Influence of test equipment and procedures on obtained accuracy in CPTU

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ABSTRACT: Fifteen years have passed since CPT'95 in Linköping, Sweden, the first International Symposium on Cone Penetration Testing dedicated only to CPT and CPTU. Since then, the method has consolidated its position as the most widely used geotechnical field investigation method world-wide. Besides the standard configuration with measurement of cone resistance, sleeve friction, pore pressure and tilt angle, a variety of special sensors may be incorporated in the probe, making it useful also for geophysical and environmental purposes.

However, the measurements may be influenced by many factors, partly related to the equipment, partly to the use of it. This is well-known by manufacturers and researchers, but there still seems to be a great need of knowledge amongst practitioners, as CPTU has become more wide-spread also in practical use. Even if available standards are followed, recorded data from CPTU can vary significantly according to which equipment is used, see for example Lunne et al. (1997).

The objective of this keynote paper is primarily to present the state-of-the-art on equipment and test procedures in light of the requirements of the forthcoming international standard on CPT and CPTU, EN-ISO 22476-1, as well as emphasizing important factors of influence on the obtained quality of measurements. Emphasis will be put on measurements of the conventional recordings in electrical CPTUs, leaving less space for geophysical or environmental measurements

1 INTRODUCTION

Since the first use of piezocones some 35 years ago, CPTU has now become a mature method, and most CPTU probes are multi-purpose electronic equipment with a broad range of applications, see Table 1. A new international standard is now forthcoming, introducing new and stricter requirements to the performance and quality of the test. The Application classes in the new standard are defined by specified accuracies of the recordings, but the expected ground conditions at the site are also emphasized. One possible consequence of the new standard is that more thorough considerations should be made ahead of testing, both by field engineers and consultants. Hopefully, this may contribute to reduce the gap between present state-of-the-art and the practical use of the method. The objective of this paper is accordingly to discuss some influence factors related to equipment configuration and test procedures on the quality of obtained measurements, and how the influence may be reduced in view of the new requirements.

Table 1. Types of CPT and their applications.

Type of CPT	Abbreviation	Measurements	Application
Mechanical Test	MCPT	q_c, f_s (optional)	Profiling in natural sands and stiff soils. Fill control.
Electric Friction Test	ECPT	q_c, f_s	Profiling in natural sands and soils above the ground-water table.
Piezocone Test	CPTU	q_c, f_s, $u_{1\text{-}3}$	All soil types without presence of stones and cobbles.
Seismic Piezocone Test	SCPTU	q_c, f_s, $u_{1\text{-}3}$ Shear-wave velocity	Shear-wave velocity for determination of G_{max}.
Resistivity Piezocone Test	RCPTU	q_c, f_s, $u_{1\text{-}3}$ Electrical conductivity	Detection of leached clay, environmental issues.

2 BASIC DESCRIPTION OF THE PIEZOCONE TEST (CPTU)

A CPT system includes the following components: (1) an instrumented penetrometer, (2) the hydraulic penetration system with rods, (3) down-the-hole or surface data acquisition unit with data transmission device (4) a depth encoder, see Figures 1 and 2.

Modern electrical penetrometers include minimum four channels, enabling direct or indirect measurements of cone resistance (q_c), sleeve friction (f_s), penetration pore pressure (u) and probe inclination (i), all by depth. An internal load cell is used to record the axial force at the front of the penetrometer (Q_c), from which the cone resistance is deduced. The axial force along the friction sleeve (F_s) is measured with a second load cell in a "tension/compression-type" probe design. For the so-called "subtraction-type" probes, the load cell is located in the back and records the added total tip force and the sleeve friction force (Q_c+F_s). This force, minus the separately measured point force provides the sleeve force. The measured axial force over the sleeve (F_s) is divided by the sleeve area to obtain the sleeve friction ($f_s=F_s/A_s$). Readings are usually taken at 20 mm or 50 mm intervals, depending on the required accuracy of the measurements.

2.1 *Test probes*

The penetrometer point is designed as an exchangeable conical tip with 60º apex angle. The probe is normally available in two standard sizes: (1) A_c=10 cm^2 and sleeve area, A_s=150 cm^2 and (2) A_c = 15 cm^2 and A_s = 200 to 300 cm^2. The 15 cm^2 version offers more space for additional sensors, and is commonly used in offshore site investigations. Acceptable geometrical dimensions and tolerances for the probe are standardized.

The pore pressure is usually recorded at the shoulder position (u_2) since this value is required for correcting the measured cone resistance (q_c) for pore pressure effects

(Campanella et al. 1982). Other locations are however also available, such as at the apex or mid-face of the cone (*u_1*) or immediately behind the friction sleeve (*u_3*). Most penetrometers measure a single value, but dual-, triple-, and even quadruple-element piezocones are also available.

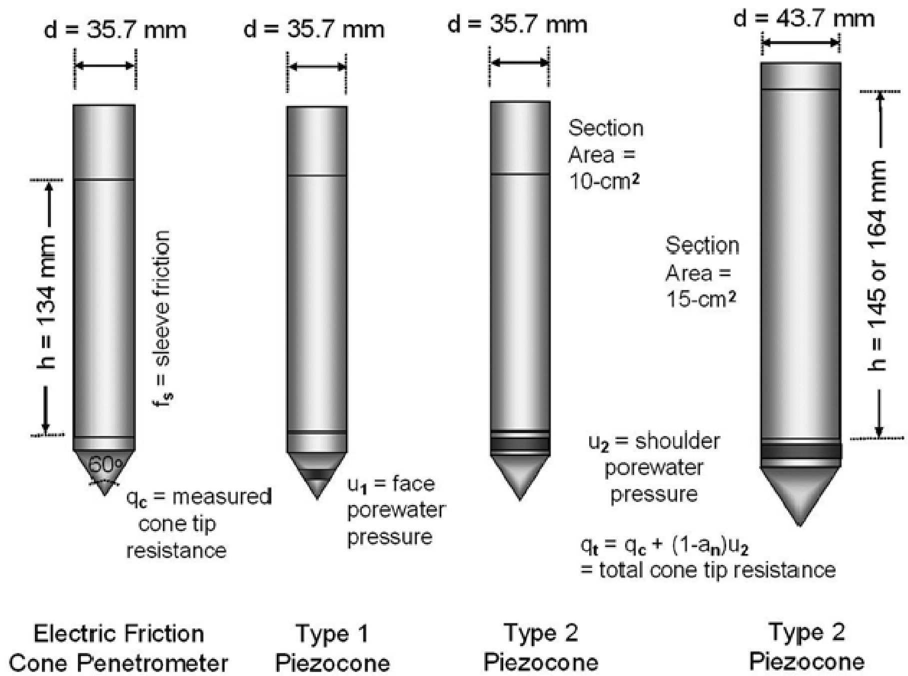

Figure 1. Standard dimensions of piezocones (Mayne 2007).

2.2 *Thrust machines and other accessories*

A thrust machine shall be able to penetrate the probe at a standard rate of penetration of 20 mm/s ± 5 mm/s by static pushing. The pushing system is usually hydraulic and can be trucks, tracks or trailers, all-terrain vehicles, skid arrangements, caterpillar belt-driven rigs or portable, light-weight units. Typically, a full-capacity hydraulic system for CPT work may have a pushing capacity between 100 to 200 kN, but specialized rigs with up to 350 kN have been built (Mayne 2007). Lightweight CPT systems in the 18 to 50 kN range are also available, but these units often require use of soil anchors to boost the capacity.

