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Additional parameters measured in a single CPT, click-on modules for the digital cone

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ABSTRACT: The paper describes a new CPT system that consists of a digital data logger "Icontrol" and a digital cone "Icone". The Icone is easily extendable by click-on modules to measure additional parameters and any module is automatically recognized by the Icontrol, thus creating a true plug & play system. This paper describes how, by moving to smart digital communication, sufficient bandwidth over a thin flexible measuring cable was created to accommodate additional parameters, without the need for changing cones, ca-bles or data loggers. The following modules are described: seismic, conductivity, magneto and vane. Feed-back from fieldwork with the Icone and a selection of click-on modules highlights the user experience with this new approach

1 INTRODUCTION

Due to its benefits, digital technology is used in many applications and is now also available to support efficient soil investigation. The possibilities of this technology have led to the development of the digital cone, the digital data logger and digital click-on modules.

2 DIGITAL CONE

The digital cone or Icone has been available since 2006. The integration of intelligent electronics provides a range of possibilities in order to make further improvements to the electrical cone and to simplify its use. In addition, the Icone is stronger due to mechanical adjustments.

The Icone basically uses the same measuring sensors as applied in the analog cone. The difference however is that the analog signals are being digitized and multiplexed already inside the cone.

Digitizing means that the analog signals are being sampled with a certain frequency and converted into a digital data stream. This digital data stream is more robust, and therefore less sensitive to distortion and loss of accuracy in comparison with the analog signals.

By multiplexing, an almost unlimited amount of sensor signals can be combined into one digital data stream and transmitted through a simple 4-wired cable.

Figure 1. Icone 10 cm^2 and 15 cm^2 area with Icontrol data logger.

A built-in memory capacity increases the user friendliness of the Icone system. For example:

- the Icone number and calibration data are stored inside and are exchanged automatically with the Icontrol data logger.
- Extreme sensor values are stored in memory and can be read for evaluation purposes.
- The memory capacity allows the data storage of a full working day.

The Icontrol data logger provides power to the Icone and synchronizes the Icone signals with the depth signal, recorded from the pushing device. The Icontrol transmits the signals to a computer system, where the CPT-parameters are shown on real time graphs.

The use of smart electronics for the Icone system has provided the following benefits:

- The accuracy of the total data acquisition system is determined only by the accuracy of the Icone.
- Interchangeable click-on modules with specific sensors can be easily added to the Icone without the need of changing cables and data loggers.
- These modules are automatically recognized by the Icontrol and the corresponding display is automatically shown on the screen.
- The Icone is able to recognize surges in measured parameters and overrule system control if needed.
- Several mechanical improvements have led to a stronger design.
- An Icone can be combined with one or more (different) modules.

3 ICONE AND CLICK-ON MODULES

In the past five years several click-on modules for the Icone were developed. In this chapter the following three are described: the seismic module, the conductivity module and the magneto module. A fourth application for vane testing is described in chapter 4. All modules can be used with a 10 cm^2 and a 15 cm^2 Icone. When CPT-data is not required, the click-on modules can also be used with a dummy tip instead.

3.1 *Seismic module*

Seismic tests are performed to investigate the elastic properties of the soil. For this purpose a shear wave (S) or a compression wave (P) is guided into the soil. Elastic soil properties are essential input for prediction of ground-surface motions related to earthquake excitation and for assessment of: foundation design for vibrating equipment, offshore structure behavior during wave loading and deformations around excavations.

Figure 2. Seismic module with 10 cm^2 Icone.

3.2 *Conductivity module*

The measurement of electrical conductivity in the subsoil is a function of the conductivity of the pore water and of the soil particles, the first being the dominant factor. With the conductivity module, changes in the concentration of (dissolved) electrolytes are determined without specifying the exact nature of these electrolytes. Therefore the module facilitates separation of zones with differentiated water content, including determining the water table depth and the thickness of the capillary ascent zone or separation of fresh and salt water carrying soil layers. Another very important application of the conductivity module is detection of (the degree of) contamination in the soil. Further soil investigation should provide details on the actual contaminants.

