA B-20) | Silicone oil 200 fluid 50 cSt | 19.09.2017 | 3 |
| 6a        | Slot        | Grease/oil       | 21.10.2015     | 1              |
| 6b        | Slot        | Grease/oil       | 08.06.2016     | 1              |
| 7         | Stainless steel, S/S 10 micron | Silicone oil, DC200, 50 cSt | 12-13.12.2017 | 3 |
| 9         | Bronze      | Glycerine        | 22-23.11.2017  | 2              |

4. **Test program and measured parameters**

Figure 2 illustrates the test locations at Halden included in this study. The tests were carried out within an area of 20 m by 15 m. Test HALC10 was carried out as part of the initial screening of the site in October 2015. HALC11 was done in June 2016 while the remaining tests were carried out from September to December 2017.
Figure 3. Measured $q_c$, $u_2$ and $f_s$ vs depth for all CPTU profiles included in the study. All tests at standard rate with some exceptions as indicated.
Figure 3 continuation. Measured $q_c$, $u_2$ and $f_s$ vs depth for all CPTU profiles included in the study. All tests at standard rate with some exceptions as indicated.

All tests were carried out with a minimum distance of 1.5 m to neighboring tests. Due to various circumstances, the number of tests carried out with each cone type varied from 2 to 4. Pore pressure measurements show that the water table has been at about 2 m below ground surface throughout the testing period. A target depth of 20 m below ground level (bgl) was specified and reached for all tests included in the study. Figure 3 shows the results of all tests from the five cone penetrometer types, in terms of $q_c$, $u_2$, $f_s$ and depth below ground surface. All tests were carried out at a standard rate of 20 mm/s with the exceptions indicated in Figure 3. The depth below ground surface was corrected for inclination. The measured results indicated that the air temperature at the time of zero reading significantly influenced the measured results. On that basis, the measured results were corrected for temperature difference (air temperature – ground temperature), see the NGI report [13] for temperature calibration for each cone type.

At the silt site, a range of different tests have been combined with the standard cone penetration test. The portfolio of tests includes seismic tests, resistivity tests, pore pressure dissipation tests and tests with variable rate. The aim of this study is to quantify the influence of cone type on the standard CPTU parameters and hence, the effect of dissipation tests and variable rate has been excluded from representative profiles in Section 5 herein. The evaluations presented herein are for each set of tests (i.e. comparison of different results with same cone type) based on results in the depth range 2 – 20 m:

- **Cone type 1**: The measurements show good repeatability. Pore pressure dissipation tests and seismic tests were carried out at specific depths for HALC13 and HALC14. The depths at which the dissipation tests were carried out can be distinguished from the pore pressure response in figure 3. HALC14 was carried out with variable penetration rate, varying between 18-23 mm/s, which can be observed in the sleeve friction plot.

- **Cone type 5**: The measurements show good repeatability in the depth range of interest. The pore pressure and cone resistance have less scatter than the sleeve friction. HALC18 show large zero shift for cone resistance, but that is not evident from the plotted results.

- **Cone type 6**: The measurements were carried out approximately 1-2 years before most of other tests in this study. Two different cones of same type were used. Both these tests show large $q_c$ zero shifts. It is interesting that we see larger zero deviations, but no impact on the data, one reason might be that tests were pushed deeper and that the influence came at the bottom.
Comparable measurements can be seen for the two tests which were carried out approximately 9.2 m apart.

- Cone type 7: Tests show good repeatability for all parameters. The effect of different penetration rates and dissipation testing were evident from the sleeve friction and pore pressure response and have been disregarded in representative results.
- Cone type 9: Tests were carried out at different days and a shift in temperature over night was registered. The results show little scatter, but the effect of variable rate in HALC17, with a varying rate between 2-40, and dissipation testing (both tests) is evident from the sleeve friction and pore pressure response, see for instance depth 7.5 and 10.5 m bgl.

5. Comparison between the different cone types

The representative average profiles for all cones studied at the silt site are illustrated in Figure 4. Results indicate a change in material type at some depth between 15 m and 16.5 m. The depth range of interest is from 5 m to 15 m depth bgl approximately and only the results within this depth range are compared herein.

The corrected cone resistance shows approximately the same level of scatter as the pore pressure, but far less scatter compared to the sleeve friction. Cone 6 produces the highest readings especially around 8 m depth bgl. Test HALC11 is the main contributor to the response in $q_c$ seen at 7 m depth bgl for cone 6. It is believed that this could be the effect of hitting a cobble.

The sleeve friction demonstrates considerable scatter between the representative average profiles. Cone 6 represents, in general, the lower bound measurements and cone type 1 represents the upper bound measurements. It is generally expected that most of the tests show results towards an average value of the upper and lower bound results. This is not the case for the sleeve friction response at Halden. The results can generally be clustered in two, cones 1 and 7 (upper bound) and cones 5, 6 and 9 (lower bound).

The pore pressure response shows reasonable repeatability except for cones 6 and 9. These cones produce excess pore pressure from 2 and 1 m bgl respectively. The ground water table is located around 2 m bgl and a permeable layer is generally encountered down to 5 m bgl. On that basis the pore pressure response from these two cones are somewhat unlikely, especially in the depth interval 1.5 to 6-8 m.