2.3 *General test procedures*

CPTU may be applied in all sorts of soils, ranging from coarse sand with occasional gravel to soft, fine grained soils. The method is however not applicable if the gravel content becomes too large, or if the soil contain cobbles and stones. Pre-drilling may be used in coarse top layers or the dry crust, sometimes in combination with casings to avoid collapse of the borehole. It may also be used in parts of the profile if the penetration stops in dense, coarse or stone-rich layers to advance past these layers. The depth of pre-drilling is commonly defined by the location of the groundwater table, and the probe can many places be lowered down to the groundwater table in the pre-drilled hole. However, in parts of the world where the distance to the ground water table is large, this procedure would not be practical. For piezocones, the pore pressure system should be fully saturated before penetration. Procedures and alternatives for saturation are discussed in further details in Section 4.2.

Figure 2. Example of complete CPTU probe with data acquisition system (www.geotech.se).

3 THE NEW INTERNATIONAL STANDARD FOR CPTU

Several international guidelines have been developed for regular CPT (ISSMFE 1979, 1988), but neither of these documents included full requirements for equipment and procedures for CPTU. In the technical report to CPT'95, Larsson (1995b) requested a new international standard for electrical piezocone testing following the significant development of equipment and procedures over the last decade. According to Larsson, a revision of the existing guidelines at the time was long overdue since many countries had already developed national standards or guidelines, partly with large discrepancies in requirements between them.

Presently, the most relevant guideline on CPTU is the International Reference Test Procedure (IRTP) (ISSMGE TC16 1999). This procedure was the first international guideline that included the CPTU, both with respect to detailed requirements on equipment and test procedures. However, no approved international standard exists for the CPTU, even if several national guidelines and standards have been developed. Among the important existing standards/guidelines on CPTU are the ASTM standard test method for "Performing Electronic Friction Cone and Piezocone Penetration Testing of Soils" (ASTM D 5778 2000), the Dutch and the Swedish national guidelines. The use of these documents is however limited outside these nations.

Since 2002, work has been taking place in the European Committee for Standardization (CEN), developing new international standards for both mechanical and electrical CPT, the latter also including detailed requirements for the piezocone test

(CPTU). The forthcoming CEN standard for CPTU is also approved by the International Standardization Organization (ISO), so the standard will be applicable worldwide as an EN-ISO standard when it is finally finished and approved. Formally, the standard is ready for formal voting, and final approval may take place within short time after that. Some countries have however already included the new requirements in their national guidelines.

The requirements given in the forthcoming standard are in agreement with the new Eurocodes EN 1997-1 and EN 1997-2 on geotechnical design. The standard is moreover based on the previously issued IRTP (ISSMGE TC 16 1999). Tests are separated in two types according to the configuration of the equipment, see Table 2.

Table 2. Type of Cone Penetration Tests with measured parameters.

Type of test	Measured parameter
TE1	Cone resistance q_c and sleeve friction f_s
TE2	Cone resistance q_c, sleeve friction f_s and pore pressure u

Furthermore, four Application classes are introduced for performance of the test and the associated accuracy requirements. The obtained quality depends to a large extent on the existing geological conditions and their influence on the choice of test equipment, see Table 3.

Table 3. Application classes and general requirements in EN-ISO 22476-1.

Application class	Test type	Soil conditions	Application
1	TE2: q_c, u_2, f_s + i	Soft soils. Stratified deposits should be avoided.	Only CPTU is performed. Interpretation of parameters possible.
2	TE1: q_c, f_s + i TE2: q_c, u_2, f_s + i	Layered deposits with both soft and stiff soils.	Interpretation in stiff soils possible, indicative interpretation in soft soils.
3	TE1: q_c, f_s + I TE2: q_c, u_2, f_s + i	Layered deposits with both soft and stiff soils.	Soil profiling. Interpretation in very stiff soils possible, indicative interpretation in stiff soils.
4	TE1: q_c, f_s	Layered deposits with both soft and stiff soils.	Indicative profiling in all soils. No parameter interpretation.

For example, Application class 1 is normally not obtainable for in-homogenous profiles including both soft and dense layers, even if pre-drilling through the dense layers can be carried out. If a high capacity probe is chosen to accommodate the stiffer layers, it may not have sufficient accuracy in the softer layers due to poor resolution of the load cell. Application classes 2 and 3 are more applicable for soil identification and profiling, and may be more than good enough for such use. Interpretation of soil parameters may be carried out in stiff or very stiff soils, but is only indicative in soft soils. Application class 4 is only intended for indicative profiling in material identification in loose to dense soils. Interpretation of parameters is not recommended.

Table 4. CPTU Application classes with allowable minimum accuracy in EN-ISO 22476-1.

Application class	Test type	Measured Parameter	Allowable minimum accuracy	Maximum measurement interval	Use: Soil	Use: Interpretation
1	TE2	Cone resistance	35 kPa or 5 %	20 mm	A	G, H
		Sleeve friction	5 kPa or 10%			
		Pore pressure	10 kPa or 2 %			
		Inclination	2°			
		Penetration length	0.1 m or 1%			
2	TE1	Cone resistance	100 kPa	20 mm	A	G, H*
	TE2	Sleeve friction	15 kPa or 15%		B	G, H
		Pore pressure	25 kPa or 3%		C	G, H
		Inclination	2°		D	G, H
		Penetration length	0.1 m or 1%			
3	TE1	Cone resistance	200 kPa or 5%	50 mm	A	G
	TE2	Sleeve friction	25 kPa or 5%		B	G, H*
		Pore pressure	50 kPa or 5%		C	G, H
		Inclination	5°		D	G, H
		Penetration length	0.2 m or 2%			
4	TE1	Cone resistance	500 kPa or 5%	50 mm	A	G*
		Sleeve friction	50 kPa or 20%		B	G*
		Penetration length	0.2 m or 1%		C	G*
					D	G*

Soil classification:
A: Homogenously bedded soils with very soft to stiff clays and silts ($q_c < 3$ MPa)
B: Mixed bedded soils with very soft to stiff clays (1.5 MPa $< q_c < 3$ MPa) and medium dense sands (5 MPa $< q_c < 10$ MPa)
C: Mixed bedded soils with stiff clays ($q_c < 3$ MPa) and very dense sands ($q_c > 10$ MPa)
D: Very stiff to hard clays ($q_c < 3$ MPa) and very dense coarse soils ($q_c > 20$ MPa)
Use:
G: Profiling and material identification with low uncertainty level
G*: Indicative profiling and material identification with high uncertainty level
H: Interpretation in terms of design with low uncertainty level
H*: Indicative interpretation in terms of design with high uncertainty level

The allowable minimum accuracy of the measured parameter, when all possible sources are added, is the larger value of the two listed in Table 4. The lower limit is used for low recorded values, whereas the percentage of the measured value is introduced for higher values. The relative accuracy applies to the measured value and not to the measured range. The inaccuracies may include contributions from internal friction, errors in the data acquisition system, eccentric loading due to inclination, ambient and transient temperature effects, zero shift errors and calibration errors.

For extremely soft soils, even better accuracies than those required in EN-ISO 22476-1 may be required locally. The existing Swedish guidelines, for example, requires a corresponding accuracy of 20 kPa for cone resistance, 2 kPa for sleeve friction and 1 kPa for pore pressure. This is probably the strictest requirement in the international geotechnical society, and is probably near the limit of what presently available piezocones can provide.