Figure 3. Conductivity module with 10 cm^2 Icone.

3.3 *Magneto module*

Unknown structures and obstacles, like unex-ploded ordnance (UXO), are a risk factor in the execution of earthworks. To avoid risks of damage and interruptions of work, these underground elements must be identified and mapped. Most underground structures contain metal such as sheet-piles, ground anchors and pipe lines or a combination of metal and concrete, such as reinforced foundation piles. Power supply cables and above structures have in common that they affect the earth's magnetic field.

Using the magneto module, metal objects in the underground can be detected by interpreting anomalies of the earth's magnetic field.

Figure 4. Magneto module with 10 cm^2 Icone.

4 ICONE VANE

The vane test is primarily used to determine the undrained shear strength s_u of saturated clay layers. The test can also be used in fine-grained soils such as silts, organic peat, tailings and other geomaterials where a prediction of the undrained shear strength is required.

4.1 *Principles*

The field vane test consists of four rectangular blades fixed at 90° angels to each other, that are pushed into the ground to the desired depth. This is followed by the measurement of the torque required to produce rotation of the blades and hence the shearing of the soil. The chosen blade size depends on the stiffness of the soil in order to perform an accurate measurement; the stiffer the soil, the smaller the blades of the vane.

Figure 5. Icone vane (without protection tube).

The Icone vane has many features that facilitate an accurate vane test. In the past the torque was measured at the surface. Now the actuator is integrated in the same compact housing, enabling easier, faster and more accurate operation. The vane is pushed out of its protection tube and retracted again after the test. This advantage allows more vane tests at different depths without the need of retrieving the tool to surface level. The vane rotation speed is adjustable from 0.1 °/s for performing very accurate shear tests, up to 12 °/s for fast remoulding.

The vane tool is pushed into the soil by means of standard casing tubes and CPT-rods. Depth is measured on the pushing device and added to the field data by the Icontrol data logger. The Icone vane tester can be used for onshore as well as offshore applications.

4.2 *Data processing and visualizing*

During a vane test, the vane is being rotated with a very low constant speed, while the required torque is measured with respect to the angel of rotation. This measured torque is analytically converted to the shearing resistance of the cylindrical failure surface of the vane used, and expressed in kPa. A typical shear curve is shown in figure 6.

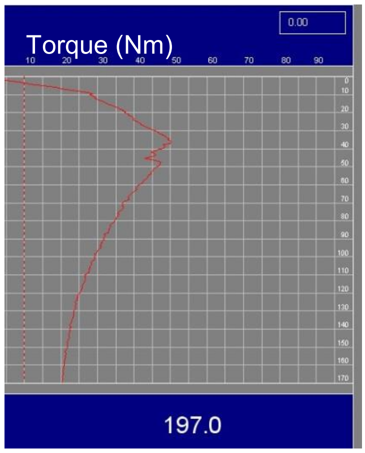

Figure 6. Results of an Icone vane test.

The highest value of this curve is a measure for the undrained shear strength of the soil material that is being investigated. A repetition of this test, after thorough remoulding of the soil, provides a uniform curve of which the highest value is a measure of the remoulded shear strength.

5 PRACTICAL EXPERIENCES ICONE VANE

5.1 *Background*

In Finland the field vane test is still the most used method to determine undrained shear strength (s_u). Nevertheless the equipment generally in use faces several shortcomings. (Ukonjärvi 2015):

- Spring elements used for propulsion are nonlinear, but the calibration factor is usually constant (Nilcon system).
- Zero shifts occur when rotating is performed from ground level.
- Some slip-coupling models don´t have constant inner friction.
- Errors and different phases of the Vane test are not that obvious in graphs using the circular coordinate system (Nilcon system).
- Rotation speed may vary when using different vane sizes.

The most common impact of these errors is an overestimation of the friction between the vane rod and the surrounding soil. Consequently this causes an underestimation of strength that may lead to expensive and uneconomic solutions.

The Icone Vane meets the requirements of application Class 1 according to the EN-ISO 22476-9 standard. By measuring torque and rotation right above the vane, the above mentioned shortcomings with the existing vane measuring tools can be avoided.

