Regional Report for the Nordic Countries

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ABSTRACT: In 1995 the first international symposium on cone penetration testing was held in Linköping, Sweden. In the Nordic countries at that time, focus was on improved accuracy of the CPT probes, national standardization and increased use of CPT due to improved experience and increased local databases. Since then, additional sensors have been added to the probes, the interpretation methods have been extended and refined and the interest for combinations with other measurements, such as resistivity or seismic, have increased.

1 INTRODUCTION

This Regional report comprises experiences of the cone penetration test (CPT) in the Nordic countries. The Nordic countries in this context include the four countries Norway, Sweden, Denmark and Finland (Figure 1). The basis for this report are the National reports from the Nordic countries to the International Symposium on Cone Penetration Testing in 1995 (CPT'95) and a questionnaire sent out by the CPT'10 organizing committee. At CPT'95 the National report for Denmark was presented by Denver (1995), for Finland by Halkola & Törnqvist (1995), for Norway by Lunne & Sandven (1995) and for Sweden by Möller et al. (1995).

The area in Northern Europe comprising the countries Denmark, Finland, Iceland, Norway and Sweden including the self-governing areas; the Åland Islands, the Faroe Islands and Greenland are normally referred to as the Nordic countries. The region is the most northern situated area in the world that at the same time comprises relatively densely populated areas. The closeness of the northern parts of the Nordic countries to the North Pole results in a cold climate, but as a consequence of the Gulf stream the climate is considerably warmer than the temperatures found at the same latitudes around the world. The geography is varied with a very long and folded coastline. The Nordic geology has been marked by recurrent ice ages, which in Sweden and Finland has resulted in many lakes and moraine deposits, as well as rather substantial post-glacial land uplift. Big areas are covered by forests, and extensive farming is mainly carried out in the flat southern parts of the area. Areas to be noted are the fjords in Norway, the mountain chain along the central Scandinavian peninsula, the flat lowlands in Denmark and in the southern part of Sweden and Norway, as well as the archipelagos of Norway, Sweden and Finland. About 25 million people live in the Nordic countries. The dominating languages are the Nordic languages and Finnish. The Nordic languages are Swedish, Danish, Norwegian, Faroese and Icelandic, which all have a common origin in the Old Norse.

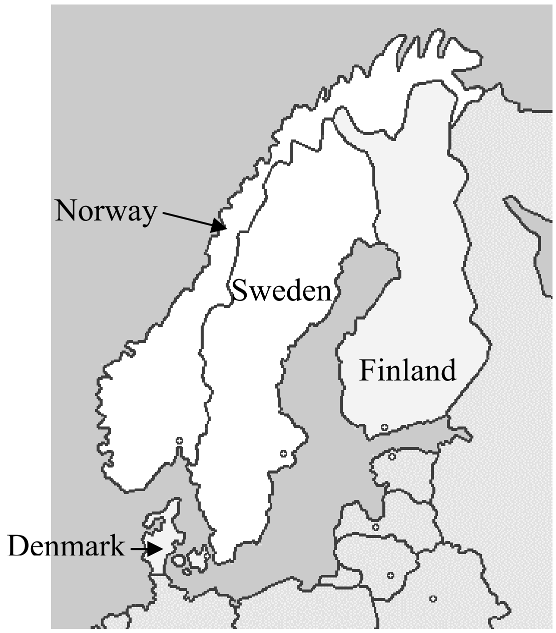

Figure 1: Map of the Nordic countries included in this report (www.luventicus.org).

2 GEOLOGY OF THE REGION

2.1 *General geology of the Nordic countries*

The geology of the Nordic countries is marked by the last 2 million years of geological history, the Quaternary period, during which the whole or parts of Scandinavia were covered by glaciers at least three times. These very cold glacial periods (ice-ages) have alternated with warmer interglacial periods, causing the ice-cap to retreat temporarily. The last ice-age, which is the origin of the main part of our present soil types, started about 75 000 years ago. Climate changes have, thereafter, to a varying degree contributed to different phases and distributions of the ice-cap. Its final withdrawal from northern Germany and Denmark took place about 18 000 years ago and its withdrawal from the south coast of Sweden about 14 000 years ago. The mountain chain was more or less ice-free about 8 000 to 9 000 years ago (Lundqvist, 1988), but remaining glaciers are still present in the mountainous areas of Norway.