4 FACTORS INFLUENCING TEST ACCURACY

As an introduction, it may be worthwhile to resume some features of the test procedure that are known to influence the data quality:

- *Choice of appropriate equipment for actual soil conditions:* The CPTU probe should have sufficient capacity to penetrate both stiffer and softer layers encountered in a soil deposit. If a high-capacity probe is chosen for penetration of dense layers, this will reduce the resolution of the measurements in the softer layers. If a low-capacity, high-resolution probe is chosen, the transducers may be overloaded or damaged in the stiffer soils, resulting in erroneous recordings of no value.
- *Influence of probe geometry and tolerances:* The geometry of the probe should be inspected regularly for wear, controlling that the geometry and surface roughness do not exceed accepted tolerances. The tip and sleeve should be replaced if damaged or excessively worn. Replacement intervals will depend on the soil test history of the probe, as sands are considerably more abrasive than clays. Typically, an annual production of 6,000 – 12,000 sounding meters would normally require the components to be replaced once per year.
- *Influence of temperature and possible zero shift:* The zero values of all electronic transducers shall be read before and after the test. In both cases, the probe shall be temperature stabile and unloaded when the zero readings are recorded. Several factors may influence the zero recordings, such as temperature gradients due to change in test environment, proper cleaning and maintenance of the probe components, mounting effects and suction developing during retraction of the probe from the ground. Permanent zero shifts may be caused by deviation from assumed conditions during penetration, such as stones or dense layers causing overload or damage of the transducers.
- *Insufficient saturation of the pore pressure system:* Measurements of correct pore pressures require sufficient saturation of all components of the pore pressure system, independent of whether a porous filter or a slot filter system is chosen. Lack of saturation may be caused by inadequate procedures when saturating the system before use, or from dilation effects causing temporary suction when passing through unsaturated zones or layers of dense soil or peat.
- *Lack of maintenance:* The CPTU probe should be properly cleaned after use, and all seals and o-rings should be lubricated and inspected for wear and damages. If not, the interior of the probe may be destroyed by water leakages and corrosion. Finally, all CPT accessories such as the data acquisition system, CPTU rods, extension rods and other parts should be tested regularly for functionality and agreement with the standard requirements.

- *Lack of user competence and wrong use of the method:* CPTU requires skilled and competent operators to achieve the highest quality. In many countries, no formal education programs exist, and the level amongst CPTU operators may be rather variable. The picture is further complicated by lack of competence amongst engineers ordering the test, causing a lack of defined assumptions and a lack of control of obtained results in the test.

These factors will be further examined in the following. Considerations are made for the most common 10 cm^2 reference piezocone with the porous filter at the reference level (u_2), penetrated into the ground at the standard rate of 20 mm/s.

4.1 *Choice of appropriate test equipment*

For commercial use, it is rational to use CPTU equipment which is applicable in a range of soil types, according to the local geological conditions. However, tests in soft and sensitive soils may require high-accuracy measurements for interpretation of soil parameters, at least in the two highest Application classes. These two ambitions are somewhat in contradiction, which means that the choice of appropriate equipment should reflect both the local soil conditions and the preferred use of CPTU data in the project. Such a strategy requires adequate preparation and high-quality performance of the tests, from desk study of the local geology supplemented by pilot soundings, control and checks of probe functionality and calibration status.

The accuracy in measurements is amongst other features limited by the resolution of the data acquisition system, relying on the number of digital units in transfer and storage of the data. The resolution is defined by the maximum measuring range divided by the number of digital units, normally in the range of 2^{12} for modern, cable-less equipment. Considerably better resolution can be obtained for the back-up data down-the-probe and for data transmitted by cable, typically improving the resolution from 2^{12} to 2^{18} (i.e. 64 times) for some newer recording systems. Usually, measuring accuracy better than ± 1 to 2 times the resolution cannot be achieved with modern piezocones (Larsson 1995).

The choice of probe configuration is also an issue. In coarse soils, pore pressure measurements are of less importance and corrections of cone resistance and sleeve friction have only marginal effects. In fine-grained soils, the pore pressure measurements are of crucial importance and is often the most reliable measurement in soft clays since the relative influence of errors is less than for the cone resistance. This requires that the measurements are carried out with adequate saturation of the pore pressure measurement system. Correction of the tip resistance, and sometimes also the sleeve friction, is mandatory and requires proper calibration of the net area ratios.

The required accuracy of CPTU measurements is usually being specified as the greatest of a percentage of 1) Full Scale Output (FSO) and 2) Measured Value (MV). The first approach is a good measure of the manufacturing quality and condition of the equipment, but it is not well suited for choosing the appropriate equipment for the given soil conditions. Using the FSO means that the accepted accuracy may become unacceptably large if a high capacity cone is used in soft soils, where only a small percentage of the measuring range is used. The disturbing effect of internal friction from o-rings etc. may in such cases have large effects on the measured values in the low stress range. A modification of MV has been introduced in some national standards, using the percentage of the maximum MV in a layer. This approach is stricter and ensures required accuracy in the critical zones, whereas the required accuracy may be impossible to reach in very soft zones. The new EN-ISO standard varies the requirements for the accuracy with the intended use of the results, and also takes into account the existing ground conditions at the site.

To summarize, testing in soft, homogenous soils should be carried out with low capacity and high sensitivity probes with load capacities of 1 metric ton or less. For such conditions it is also possible to increase the probe area to 15 cm^2 to achieve better accuracy. One should note that high capacity probes may give as repeatable and accurate results as lower capacity probes (Lunne et al. 1996), provided they are calibrated and amplified over the same load range. The results may however vary between different probes, and it is recommended to check this feature for the applied probe.

4.2 *Pore pressure measurements – choice of saturation procedures*

The pore pressures are commonly measured using a porous, saturated filter, a saturated cavity and channels connecting to a pressure transducer mounted inside the probe. The purpose of the filter is to distinguish the generated pore water pressure in the water from the pressure existing between the soil particles. Entrapped air or gas pockets within the system may result in sluggish pore pressure response, and penetration pore pressures may not reach their full magnitude, particularly at shallow depths where the ambient pore pressure is small. At larger depths, typically corresponding to about 8-10 m of water column, the ambient pore pressure may enable saturation of insufficiently saturated probes due to the occurring pressure gradients.

Porous filters: Materials such as porous plastics, ceramics and sintered metals are used to construct porous filters for CPTU probes. The various materials may have their advantages and disadvantages with respect to saturation features, maintenance and the effect of clogging, smearing and compression.

Plastic filters are increasing in popularity because they are cheap, disposable and can be replaced with new ones after each sounding. Hence, they will not be subjected to long-term wear. However, plastic filters are soft and may be compressed when used on the face of the cone (u_1). For face elements, ceramic filter materials are preferred because it offers better rigidity, and they are less prone to abrasion than plastic filters. Filters made of sintered metals show good performance when mounted at the reference level behind the tip (u_2). They are however not recommended for locations on the face of the cone due to the risk of smearing in granular soils. It is common to replace the porous filter after each sounding, but filters made of re-usable materials can be cleaned in an ultrasonic bath and stored in a sealed box submerged in the saturation fluid.

Saturation fluid: Various types of saturation fluids may be used, such as glycerin, paraffin, anti-freeze liquid and de-aired water. Water is usually sufficient when performing the test beneath the groundwater table. It is also possible to use water and glycerin in a 50/50 % mix, but such a mix of fluids requires more caution during cone assembly. According to Larsson and Mulabdic (1991) there is no obvious influence from the choice of liquid used in the filter and the cavities inside the cone, based on tests in Swedish clays. Identical results were obtained using water, glycerin, paraffin and syrup as the saturation media.