Although a correctly performed field vane test can be regarded as a very reliable way to measure the average undrained shear strength, the test procedure is rather time-consuming. The values are obtained at multiple depths, often with 0.5 or 1.0 m intervals. To shorten this procedure, a sensitive Icone CPTu has been taken into use in parallel with the Icone Vane. As Finnish clays can be very soft with undrained shear strengths as low as 5 kPa, the requirements for accuracy of the equipment and measurements are very high.

The accuracy of the torque measurement of the Icone Vane is very good. However to transform the torque into shear stress, some assumptions have to be made. Usually it is assumed that soil shears as a cylinder and shear stress is distributed uniformly across the horizontal area at the top and bottom of the vane. These assumptions could cause a bit error to the interpretation of the undrained shear strength (Wroth 1984). However, if the torque measurement was accurately determined, this error can be neglected.

5.2 *Aim of the study*

The aim of the ongoing study at the Tampere University is to determine reliable cone factors with which the undrained shear strength can be determined by using a sensitive Icone. The Icone Vane is used as one of the reference methods to calibrate the undrained shear strength. In addition, laboratory tests will be performed on high quality undisturbed samples.

The key goal is to find the best practice for the determination of the undrained shear strength in very soft soils. The future practice could well be that the investigation plans contain one Icone Vane field test with torque and rotation measurements just above the vane, supplemented by several CPTu tests with a sensitive Icone.

5.3 *Equipment used*

In-situ soil investigations were made by a CPT Crawler with a hydraulic cone penetrometer (100 kN max. pushing load), an Icone Vane and a sensitive Icone (7.5 kN max. tip load), see Figure 7.

Figure 7. 12 ton CPT rig in Perniö (Salo).

5.4 *Test site*

The test site is located in Perniö, directly next to the coastal railway track between Helsinki and Turku on the edge of a marine clay area. A full scale embankment failure test was conducted in 2009 in this area (Mansikkamäki and Länsivaara 2010). The present study includes investigations outside the failure test area on natural ground. The subsoil comprises the following layers (from top to bottom):

- Organic material 0.0 - 0.3 m
- Dry crust 0.3 - 1.4 m
- Stiff clay 1.4 - 1.8 m
- Soft clay 1.8 - 11.7 m
- Silt 11.7 - 12.8 m

The soft clay has a very high water content varying generally between 70 and 110%, which is above the liquid limit. Previous investigations on the test site indicate a very high sensitivity with an average value of around 40. The sensitivity is the relation between the undisturbed and fully remoulded undrained shear strength. With the field vane test the remoulded strength is determined after the vane is turned 20 full rotations with higher speed than the undisturbed test. The clay is just slightly over consolidated.

5.5 *Test results*

In the preliminary interpretation of the CPTu tests existing formulas and cone factors that have proven to perform well in similar conditions have been used.

To determine the undrained shear strength by measuring the tip resistance, the standard formula $s_u = (q_T - \sigma_{vo})/N_{kT}$ has been used. Because the undrained shear strength is anisotropic, i.e. its values depend on the mode of shearing, the value of N_{kT} depends on which test the results are compared to. It is common to compare results to either direct shear tests (DSS) or triaxial compression tests (UC). DSS strength is generally close to the average strength and comparable to field vane, while the triaxial compression corresponds to the active strength. As the triaxial compression strength is higher than the direct shear strength, the value for N_{kT} should be higher when comparing to DSS strength. Larsson and Åhneberg (2003) recommend to use the tip resistance factor $N_{kT} = 16.3$ to rough estimation for the average undrained shear strength for normally consolidated inorganic clays. Another method that was used herein is the one by Larsson & Mulabdic (1991) where the cone factor is estimated, based on the liquid limit as $N_{kT} = 13.4 + 6.65 * w_L$. The ground conditions are very similar in Finland and Sweden, so these interpretation methods were considered to provide a good first estimate.