The ice-cap, with a thickness of probably more than 2 000 m in the central part, pressed down the land masses, and the ice floated out from the central part to the peripheral parts. The ice-cap moved on the underlying rock or earlier deposited soil, and transported eroded material in front of, beneath and incorporated in the ice. During transportation to the periphery, the material was crushed to a varying degree. The material that later formed the moraine was transported in the bottom, in the ice and to some extent on the surface of the ice. When the climate became warmer, the ice-cap started to melt and the ice front retreated. During the permanent retreat of the ice-cap, warmer and colder periods occurred. When the ice-cap retreated, the heavy load diminished and the area of the Nordic countries was slowly uplifted, a process which is still in progress, but with declining intensity. During this period, many areas that are found as dry land today were in different phases covered by respectively the sea and ice-lakes to considerable depths. The highest shore line is the highest level above the present sea level to which ice-lakes or ice-sea has reached during deglaciation. This level can be as high as 200-220 m above sea level in the north and central parts of Norway and Sweden.

During the retreat of the ice-cap, melt water streamed on the surface; inside and under the ice and glacially transported materials were deposited into the ice-lakes or into the sea. The largest particles were deposited close to the mouth of the melt water stream, whereas material with decreasing grain size were deposited successively further away. The finest particles were often transported far away from the mouth by the melt water stream. Gradually they sank to the bottom in the ice-lakes or in the sea, forming glacial or marine silt and clay (Bygg, 1984).

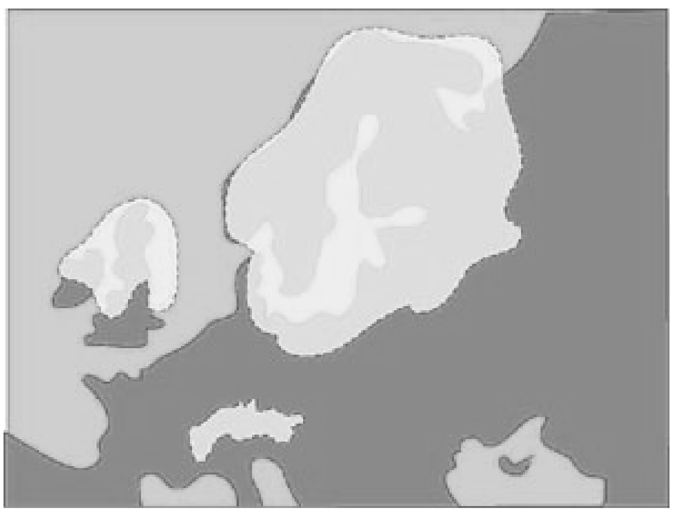

Figure 2: The largest distribution of the ice-cap, about 20 000 years ago (www.sgu.se).

A brief description of the geology of each country, based on descriptions in the National reports to the CPT'95 is made in Table 1.

Table 1. Geology of the Nordic countries.

Denmark	A remarkable scenic boundary can be traced along Denmark in the direction north-west to south-east. This boundary represents the extreme limit of the ice-cap during the most recent deglaciation. The ice front is marked in the contrast between the flat west Jutland region composed of sands and gravels from melt water pouring west from the melting ice-cap, and the fertile loam plains and hills of eastern Denmark which become markedly sandier toward the ice front. A typical soil profile from Denmark exclusive of Bornholm consists of a top soil of different thickness and soil types underlain by clay till and lime stone. On the island of Bornholm solid rock cover large areas.