For the derived parameters $F_r$ and $B_q$ the scatter is seen to be larger than the measured parameters which is expected from combining several parameters with scatter. The pore pressure parameter $B_q$ shows less scatter than the normalized friction ratio. The lower and upper bound cones from sleeve friction are also the lower bound and upper bound for the normalized sleeve friction. The pore pressure parameter $B_q$ is influenced by the unlikely results produced by cones 6 and 9.

### Table 3. Ranges in CPTU measured parameters for the three sensor types at Halden

| CPTU parameter | Cone type 1 | Cone type 5 | Cone type 6 | Cone type 7 | Cone type 9 | Unit |
|----------------|-------------|-------------|-------------|-------------|-------------|------|
| $q_c$          | 150 (3)     | 150 (3)     | 200 (2)     | 210 (3)     | 110 (2)     | kPa  |
| $f_s$          | 19.2        | 19          | 20          | 26          | 15          | %    |
| $u_2$          | 45          | 50          | 50          | 45          | 10          | kPa  |
| $u_2$          | 30          | 4.2         | 29          | 26          | 5.6         | %    |

Notes: Number in bracket gives number of tests. Red color indicates the range of measured values do not meet criteria for application class 1 in ISO 22476-1:2012.

Table 3 gives the variations in ranges for the cone types in absolute values in kPa and in % of the average reading at 8 m at the Halden site. These values are considered to represent well the range of variation in the complete silt layer. The number of tests carried out with one cone type at any of the sites vary from 2 to 3. ISO 22476-1:2012 [13] (and NGF guideline [15]) gives requirements for minimum allowable accuracy in terms of a specific value or percentage of the measured value. Red color indicates the range of measured values do not meet criteria for application class 1 in ISO 22476-1:2012. For the
Figure 4. Measured and derived CPTU parameters. All cone types used at NGTS silt site.
Halden silt site the variation in $f_s$ values are about the same as the variation in $q_c$ and $u_2$. Similar tests in clay sites [9] showed that the variation in measured $u_2$ values is smaller than the variation in $q_c$, and the variation in $f_s$ is largest. The reason for this difference may be that at the Halden site the penetration is partially drained.

In general, measured $u_2$ and $q_c$ shows less variation for one cone type to another. The sleeve friction, $f_s$, shows the largest variation. It should be remarked that this might be the expected behavior considering that $f_s$ is only measured at about 0.6% of the measuring range of the sensor, while $q_c$ is at 2% and the pore pressure ($u_2$) gauge is at 10%. A sensor will always have more inaccuracy in small measurement areas which is stated as a percentage value of full scale (i.e. FS%) in the calibration sheet. The friction ratio, $F_r$, shows much larger variation compared to the pore pressure parameter $B_q$. Due to the large uncertainties with the $f_s$ readings one should be careful using this parameter, and the friction ratio, when interpreting soil parameters for design. Since the measured $u_2$ values appear to frequently be the most reliable parameter it should be used in addition to $q_c$ for deriving soil parameters.

Some major contributing factors to the uncertainties in $f_s$ measurements are reproduced from Lunne and Andersen [16]:

- Pore pressures acting on the ends of the friction sleeve. The effect depends on the actual areas at each end of the sleeve and the difference in pore pressure at top ($u_3$) and bottom ($u_2$) of cone. Normally $u_3$ is not measured, so correction can only be made by assuming the $u_3/u_2$ ratio.
- Distribution of the side friction behind the cone tip.
- Roughness of the sleeve surface.
- Amount of remoulding as a function of distance behind the cone tip.

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. [17] 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.

6. Recommendations for future testing
The most important recommendation for future testing is that the requirements and recommendations given in ISO 22476-1:2012 (Geotechnical investigation and testing - Field testing - Part 1: Electrical cone and piezocone testing) and Norwegian Geotechnical Society (NGF) Guideline No. 5 (2010) are followed. Some key issues from these two documents are:

- Zero readings to be taken before and after each test with the cone penetrometer at a temperature as close as possible to ground temperature. It is important to wait until the readings have stabilized before taking zero readings
- The thrust machine shall push the rods so that the axis of the pushing force is as close to vertical as possible. The deviation from the intended axis of the cone should be less than 2
- The pore pressure measurement system shall be saturated to give good pore pressure response during penetration
- For deep CPTUs, it is important to correct the penetration length for inclination effects
- Recommended minimum distance between a CPT and adjacent boreholes is 2 m

It is of course important to also follow the other requirements and recommendations given in the ISO standard (or NGF Guideline).

7. Summary and conclusions
Five different cone penetrometers from different manufacturers have been used in comparative testing program at the Norwegian GeoTest Site (NGTS) on silt at Halden, Norway. Two to three tests were carried out with each cone type and the results have been systematically compared. The main findings are:

- Tests with all cone types gave very repeatable penetration pore pressure, $u_2$, for the silt deposit (i.e. depth between 5-15 m). From 13-15 m, cone type 9, the $u_2$ readings are somewhat higher
than the general trend shown by the rest of the cone types, which may be caused by varying soils.

- Measured cone resistance, $q_c$, and the corrected cone resistance, $q_t$, shows little variation between the different cone types.
- Some of the cone types give good repeatability for sleeve friction, $f_s$, readings, while some show relatively large variations, which is in line with previous experience.

In general, a significant number of tests with add-on sensors to the standard cone penetrometer have been carried out at the Halden silt site. These are not believed to influence the results of the standard CPTU parameters investigated herein. Most of the tests show good repeatability. The pore pressure is the parameter which produces less scatter compared to sleeve friction and cone resistance. Sleeve friction displays the most cone type dependent results.

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