If a viscous fluid is used for saturation, it may be drained out from the pore pressure system when lowered down to the groundwater table, or during penetration of unsaturated or dilative zones in the soil. In the latter case, typically occurring in stiff clays and dense sands, the dilation may suck the saturation liquid out of the pore pressure system or cause small air bubbles to come out of solution in the saturation liquid, causing sluggish pore pressure response in the remaining profile. Fluids such as glycerin or paraffin should be chosen under such circumstances. Due to the larger molecules and higher surface tension, these fluids will show larger resistance towards drainage from the pore pressure system than for example de-aired water.

Pre-saturated, vacuum-sealed filters, using a glycerin/gel mix are now available from some manufacturers. They have not yet been fully tested out in various soil conditions, but so far they show promising results. These filters may reduce necessary preparation time and hence make the CPTU test procedures even more rational.

Figure 3. Saturation of the CPTU probe with a) Submerged mounting and b) Vacuum treatment.

Saturation methods: Before porous filters are used, it is recommended to pre-saturate the elements submerged in the saturation liquid and exposed to vacuum overnight, or at least 24 hours if glycerin or paraffin is used. The filters should be transported to the test site in air-sealed transport boxes, submerged in the saturation fluid.

The saturation fluid may be injected into the channels and the pressure chamber by a syringe. However, this method does not always give sufficient saturation since air bubbles may be present in the cavities after injection. A better way would be to mount the probe elements submerged in a sealed funnel filled with the saturation fluid, see Figure 3a. A superior technique is to mount the probe in a pressure cell connected to a vacuum pump in the field, see Figure 3b. Vacuum is applied on the assembled probe until no air bubbles escape from the pore pressure system.

It is common practice to place a rubber membrane containing saturation fluid over the front end of the probe to maintain saturation as the probe is lowered down to the groundwater table. This is particularly important if the probe is saturated by water, but may also be used for added security when using other liquids. The rubber membrane will easily rupture on its first penetration of the soil.

Slot filter: Since the mid 1990s, probes equipped with a slot instead of a porous filter have been used (Elmgren 1995, Larsson 1995a). The cone tip comprises two separate parts, the cone and a steel ring, in addition to two rubber O-rings. Prior to saturation, the cone and the ring are pressed together, defining the size of the slot filter to become only 0.3 mm wide, see Figure 4. The main purpose of the slot is to break the structure of the soil particles, so that only individual grains floating in the liquid can enter the slot. In this concept, the inner cavity is usually saturated with a liquid, whereas the outer cavity is saturated by petroleum grease.

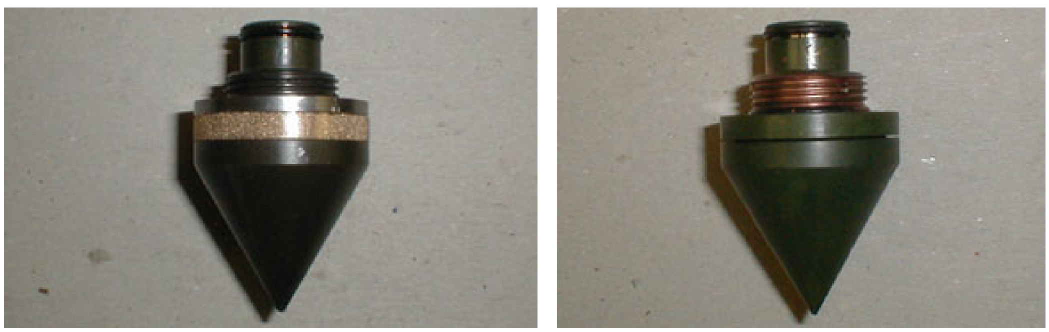

Figure 4. Cone tips with porous filter of sintered bronze (left) and slot filter (right) (www.envi.se).

The slot filter system does not present the same problems with pre-saturation of the porous filters, although care should be taken when pressing grease into the slot and tip cavities. The grease should not contain air bubbles, and should be injected into the slot in a controlled way, using a grease pump or similar.

The properties of the grease are also important. Elmgren (1995) presented results from a laboratory study, using different combinations of grease and oil for saturation of the pore pressure system. A significant change in behaviour was observed, depending on which quality of grease that was used. Elmgren (1995) concluded that for normal use, a combination of grease and oil is acceptable. Experience from the field has however indicated that grease saturation may cause some hysteresis in the pore pressure measurement. For rapid changes of pore pressures, the hysteresis could become as much as ±25 kPa for saturation with water and grease, somewhat lower (± 2-3 kPa) with grease used in combination with hydraulic oil. Some types of grease are also temperature sensitive and may become more rigid in cold temperatures. The pore pressure system may then behave less dynamic when exposed to rapid pore pressure changes in the ground. Friction heat generated by penetration of dense layers may moreover warm up the grease so that it becomes less viscous. The grease can then more easily be sucked out of the slot when penetrating dilative soils.

Use of gelatin as a saturation medium was also included in the study. The cone tip is then submerged in boiling gelatin and then cooled off before use. Gelatine in combination with a liquid (water, glycerine or oil) showed excellent pore pressure response, also with respect to dynamic changes of the pore pressure. The hysteresis was less than 1 kPa, which corresponded to the highest accuracy of the test probe. When ultimate accuracy is needed, the use of gelatine for saturation of the probe may hence be recommended.

Probes with slot filter have become popular for practical reasons in recent years, as the time needed for preparation of the probe prior to testing can be reduced. In addition, the slot filter better maintains the saturation when passing through unsaturated or dilative soils, and may hence be the preferred option in many cases. Despite the apparent simplicity of this system, the pore pressure response may sometimes become more sluggish and less detailed for various reasons. The user should hence carefully consider alternative saturation strategies, depending on the geological conditions, the possibility of penetrating dilative soils and the required accuracy of the pore pressure measurements.

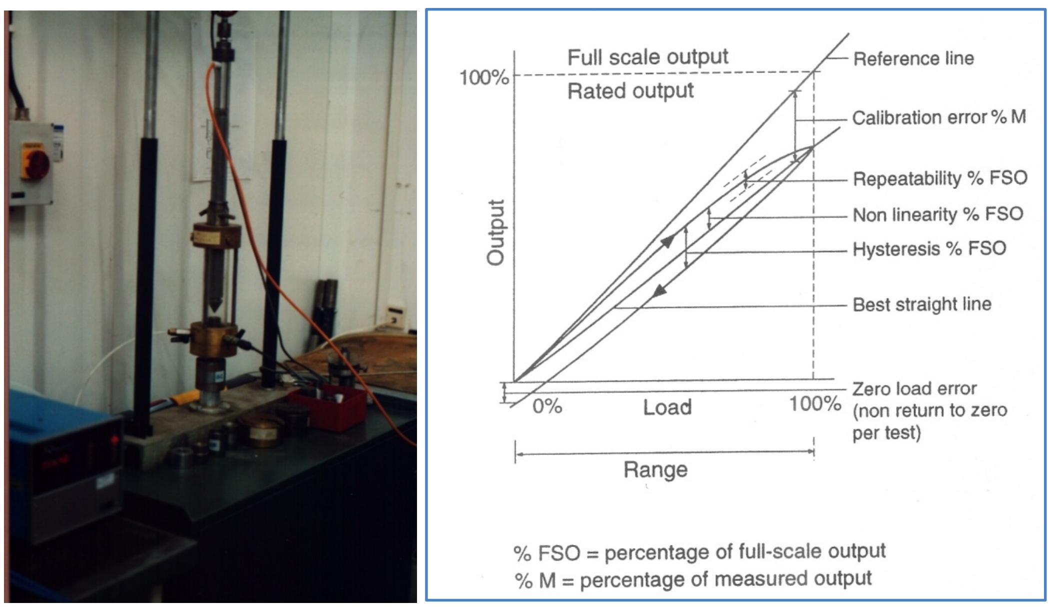

Figure 5. a) Calibration arrangement for CPTU and b) Calibration features for electronic transducers (after Lunne et al. 1997).