Finland	The superficial deposits originate mainly from the most recent deglaciation or the time thereafter. The material either derives from the bedrock (mineral soils such as till, gravel, sand and clay) and plant remains (organic deposits such as peat), or is made up of precipitates of compounds dissolved in water (lime gyttja). Moraine and till deposits cover over 50% of the total superficial deposits, 15% are peat deposits, 13% rocky terrain and 10% clay and fluvial deposits. Because the densely populated areas are situated mostly in the low-lying coastal areas in south and south-west, the marine and lacustrine deposits, silt and clay have great importance from a geotechnical point of view.
Norway	The major part of the land area in Norway is dominated by bedrock or a thin cover of moraine. Only about 25% is covered by soil deposits. Areas covered by deep soil deposits are concentrated to the lowlands, to the bottom of the valleys and to a narrow strip along the coast line. The geology below the highest shore line is dominated by clay and silt. At some locations glacialfluvial deltas have been formed, mainly containing gravel and sand, but also finer material. Glacial tills usually cover the bedrock. Above the highest shore line the thickness of the soil deposits is generally less than in the lowlands. The geology is dominated by glacial tills, glacialfluvial sediments or dead-ice deposits from a stagnating glacier. Lacustrine clays or silts are scarce.
Sweden	The soils in Sweden are either glacial or post glacial. The glacial soils are either tills or glacial sediments. Till material, as uppermost layer, covers about 75 % of the land area and normally underlies other soils. The composition of the tills is highly varied, ranging from fine grained boulder clay to coarse grained gravel till. The glacial sediments consist of coarse grained sediments (sand, gravel and cobbles) in eskers and deltas and of fine grained sediments (clay and silt) deposited outside the edge of the ice. The postglacial soils can be divided into re-worked and re-deposited soils and organic soils. Post-glacial silts and clays are normally found as a relatively thin top cover on glacial clay. Of special geotechnical interest is that wave washed and eroded gravels and sands in many places cover clay and silt in the lower parts of slopes and valley floors.

3 GEOTECHNICAL CHALLENGES

The geotechnical challenges in the Nordic countries vary depending on the geological and geotechnical conditions within each country. Geotechnical challenges typical for each country are listed in Table 2.

Table 2. Summary of geotechnical challenges in the Nordic countries

Denmark	▪ Foundation of roads, railways, buildings and other infrastructures on flat tertiary, clay with a high plasticity in the western part of Denmark, and on late glacial and glacial sand, clay and tills with various content of silt. Various numbers and sizes of boulders in the till. ▪ In general, a very high groundwater level in the eastern part of Denmark with a groundwater table 1-3 meters below terrain level. Anchoring of deep constructions against uplift. ▪ Deep excavations with temporary groundwater lowering and reinfiltration next to very old buildings with wood foundations close to or below the groundwater level. ▪ Offshore foundation of monopiles for wind turbines up to 30 meters below sea bed level at water depths of 10 – 30 meters. ▪ Offshore foundation of caissons for wind turbines on late glacial and glacial deposits at water depths of 5 – 15 meters. ▪ Deep excavation with cut-off walls (secant piles) in limestone with flint layers.