Using only the pore pressure measurements for the interpretation of the undrained shear strength, the formula $s_u = (q_T-\sigma_{vo})/N_{\Delta u}$ was used. The value of the $N_{\Delta u}$-factor given in the literature varies quite much. Based on cavity expansion theory the value of $N_{\Delta u}$-factor varies between 2 and 20 (on a global basis for any comparison test). La Rochelle et al. (1988) found that $N_{\Delta u}$ varied between 7 and 9 for three Canadian clays using uncorrected field vane measurements as reference strength when OCR ranged between 1.2 and 50. The over consolidation ratio (OCR) is the ratio between the highest stress experienced divided by the current stress.

Larsson suggested to determine the pore pressure factor as a function of liquid limit by equation $N_{\Delta u} = 14.1 - 2.8 \cdot w_L$ (Larsson 2007). Values of liquid limit are between 55 and 79. The liquid limit is an index property of fine-grained soils. The liquid limit is defined as the moisture content where soil behaves as liquid. According to the mentioned range for the liquid limit, the value of $N_{\Delta u}$ is between 11.3 and 12.4 when comparing to corrected field vane values. In figure 8 profiles of corrected field vane results and undrained shear strength evaluated from CPTu are presented.

Although there is some scatter in the results, the different interpretation methods show quite good correlation and consistency to the Icone vane tester results. In the future the scatter will be narrowed by developing the methods to evaluate the cone factors for Finnish clays.

The difference between interpreted undrained shear strength and corrected field vane results at depth 5 – 6 m could be the result of silty inclusions like previous study has shown (Mataic 2016).

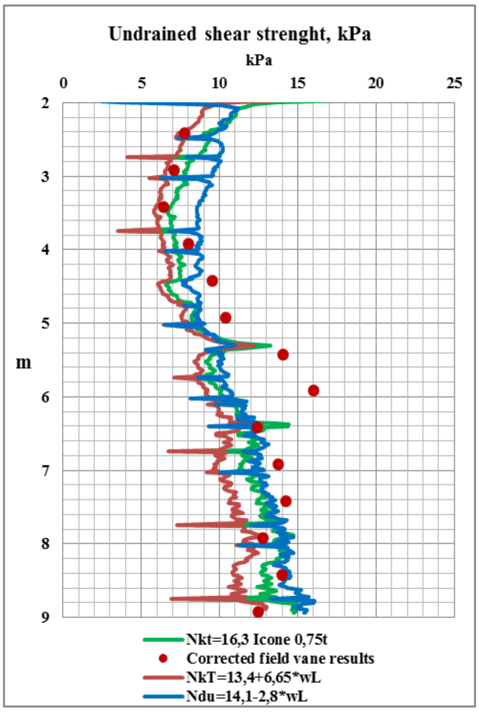

Figure 8. Interpretations of CPTu tests and corrected field vane results.

In figure 9 the shear stress-deformation behavior with the Icone Vane in Perniö is shown. The torque (T) is measured every 0.1° of rotation and the torque is converted to shear stress with equation $\tau_{fv} = 273 \cdot T/D^3$ where D is the diameter of the vane. A very illustrative strength profile with softening can be seen for the sensitive structured Perniö clay. In some of the results small steps can be seen at the start of the rotation indicating that rods have not been tightened well enough.

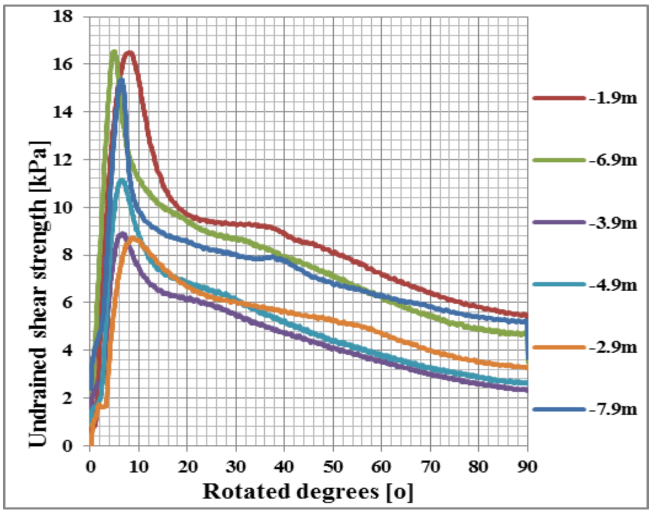

Figure 9. Shear stress-deformation behavior with field vane test in Perniö.