4.3 *Calibration features*

The calibration of a new cone shall give a nominal accuracy of the probe, providing calibration factors for the various transducers, including features like repeatability, linearity, zero stability, cross-talk between transducers and influence of temperature changes. Most CPT companies send their probes to their respective manufacturers or accredited calibration centers for re-calibration at regular intervals, including checks for geometrical tolerances and other maintenance. However, most companies have inhouse facilities to do regular function checks of the equipment, but only a few can calibrate their probes against load cells and pressure sources, referring to high-precision load cells and pressure gauges.

The probe should be calibrated and maintained regularly. The calibration intervals depend on how frequently the equipment is used and how it is taken care of and stored between soundings. The performance of each probe with respect to output from measurements is specific and may vary during the lifetime of the equipment. Small changes in function and geometry of the probe hence require regular re-calibrations, normally according to the following recommendations (ISSMGE 1999, EN-ISO 22476-1):

- *Regular time intervals:* The probe should be re-calibrated every 6 months, if it is in continuous use. For probe systems that allow scanning of the history of zero load readings, longer calibration intervals may be accepted if the history shows only small acceptable deviations.
- *Number of sounding meters:* If the probe is used irregularly, it is suggested to re-calibrate the probe according to the number of sounding meters used. Re-calibration of the probe is usually suggested when the amount of sounding meters exceeds 3000 m.
- *After overloading or loading near to the probe capacity:* A new calibration should be carried out after soundings under difficult conditions, where the probe has been overloaded or loaded close to its maximum capacity. Such cases may result in a loss of calibration and/or a significant shift in zero values, even if the transducers can sustain a certain overload without getting seriously damaged.
- *Function control:* Regular function control of the equipment should be carried out as a part of the daily routine in the field.
- *Calibration according to history of zero load readings:* For probe systems that allow scanning the history of zero load readings, a longer calibration interval than suggested above may be accepted, if the history shows only small and acceptable deviations of the zero load readings.

Details concerning the calibration of probes are given by e.g. Mulabdic et al. (1990) and Lunne et al. (1997). Specifically, the calibration of the probe is normally carried out according to the following procedure:

Calibration of cone resistance and sleeve friction: The cone resistance and sleeve friction is calibrated in a special rig using incremental, axial loading and unloading, see Figure 5a. Usually, the calibration is carried out for various measuring ranges, including those commonly encountered in practical use. If a new probe is calibrated, the sensors should be subjected to 15 to 20 repeated loading cycles up to the maximum load, before the actual calibration is carried out. If the calibration curve is non-linear, the approximation used in the processing of data should be reported. This is particularly important when testing soft soils where only a small percentage of the load cell capacity may be utilized. Calibration of the friction sleeve requires a specially adapted calibration unit to substitute the cone, transferring the axial forces to the lower end area of the friction sleeve.

Calibration of pore pressure and net area ratio: The calibration of the pore pressure and net area ratios requires a sealed pressure chamber, constructed so that the lower part of the probe can be mounted in the chamber and be sealed above the friction sleeve. In the calibration, the probe is subjected to an increasing chamber pressure, and cone resistance, sleeve friction and pore pressure are recorded. In this way a calibration curve for the pore pressure transducer is obtained and the net area ratios α and β can be determined from the response curves for cone resistance and sleeve friction. As for the other transducers, the response of the pore pressure transducer to cyclic pressure variations is also controlled.

Calibration of the inclinometer: The inclinometers in the probe shall be calibrated over a range of at least + 20^o and – 20^o with the vertical in 2 orthogonal directions. Calibration should be carried out for every 5^o intervals. The required output accuracy should be better than 2^o or 5^o respectively, depending on the Application class.

Special features: The calibration of a probe may also include special features such as influence of internal friction and possible interference effects between transducers and mechanical components. Most available cones today are designed to avoid the effect of axial load on the pore pressure readings, so-called cross-talk, but this was a problem with older cones where the load caused deformations in both the pore pressure transducer and the porous filter. The sensors should be checked individually to ensure that the applied load action does not influence them.

The effect of changes in the ambient temperature is also an important calibration feature. The probe is installed in water baths at different temperatures, and the transducer signals are supervised to ensure that the values stabilize. From these results a unit measure for changes in zero readings per ^{o}C is obtained, and an impression is obtained of the time needed for the probe to temperature stabilize when exposed to different ambient temperatures in the field. The calibration should be carried out using the same data acquisition system as in the field test.

4.4 *Accuracy of the transducers*

The total obtained accuracy in a CPTU should take into account all possible sources of errors, both related to the equipment and the procedures, and it is this accumulated value that should be acceptable for the required Application class. As shown in Figure 5b, the measuring accuracy of any transducer involves different contributions such as:

- *Resolution:* Result of the digitalization process, function of the transducer capacity.
- *Non-linearity:* Deviation in the calibration curve from a linear relationship between output and measured value (% of FSO).
- *Repeatability:* Ability of the transducer to show the same reference value after repeated cycles of loading-unloading (% of FSO).

- *Hysteresis:* Deviation between a reference value at loading and unloading (% of FSO).
- *Zero load error:* Absolute difference of the zero load readings at start and completion of the test.
- *Calibration error:* Deviation between the real value and the transducer output (% of MV).

Unfortunately, the cone manufacturers have no standardized way of giving the measurement precision of their products. Some use the term accuracy, which is understood to be the effect of all relevant contributions listed above, relating to the specific properties of the probe transducers and how they are calibrated. Others specify the relative contributions of effects like non-linearity, temperature influence and resolution. The relative contributions between the influence factors to the total accuracy is somewhat unclear, but in general, the resolution of the measuring system shall be better than one-third of the accuracy applicable to the required accuracy given in EN-ISO 22476-1.

The amount of electrical noise influencing a small voltage output may have considerable effect on the accuracy of the measurements, and the output should be large enough to be unaffected by this noise. In addition, the obtained measurements are influenced by factors relating to the test procedure. A comprehensive summary of these issues, with respect to soft soils, is given by Lunne & Andersen (2007).

It is a difficult task to fully verify the real, obtained accuracy in a CPTU, but the following list of influence factors should be relevant to consider:

- Appropriate transducers by choice:
  - Transducer capacity
  - Components with sufficient resolution and stability
  - Transducers unaffected by noise and variation in zero readings
- Calibration certificate in agreement with the use of the probe, including:
  - Measuring range and gain factors for the tip load cell, pore pressure transducer and friction load cell.
  - Temperature influence for all transducers
  - Net area factors for correction of measured cone resistance and sleeve friction
  - Resolution, non-linearity and hysteresis effects of all transducers in the probe
- Zero load values before and after testing, including:
  - Description of procedures for temperature stabilization and reading of zero load values in the field
  - Numerical documentation of discrepancies in zero load values and the influence on accuracy in engineering values
- Description of test procedures, including:
  - Saturation of the pore pressure element
    - Saturation medium used
    - Field saturation method used
    - Procedures for control of pore pressure response

    - Control of penetration rate
    - Control of probe inclination and procedures for correction of penetration depth
- Final evaluation of test records

4.5 *Specifications for commercially available probes*

Cone resistance: Application class 1 of the forthcoming international standard requires that the “minimum allowable accuracy” should be the larger of: q_t = 0.035 MPa or 5 % of the measured value. The relative accuracy applies to the measured value and not the measured range. A review of presently available piezocones shows that the accuracy of the load cell is claimed to be between 0.2 and 0.4 % of the FSO. For a probe with 5 metric tons axial capacity, this corresponds to an imprecision in the measured cone resistance of 100-200 kPa. The resolution contributes between 0.0025 and 0.08 %, corresponding to a contribution of 1-40 kPa of the total accuracy, somewhat dependent on the resolution of the data transmission system. The inherent effect of non-linearity, hysteresis and other factors contribute the rest.