	▪ Tunnelling in quarternary deposits with boulders and in limestone with flint layers. ▪ Fill and postglacial deposits underlain by overconsolidated tills with high strength properties ▪ Soft organic soils – peat and gyttja
Finland	Adoption of ISO/CEN standards
Norway	Geology dominated by deposits of soft, sensitive and partly quick clay in populated areas in the lowlands and along the coast. In parts, the topography is rugged, particularly in mountainous regions. The climate is wet with locally large precipitation. Together these features represent challenges such as: ▪ Stability problems, such as quick clay slides, mud slides, snow avalanches and rock falls. ▪ Bearing capacity for structures due to soft and sensitive subsoil ▪ Problems with total or differential settlements due to large variations in soil conditions. ▪ Frost susceptible soils may cause bearing capacity and settlement problems for roads, railways and airfields. ▪ Deep excavations in soft soils beneath the groundwater table. Design of support structures. ▪ Need for soil stabilization (e.g. lime-cement columns) or use of lightweight fill materials in many projects due to soft subsoil. Design of solutions. Foundation engineering for marine structures is a particular challenge related to exploration of oil and gas on the continental shelf, including challenges such as: ▪ Large water depths that complicate ground investigations. ▪ Partly soft subsoil with gas content. ▪ Foundation of pipelines and seabed structures and infrastructure, jackets and gravity platforms. ▪ Scour and erosion, including gas migration. ▪ Risk for marine geohazards (e.g. mudslides, earthquakes)
Sweden	Country with several types of soil e.g.: in the south clay till; in the west and middle part soft clay, partly quick, and silt; in the north sulphide clay and silt. However, most challenges are related to soft subsoil. ▪ Stability problems such as clay slides, quick clay slides, silt slides, mud slides and moraine slides. ▪ Sulphide soil with potential of acidification and chemical influence on other materials. This entails that excavation should be avoided and that certain reinforcement methods are affected. ▪ Erosion of soft soil along the coast and along lakes and rivers in the inland. ▪ Areas with contaminated ground. ▪ Climate changes with, in many areas, increased precipitation resulting in an increased risk for slides, inundations and erosion as well as increased spreading of contaminations. ▪ Need for soil stabilization (e.g. lime-cement columns, vertical drains) or use of lightweight fill materials due to soft subsoil. ▪ Bearing capacity for structures and problems with total or differential settlements due to soft, normally consolidated soil and variations in soil conditions. ▪ Deep excavations in soft soils beneath the ground water table. Design of support structures. ▪ Frost action damages, as bearing capacity and settlement problems for roads and railways in frost susceptible soils, e.g. silt. ▪ Underground constructions as tunnels in alternating eskers and rock.

4 CPT EQUIPMENT & PROCEDURES

4.1 *Standards, special equipment and procedures*

The standards in use in the Nordic countries are listed in Table 3.

Table 3. Standards used in the Nordic countries.

Denmark	The standards used are: IRTP, BS, NORSOK and others. No national standard is used.
Finland	No standards are used, only a national Guide.
Norway	Norwegian Geotechnical Society, guideline 5 (1995): Cone Penetration Test with Pore Pressure measurements (in Norwegian) (under revision). NORSOK. ISSMGE (1999): International Reference Test Procedure (IRTP) for CPTU. No formal national standard is used.
Sweden	Since 1992 there is a standard for CPT recommended by the Swedish Geotechnical Society (SGF Report 1:93E). In addition there is an international standard worked out by CEN\TC341\WG2 in Sweden to be denoted SS EN ISO 22476-1. However, although the work was finalized in 2005, the standard has not been approved yet. Just now it is sent for Formal Voting to the CEN member countries. Compared to the SGF recommendation from 1992 there is a requirement for a correction of the sounding depth with regard to the inclination of the cone. The general demands for accuracy are lower in SS EN ISO 22476-1, but higher demands may be applicable in regions with very loose or soft soils.

4.2 *Equipment*

The pushing equipment, cones and data acquisition systems used in the Nordic countries are summarized in Table 4.

Table 4. Equipment used in the Nordic countries.

Country	Pushing equipment	Cones	Data acquisition systems
Denmark	Continous dual hydraulic clamp system or the CPT probe is pushed down by the hydraulic system on the drilling vehicle.	The "ENVI Memocone II" CPTU probes or the 10 cm^2 v.d. Berg cones are used	ENVI, C-Mon Data logger for CPTU or self-made in-house system (by GEO).
Finland	Multipurpose drilling machine or Static-dynamic penetration rig.	Normal 10 cm^2 cones are used.	Envi and Geotech
Norway	Hydraulic drillrigs with caterpillar belts mainly used by industry. Continuous pushing equipment used in research and occasionally in offshore soil investigations.	Environmental Mechanics and Geotech 10 cm^2 piezocones with filter position at reference level used more or less exclusively by industry. 15 cm^2 piezocones used in offshore soil investigations. 15 cm^2 triple piezocones used occasionally in research. Miniature piezocones used	Stand-alone data-acquisition registration units with storage disk or card. In-probe digital memory cards for subsequent in-house data transfer. Field PCs with data acquisition program and modem for data transfer from the field.

		occasionally in research and in offshore soil investigations. 15 cm^2 Resistivity piezocones used increasingly in research. 10 cm^2 friction cones used occasionally.	Special data acquisition systems for offshore and research use.
Sweden	Multipurpose crawler mounted drilling-, sounding- and sampling-rigs.	Cordless acoustic or radio wave real time system CPTU probes used. Cones from Environmental mechanics or Geotech.	Environmental Mechanics and Geotech.