The study will be continued by doing laboratory tests for further verification of data. Several test sites will be studied to create a reliable data base for the study. Finally recommendations will be given for the most suitable interpretation methods and cone factors for the Finnish soft clay conditions.

6 CONCLUSIONS

Cone Penetration Testing (CPT), as a technique for in-situ soil investigation, is a recognized and widespread method for efficiently performing soil surveys. In the course of time CPT is continuously improved by the effective use of the latest state of the art. Recent developments, concerning the application of digital electronics inside the cone, offer a range of new features and benefits. The most prominant of these is the ability to easily extend the digital Icone by click-on modules to measure additional parameters. Any module is automatically recognized by the Icontrol data logger, creating a true plug & play system.

The new Icone Vane with rotation and torque measurement right above the vane gives an accurate direct measurement of the average undrained shear strength of soft soils. In addition, it provides valuable data on the strength deformation behavior of soils. It still takes time to do the testing and the results are given only for certain depths.

CPTu with the sensitive Icone has proven to give very reliable and repeatable results from soft Finnish clays. For the determination of the undrained shear strength, the accuracy is very much dependent on the cone factors used to convert the CPTu measurements into undrained shear strength.

By combining these two pieces of equipment as in the A.P. van den Berg system, the redeeming features for both can fully be utilized. CPTu testing provides a fast way to versatile continuous data, which among many other things can be used for the determination of the undrained shear strength. With the aid of the accurate new Icone Vane, the cone factors used can be adjusted to correspond to the local soil conditions. The authors strongly believe that this combination can significantly reduce the uncertainties in relation to the undrained shear strength.

7 REFERENCES

EN-ISO 22476-9:2009 *Ground investigation and testing – Field testing – part 9: Field vane test.*

Ukonjärvi, P., 2016. On the reliability of undrained shear strength in railway environment (in Finnish). Master thesis. Tampere University of technology.

Mansikkamäki, J., Länsivaara, T. 2010 Analysis of a full scale failure test on old railway embankment. In Thomas Benz (ed.), *Numerical Methods in Geotechnical Engineering; Proc. euro. conf,. Trondheim, 2-4 June 2010*. Abingdon: Taylor & Francis.

Mataić, I. 2016. *On structure and rate dependence of Perniö clay.* PhD Thesis, Aalto University, Helsinki, Finland

Larsson, R., Åhnberg, H., 2003. *Long-term effects of excavations at crests of slopes.* Swedish geotechnical institute. Linköping 2003. Report 61. s.130

Larsson, R., 2007 *CPT-sondering utrustning – utförande – utvärdering En in-situ me-tod för bestämning av jordlagerföljd och egenskaper i jord.* Swedish geotechnical institute. Linköping 2007. Information 15. s.71

La Rochelle, P., Zebdi, P.M., Leroueil, S., Tavenas, F. and Virely, D., 1988. *Piezocone Tests in Sensitive Clays of Eastern Canada. Proceedings of the International Symposium on Penetration Testing,* ISOPT-1, Orlando, 2, Balkema Pub., Rotterdam., 831-841.

Wroth, C. P. 1984 The interpretation of in situ soil tests. Geotechnique, 34(4) 449-488.

Vesic. A. S. 1972 Expansion of cavities in infinite soil mass. *Journal of the Soil Mechanics and Foundation Division, Proc. of the ASCE, Vol. 98, No. SM3., 265- 290.*

Woollard, M., Storteboom, O., and Coto Loria M. 2013 Additional Parameters Measured in a Single CPT, Cick-on Modules for the Digital Cone. In *Proc., Geotechnics for sustainable developments*: *Geotec Hanoi 2013, Hanoi, Vietnam, 899-908.*