Pore pressure: Application class 1 requires that the “minimum allowable accuracy” should be the larger of: u_2 = 0.01 MPa or 2 % of the measured value. One should hence be able to measure the pore pressure with an accuracy of ±1 kPa, using a transducer with a measuring range of 10 bars (1000 kPa). This implies a measuring accuracy of about ± 0.10 %, involving all sources of error, using the full scale measuring range as reference. According to the overview of available piezocones, the accuracy is reported to vary between 0.2 and 0.5 % of the FSO, indicating a best obtainable accuracy for a 1000 kPa transducer to fall between 2 and 5 kPa, with the resolution representing about 50 % of the total accuracy. The standard requirement may hence be too strict for some of the available piezocones under normal conditions. However, high precision transducers are available and should be mounted in the probe if the ambition is to produce high quality pore pressure as required by the new standard. The obtainable accuracy obviously relies on a fully saturated pore pressure element. If not, the requirements given in the standards are easily violated, even if the transducer specifications are good enough.

Sleeve friction: The measured sleeve friction is considered by many as the most unreliable measurement made in a CPTU (Lunne et al. 1986, 1997). The recorded sleeve friction is influenced by the pore pressures acting on both ends of the friction sleeve. These areas are usually not of similar size and will cause an unbalanced friction force that has to be corrected for. However, since pore pressures are usually not measured at both places (u_2 and u_3), this correction is difficult to do accurately and is often omitted. Other factors that contribute to the errors in friction measurements are the distribution of the side friction and the degree of remoulding behind the tip, together with the surface roughness between the soil and the sleeve. The measured friction value is typically much less than the full range of the load cell.

The ASTM standard does not give any requirements to the total accuracy of the measurements, but specifies calibration requirements both for newly manufactured cones and for cones used for production, see Table 5.

Table 5. Required accuracy in ASTM Standard Test Method for electric cone and piezocone testing of soils (ASTM 2000).

Calibration parameter	Element	Requirement Newly manufactured cones	Requirement Cones under production
Zero load error	Cone	≤ ± 0.5% FSO	≤ ± 0.5% FSO
Zero load error	Sleeve	≤ ± 0.5% FSO	≤ ± 1.0% FSO
Zero load thermal stability	Cone Sleeve	≤ ± 1.0% FSO	-
Non-linearity	Cone	≤ ± 0.5% FSO	≤ ± 1.0% FSO
Non-linearity	Sleeve	≤ ± 1.0% FSO	≤ ± 2.0% FSO
Hysteresis	Cone Sleeve	≤ ± 1.0% FSO	-
Calibration error	Cone	≤ ± 1.5% MO at 20% FSO	≤ ± 2.0% MO at 20% FSO
Calibration error	Sleeve	≤ ± 1.0% MO at 20% FSO	≤ ± 3.0% MO at 20% FSO
Apparent load transfer	Sleeve transfer	≤ ± 1.5% FSO of sleeve	≤ ± 2.0% FSO of sleeve
Apparent load transfer	Cone transfer	≤ ± 0.5% FSO of cone	≤ ± 1.5% FSO of cone

The specifications are based on past experience and may hence not fully reflect what can be achieved nowadays. According to the standard, it is required to have some form of periodic calibration checks.

The forthcoming EN-ISO standard requires that the "minimum allowable accuracy" should be the larger of: f_s = 5 kPa or 10 % of the measured value in Application class 1. Manufactured piezocones are reported to have an accuracy of the friction load cell similar to that of the cone resistance, say between 0.2 and 0.8 % of the FSO. However, the influence factors on the measurements outlined above are of such significance that the inherent accuracy of the transducer is less interesting. Besides, in many soils, such as soft, sensitive clays, the measured friction values may be smaller than the accuracy required in the standard.

4.6 *Temperature influence*

Most CPTU tests in practice are performed without temperature measurements during preparation and sounding. This is a pity since no control exists of the temperature level in the probe, or if transient temperature gradients occur during testing. It is a relatively simple task for the manufacturers to install a temperature transducer routinely, as most modern data acquisition systems easily accommodate the extra recording channel.

Modern piezocones are temperature compensated and less vulnerable to the ambient temperature than they used to be. They are however not compensated for the effect of temperature gradients, as only the permanent, temperature induced zero shifts could be accounted for, not the transient errors. At low stresses this effect still needs to be considered, and piezocones used for tests in soft soils should hence have high temperature stability. Accordingly, the Swedish guidelines require the following temperature stability for all transducers mounted in the probe:

- 2.0 kPa/^{o}C for cone resistance
- 0.1 kPa/^{o}C for sleeve friction
- 0.05 - 0.1 kPa/^{o}C for pore pressure (1000 – 2000 kPa measuring range)

This seems to be within reach for most available probes today. The relationship between temperature and load cell output, obtained under static conditions in the laboratory, may however be somewhat different from the field conditions, since a heat flux may flow through the probe during penetration.

When the probe is lowered from the surface into the ground, small temperature gradients will occur if the air temperature differs from the ground temperature (typically 5-7^{o}C). The temperature gradients will influence the metal in the probe and the readouts will be misleading for a period of time until the temperature again stabilizes. The largest gradients in the probe will normally occur after 2 to 3 minutes, depending on the difference in surface and ground temperatures, and the probe will usually be completely stabilized after 10 to 15 minutes. It may be a difficult task to overcome the temperature gradient problem technically, so the best way to eliminate these effects would be to adapt the in situ procedures, so that the influence of the temperature gradients is minimized.

Lunne et al. (1986) suggests two approaches to account for the effects of temperature zero shifts:

- Carry out zero load readings of the transducers before and after completion of the test, with the probe having a temperature equal or close to that of the ground.
- Mount a temperature sensor in the probe and correct the measured results based on the laboratory calibration curve for temperature influence.

During penetration of dense and coarse layers, the friction between the probe and the soil particles may result in a heat flux and temperature increase in the probe. This temperature effect may have little significance in the dense layer where the cone resistance is large, but may influence the readings in the underlying soil. If the soil profile consists of a dense sand layer over soft clay, the temperature effect may become significant in the clay, since the temperature compensation may take some time to suffice. One way to overcome this problem is to arrest the penetration immediately after passing the sand layer, and wait for the temperature to stabilize shortly after entering the clay. This procedure may also contribute to a re-saturation of the pore pressure system if the saturation has been lost in the dense layer.

The effect of temperature gradient on cone readings was studied recently by Boylan et al. (2008), using commercially available cones in a comprehensive test programme in peaty soils. Due to the soft highly compressible nature of the peat, q_t and f_s values are very low and occasionally become negative. The measurements are thus very sensitive to measuring errors, such as the effects from temperature gradients. Initially, the tests were carried out without temperature stabilization of the probe prior to testing, resulting in very large temperature effects on the cone resistance and friction readings. Only the pore pressure readings appeared reliable. Later, the probe was adapted to ground temperatures by immersing it in a container of water, and this resulted in much more dependable profiles. This confirms that the temperature effect on recorded values may become significant and that the probe should be allowed to temperature stabilize before the test commences.