Figure 3: Typical site investigation rig (www.geotech.se).

In Denmark the number of CPT systems is about 13 to 14 in total. In Western Denmark about 10-15 % of the larger site investigations (>10-20 boreholes) make use of the CPT, the percentage is slowly increasing. In Eastern Denmark less than 2 % of the larger investigations make use of the CPT. CPTU is most often/always used as it is common always to measure pore pressure. Offshore, CPTU is always used.

In Finland the number of CPT systems is about 10. About 2% of the site investigations conducted make use of the CPT. All the CPT's carried out are CPTU, i.e. measurement of pore pressure is always done.

In Norway the total number of CPT systems is between 25 and 30 in complete package with probe, rods and data-acquisition units. Each system may include several cones with different capacities to accommodate local variations in soil properties. In larger site investigation programs (> 15 boreholes) CPTU is used extensively if favourable ground conditions apply (no stone content and fine- to medium grained soils). Percentage estimated to 60-70 % of the investigations. In smaller site investigation programmes (< 5 boreholes) CPTU is less common, estimated to only 15-20 %

of the investigations. Numbers are indicating a nationwide average with some regional variations depending on local geology and availability of equipment. CPTU comprises about 10-15 % of the total amount of sounding meters in Norway. About 100 % of commercial tests are CPTU, very few tests are carried out without pore pressure measurements.

A rough estimate of the number of CPT systems in Sweden is about 100 to 200. The use of CPTU varies in different parts of the country, depending on soil type in the region in question. In the areas with soft clay (e.g the western part of Sweden), CPTU is nearly always used, i.e. in 90 – 100% of the site investigation programmes. In the eastern part of Sweden CPT is used in about 50 – 80% of the large site investigation programmes, e.g. for roads and railroads and in less extent, about 20%, in smaller site investigation programmes, e.g. for buildings. In regions where till cover large areas the CPTU is used to less extent, i.e. in 20 – 30% of the investigation programmes. The CPTU is nearly always used, i.e. it is normal always to measure pore pressure together with tip resistance and sleeve friction.

Figure 4: Common CPT probes (www.geotech.se and www.envi.se)

There are some special equipment and procedures used in the Nordic countries, except for Finland where no special equipment is used. In Denmark, land based rigs as well as offshore seabed rigs are used.

In Norway CPTU-R (resistivity probe) has been introduced recently at research level in mapping of quick clay deposits. Triple piezocones and miniature cones are used at research level. Full-flow penetrometers (T-bar, ball) are used occasionally at research level and special CPTU equipment is used in offshore soil investigation. Dissipation test is used occasionally in industry projects. No activity on SCPTU, but this may change in the near future due to stricter requirements for influence from earthquakes in design.

In Sweden resistivity CPTU (CPTU-R) is used occasionally, mainly at research level for e.g. detection of salt from roads, soil profiling and detection of quick clay. Seismic CPT (SCPTU) is used occasionally, mainly at research level for e.g. integrity of driven precast concrete piles (Rankka & Holm 2006) or evaluation of initial shear modulus and/or shear wave velocity of soil. Miniature CPTU has been used recently at research level in laboratory for a study on the influence of stress conditions on the evaluation of the undrained shear strength (Löfroth, 2008a, 2008b). The FFD-cone (Fuel Fluorescence Detector) is used mainly at research level for detection of various organic compounds e.g. petrol, diesel and creosote (e.g. Nilsson-Påledal et al. 2003). Pore pressure dissipation tests are used occasionally for determination of drainage conditions in the soil profile.

4.3 *Challenges with equipment and procedures*

In Denmark the main challenges are related to the capability of penetration. Large areas in Denmark have boulder clay (glacial till) close to the surface. Sometimes the probe gets stuck because it is not possible to penetrate the soil, and pushing capability and backhold are limited. Another challenge is identification of thinner layers (< 1 m), differing between silty, clayey sand or sandy clay and differing between silty sands and very soft limestone.

Also in Finland the main challenges are related to the capability of penetration, particularly where the soil consists of till layers and boulders.

In Norway the main challenges are related to saturation, zero drift, penetration, equipment and competence, given the level of accuracy needed in the soft and sensitive soils. Challenges related to saturation of pore pressure systems are e.g. lack of saturation due to inadequate procedures or saturation equipment, or loss of saturation when passing through dense, dilative layers, such as the dry crust or dense sand layers. Challenges can be associated with the control of factors that influence the zero drift of the cone, e.g. temperature gradients during zero reading, mounting and retraction effects causing temporary effects such as suction or pressure build-up or proper cleaning of friction sleeves before zero readings are taken. Penetration challenges can be related to the difficulty to choose the appropriate equipment in layered soils. Cones are usually chosen so that one has enough capacity to penetrate both stiffer and softer layers encountered in a deposit. This may lead to poor resolution and lack of accuracy in the softer layer if a high capacity probe is chosen, or overloading of the probe in denser layers if a low capacity probe is chosen. Content of stones and cobbles may influence recordings and in worst case damage the cone. There could be a lack of competence and knowledge of the method as which factors that influence the measurements, what are the potential and the limitations of the method. This could be due to the fact that no standardized and formal education programmes for drillers are present in Norway.

Also in Sweden there are challenges related to saturation in unsaturated or strongly overconsolidated soil. When sounding through dry crust above very loose soil, there is a risk that the saturation of the cone is lost and the pore pressures at greater depths become irrelevant. This is due to the fact that the dry crust normally is not saturated and high negative pore pressures can be encountered. Therefore, pre-drilling through the dry crust should be carried out. There are also problems with negative pore pressures in silty soils at greater depths. This can be taken care of by a saturation process using glycerine instead of water, or by using a slot filter saturated with grease. Other challenges related to the soil are the clogging of filters when sounding in gyttja and organic clay, and fill in urban areas overlying looser soil that is difficult or impossible to penetrate with the piezocone. There is also a challenge with temperature drift. The cone ought to be handled in a way so that it always is as close to the ground temperature as possible (7 to 8°C).

In Sweden, as well, there is sometimes a lack of competence and knowledge of the method by drillers and a lack of knowledge by engineers; as how to control accuracy demands, potential and limitations of the method e.g. in evaluation of parameters. These are all challenges to be dealt with. Finally, CPTU research in Sweden, especially concerning interpretation of parameters from CPTU in Swedish fine-grained soils has very much been the work of one person. It is a challenge to broaden the knowledge and get others to learn from his experience and continue the development work. These last challenges are currently addressed by arranging CPT courses both for drillers and engineers.

Figure 5: CPT tip with porous filter and slot filter respectively (www.envi.se)

5 CPT INTERPRETATION

5.1 *Interpreted parameters*

In the Nordic countries the CPT is most commonly used for identification of soil type and undrained shear strength in fine grained soils. In Finland identification of soil type is usually the only interpretation used. In Norway and Sweden it is also commonly used for evaluation of preconsolidation pressure and overconsolidation ratio. In Denmark it is also used for evaluation of soil relative density, friction angle and deformation (M-modulus) and in Denmark and Norway for determination of pile bearing capacity. In Norway the CPT is used occasionally for estimation of deformation modulus (M, G), friction angle, sensitivity/remolded shear strength and coefficient of consolidation. Empirical or semi-theoretical relationships are then used. In Sweden the CPT is also used, although less frequently, for evaluation of friction angle in sand, evaluation of strength properties in silty soils and for evaluation of deformation properties in sands and silts. Empirical relationships are then used.