The data acquisition system may also be sensitive to temperature changes, which may result in zero shifts in the recorded data. The temperature changes may be caused by warm-up effects or by changes in the ambient temperature. The effect will vary depending on the data acquisition system, and this should be tested before use. With modern days data acquisition systems the influence from temperature changes is certainly less of a problem than some years ago.

4.7 *Shift in zero load readings*

The zero load readings of cone resistance, sleeve friction, pore pressure and inclination of the probe shall be recorded before and after the penetration test, with the probe withdrawn to the surface. The readings shall be taken with the probe unloaded and temperature-stabilized, ideally at the ground temperature. The zero load readings should be logged and presented as a part of the test results, being an important part of the quality check of the CPTU records.

Shift in zero load readings can have a very significant influence on the results and may be caused by one or more of the following reasons:

- Mechanical damages to the probe caused by overloading or encounters with objects in the ground.
- Shortcomings and damages in the electronic systems causing a change in calibration values.
- Hysteresis effects and zero shift in the transducers after repeated loading-unloading cycles in the test.
- Shortcomings in test procedures, such as:
    - Insufficient temperature stabilization, resulting in effects of temperature gradients on the transducer read-outs
    - Loading of the probe or any of its components. During saturation and mounting of the rubber membrane, the probe will for example be subjected to small stresses, so that the sensors can show values different from zero. Mounting of the tip element may particularly influence the pore pressure readings. Normally, 5 minutes relaxation time is recommended after mounting, before the zero load readings are taken.

- Residual pore pressures (suction) after withdrawal of the probe to the surface. It is recommended to loosen the cone tip after retraction to release the remaining suction. Alternatively, some 5 minutes waiting time is recommended after withdrawal before repeated zero load readings are taken.
- Insufficient cleaning of the friction sleeve after withdrawal to the surface, causing stresses acting on the friction sleeve.

A special problem may occur when penetrating very soft soils, underlying stiff layers or a dry crust. The large forces developed in the stiff top layer may result in shifts in zero load values and hysteresis in the load recordings in the softer layers. For such ground conditions, it is hence recommended to carry out pre-drilling/punching through the stiff top layer, which may eliminate overloading of the probe in the top layer if a low-capacity, high-resolution probe is used.

Peuchen et al. (2005) investigated zero drift data for three CPT projects all with Fugro offshore systems. They found that the mean zero drift for the cone resistance q_c in 5 cm^2 cones was about 30 kPa, which alone may violate the required accuracy of measured cone resistance in clays.

According to Lunne et al. (1997), no strict requirements exist on the deviations in zero load readings, but one should check if the differences in zero values before and after a test are acceptable. In soft clays this may correspond to ± 20 kPa for the cone resistance readings, according to Lunne et al (1997). If the measuring range and the resolution of the probe are known, it is possible transform the numerical discrepancies in zero readings to engineering units (kPa). By this, the contribution to the total accuracy from differences in the zero readings can be found and related to the required accuracy in the corresponding Application class.

For some older CPTU systems, such as those relying on signal transfer through the CPT rods, the zero load readings had to be taken at the surface with the sender unit in the probe held close to the receiver unit on the thrust device. This is no longer the case for newer systems, and it is now possible to take zero load readings at any stage of the test, with the probe in arbitrary positions. Quality-wise, this may open for a more controlled procedure of zero load readings, improving the documentation of the test and also help assess rational calibration intervals of the equipment, see Figure 6. This will reveal the status of the calibration and transducer functions, as any instability of the zero read-outs may indicate the need for a re-calibration or a function control of the probe.

A recommended procedure for zero load readings may hence be as follows:

- The first zero load reading is taken with the probe unloaded and temperature stabilized on the surface. Any mounting effects on the transducer readings should be stabilized.
- Control reading of the zero load readings taken after insertion of the probe into a pre-drilled hole in the ground. Temperature gradients should be allowed to stabilize before the testing commences. The stabilization of the zero load readings can be monitored in real time on modern data acquisition systems.

- Withdrawal of the probe to the top of the borehole, where it is allowed to relax to enable any suction effects to dissipate before the final reading of the zero load values is taken. The pore pressure may also be logged during withdrawal. The cone tip should be released somewhat to release the suction. The seals above and below the friction sleeve should be cleaned to ensure that the friction sleeve can easily be rotated.

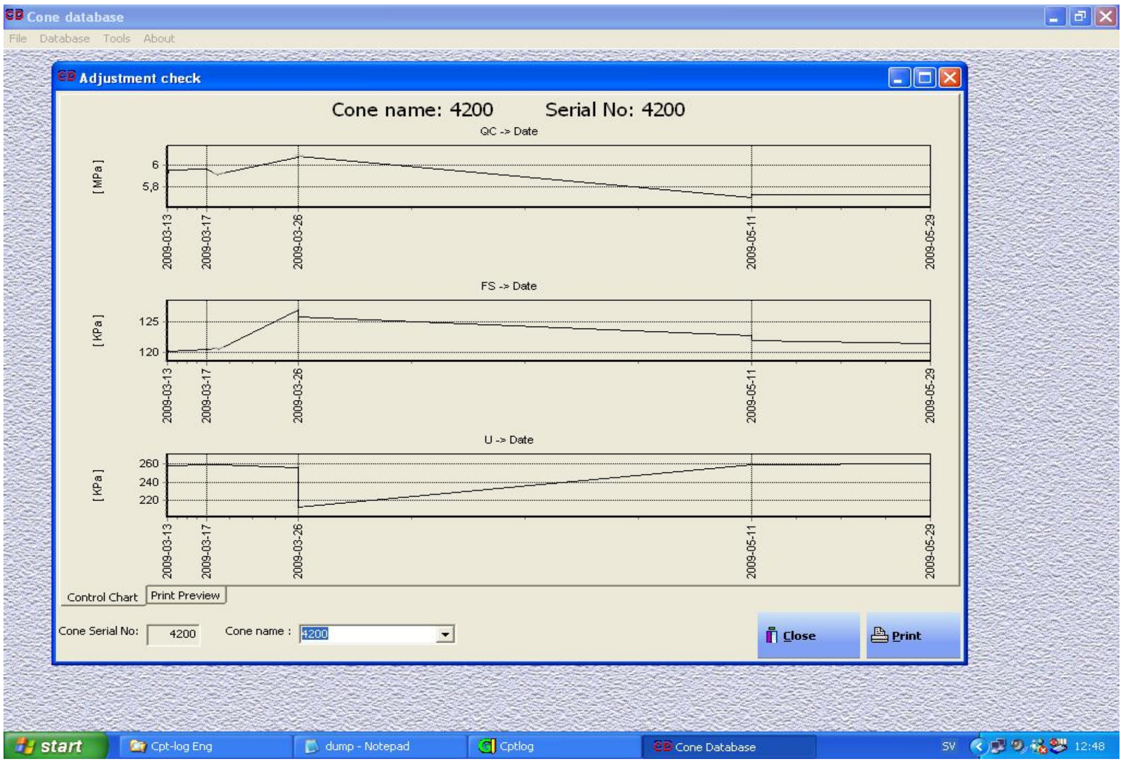

Figure 6. History of zero load readings for a Geotech piezocone (www.geotech.se).

4.8 *Inspections for wear*

Penetration of coarser soils leads to an unavoidable effect of wear on the cone tip and the friction sleeve of the probe. This was taken into account in the first CPT standards, where tolerances for changes in dimensions of the equipment were given and rather large. The increasing demands on accuracy in many test applications have defined much more narrow limits, particularly for CPTUs and conventional CPTs with high demands on accuracy. The cone tip and friction sleeve should hence be inspected regularly by a geometry guide and roughness indicator to control if the probe geometry is within the tolerances. The actual dimensions of the cone tip and friction sleeve can alternatively be measured and used in the evaluation instead of the nominal values.

4.9 *Comparative studies*

Several recent studies have addressed the accuracy of CPTU measurements, and the variation of recorded data obtained by different manufactures. A series of CPTU's involving six different probe manufacturers were carried out at NGI's test site of soft clay at Onsøy in Norway (Lunne & Andersen 2007). The main objective of the work was to evaluate the influence of probe type, and to check if commercially available equipment could meet the requirements of Application class 1 of the forthcoming EN-ISO standard. The following conclusions were made:

- The range of obtained q_t and u_2 values was better than the accuracy requirement of Application class 1, whereas the range of f_s values was in the same order of magnitude.
- The scatter in u_2 values was relatively small, provided that the pore pressure measurement system was well saturated. The measured pore pressures showed the smallest variations from one type of CPTU equipment to another.
- Compared to the pore pressure records, the scatter in q_t and f_s values was relatively large.

Numerous CPTUs have been carried out the Bothkennar site in the UK over the years. The overall uniformity of the site has been confirmed by a large number of tests, finding that tests in the same small area with different probes can produce variable results. Long et al. (2008) compared recent work carried out by University College Dublin in cooperation with Lankelma (UK), to earlier work at the site carried out by e.g. Powell & Lunne (2005b). Their work made use of five different piezocones, carefully calibrated to minimize any potential equipment errors. Similar to the results found by Lunne et al. (1986) in the Onsøy tests, Powell & Lunne (2005b) found the pore pressure to yield the smallest scatter in results. Somewhat higher scatter was found for the cone resistance, but significantly less than that found for the sleeve friction. Long (2008) found their work at the same site with just one probe manufacture to give higher cone resistances than those reported by Powell & Lunne (2005b), whereas sleeve friction and pore pressure recordings were very similar. Their results were more in line with those obtained using Fugro McClelland piezocones (Jacobs & Coutts 1992). These studies compared corrected cone resistance values (q_t) but compared uncorrected sleeve friction values (f_s).

Generally, these example studies show that there still exist some equipment specific features in the obtained quality of CPTU data, even if improvements in transducer technology in recent years have brought this field forward. One conclusion from the studies is that, in soft clays, cone resistance values show somewhat more variation from one type of equipment to another, as compared with the measured pore pressure. It is hence expected that derived soil parameters or soil classification based on pore pressure readings are more reliable compared to classification and interpretation based on cone resistance or sleeve friction measurements, at least in soft clays where the measured pore pressures are high and cone resistance and sleeve friction values are small. For high pore pressures, the relative influence of errors then become relatively small, whereas they contribute more to the small cone resistance values. In stiff clays, the cone resistance and sleeve friction is higher and pore pressure smaller, making cone resistance measurements the more reliable option.

5 FUTURE TRENDS AND DEVELOPMENT

Cone penetration testing with modern, data-assisted equipment can provide site-specific information of the soil properties in a rational and cost-effective way. CPTU results may be used to evaluate stratification, depths and thicknesses of soil layers, presence of lenses or thin layers of contrasting materials and relative penetration resistance of the encountered soils. Where the local soil conditions allow for it, CPTU provides a lot more information than conventional CPT soundings. Provided that high-quality data exist, interpretation of parameters is cheap and can be performed very quickly compared to the traditional procedures for sampling and associated laboratory testing. However, the two approaches are complementary, with CPTU providing immediate profiling of the subsurface conditions with subsequent confirmation obtained by selective sampling and laboratory testing.

At the time of CPT'95, the then present trends and developments could be summarized as follows:

- Improved accuracy in manufacturing of electrical CPTU probes
- Extensive national standardization of CPTU
- Improved understanding of factors with influence on the quality of CPTU measurements
- Increased use of CPTU in many countries, providing improved experience and extensions of local databases
- Implementation of inventive sensors to broaden the CPTU measurement repertoire, particularly for environmental testing

The most modern electronic probes collect the data directly in digital format, with a potential of recording of as many as ten different transducers in the probe. This may include recordings of cone resistance, sleeve friction, several pore pressures, resistivity and a number of environmental parameters. CPTU data can be used together with other sounding and sampling results to create cross sections and subsurface profiles for sophisticated views of the general ground conditions. The digital CPTU data can also be post-processed to provide soil parameters for geotechnical analyses or used in direct CPTU methods for estimates of foundation capacity or settlement predictions.

Further development may include interpretation of properties in special soil types and geologic materials, such as peats, residual soils, silts and collapsible soils. On this background, there are many reasons to believe that the growth in use of CPTU in future site investigations will continue, with research and development in the field of equipment and procedures along the following axes:

- *Test equipment:* As CPT now is used also for stiff and hard soils in many parts of the world, high-capacity cones will become more extensively used. Development of heavy or super-heavy trucks and thrust equipment in such soils will also increase. On the other hand, lightweight, miniature cones will be considered for shallow investigations, reducing the necessary gear and thrust capacity for such investigations.

If already not so, CPTU will become the preferred penetration method in testing of saturated soils, more frequently with recording of pore pressures at several locations. Temperature sensors should become standard for all new probes, allowing more control of temperature effects both during test preparations and performance. The manufacturers will continue to pay attention to improve accuracy and sensitivity of new probes, as this is now rapidly becoming a competitive future after the advent of the new international standards.

- *Data acquisition systems:* Developments in microelectronics over the past decade have produced significantly improved data acquisition and processing systems. This development will continue in the future, but probably not with the same speed. Cordless CPT systems will continue its growth, with implementation of new techniques for data transfer, like the radiowave technique recently developed by Geotech in Sweden. Computer modem technology allows easy transmission of data, and test data can now be conveyed over telephone lines or wireless almost immediately after test completion.
  Besides the efficiency and rationality this opens for, it is also a quality asset as the engineer and field operator can have a quality evaluation of the data before further testing takes place. This allows the operator to redo the test if necessary, with the machines being at the location and can result in a more flexible performance of the site investigations. Real-time computer interpretation of CPTU data has become common, including sophisticated presentation techniques allowing 3D visualization of the soil conditions.
- *New international standards:* The new international EN-ISO 22476-1 standard for CPTU will set stricter requirements to the application of CPTU for different soil conditions, separating the performance of CPTU into four Application classes, each class with given requirements to measurement accuracy. This requires a higher level of quality control and preparation in all stages of the test. Communication and interaction between engineer and field operators should improve, and education and accreditation of CPTU operators is expected to be more common. The accreditation agency checks that the operating company has the required facilities and procedures for quality control, that the procedures and relevant standards are followed, that the operator has the required formal education and skill, and that the quality is verified. Despite the large advances in test equipment and procedures, there may still be too large discrepancy between actual test performance and best practice in many cases. This may also be extended to calibration and maintenance of the equipment. Hopefully the new international standard will contribute to remedy this situation.

Several advances in research and development have not yet been fully developed for practice, or have not been made known to the practicing engineers for implementation. This is expected to be less of a problem in the future, along with the improvement in technology and more comprehensive international standards. Still, CPTU has been used for more than 30 years, enjoying wide-spread use in many different soil types and for many types of applications. The development of the method is going on and new applications are coming into use. CPTU is hence expected to further enhance its status as a profiling and in situ tool of major importance in the future.

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