5.2 *Methods for interpretation*

In Finland the Eurocode 7, Part 2 Appendix is used for interpretation. Both in Denmark and in Norway generally the summary of methods given in the book 'CPT in Geotechnicall Practice' (Lunne, Robertson & Powell, 1997) is used for interpretation of CPT results. In Denmark, different empirical interpretation methods are also used.

Some highlighted methods from the book 'CPT in Geotechnical Practice' applied for interpretation of various soil parameters are given below:

FINE-GRAINED SOILS:

- Identification of soil type and stratification ((Robertson et al. (1986), Robertson (1990), Senneset et al. (1982, 1989))
- Undrained shear strength s_u (empirical and theoretical relationships) ((Senneset et al. (1982, 1989)), Karlsrud et al. (1996), Karlsrud et al. (2005), Konrad & Law (1987))
- Preconsolidation stress, σ'_c, and stress history OCR (semi-theoretical and empirical relationships) ((Senneset et al. (1989), Sandven (1990), Lunne et al. (1989), Brooker & Ireland (1963))
- Deformation moduli M, G (empirical relationships) ((Senneset et al. (1982, 1989), Sandven (1990), Kulhawy & Mayne (1990), Mayne & Rix (1993), Larsson & Mulabdic (1991))
- Friction angle (semi-theoretical and empirical relationships) ((Janbu & Senneset (1974), Senneset et al. (1982, 1989), Sandven (1990))
- Sensitivity/remoulded shear strength (empirical relationships) ((Rad & Lunne (1986), Quiros & Young (1988))
- Coefficient of consolidation (semi-theoretical relationships) ((Torstensson (1975, 1977), Senneset et al. (1982), Levadoux & Baligh (1985), Houlsby & Teh (1988))

COARSE-GRAINED SOILS:

- Identification of soil type and stratification ((Robertson et al. (1986), Robertson (1990), Senneset et al. (1982, 1989))
- Relative density D_r ((Robertson & Campanella (1983), Baldi et al. (1986), Kulhawy & Mayne (1990))
- Deformation moduli M, G (empirical relationships) ((Senneset et al. (1982, 1989), Sandven (1990), Lunne & Christophersen (1983), Eslaamizaad & Robertson (1996), Rix & Stokoe (1992))
- Friction angle (semi-theoretical and empirical relationships) (Schmertmann (1978), (Janbu & Senneset (1974), Senneset et al. (1982, 1989), Kleven et al. (1986), Sandven (1990))

In Sweden, most commonly, interpretation of CPT results in fine grained soil is carried out based on the work performed at the Swedish Geotechnical Institute. For coarse grained soil interpretation methods developed outside Sweden, are used. The interpretation methods are described in the now updated version of the Swedish Geotechnical Institute (SGI), Information 15 (Larsson, 2007). The methods are as follows:

- Evaluation of stratigraphy and classification of soil from Larsson & Mulabdic (1991), and Larsson (1993).
- Evaluation of undrained shear strength (s_u or c_u):

- in normally consolidated and slightly overconsolidated clay from Larsson & Mulabdic (1991); $c_u = \dfrac{q_T - \sigma_{v0}}{13.4 + 6.65 w_L}$
- and extended to include also overconsolidated clays from Larsson & Åhnberg (2005, 2007); $c_u = \dfrac{q_T - \sigma_{v0}}{13.4 + 6.65 w_L} \left[\dfrac{OCR}{1.3}\right]^{0.2}$
- in sulphide soils from Larsson et al. (2007); $c_u = \dfrac{q_T - \sigma_{v0}}{20} \left[\dfrac{OCR}{1.3}\right]^{0.2}$
- in silty soils from Larsson (1995); $c_u = \dfrac{q_T - \sigma_{v0}}{14.5}$
- in clay till from Larsson (2000); $c_u = \dfrac{q_T - \sigma_{v0}}{11}$

- Evaluation of preconsolidation pressure and overconsolidation ratio
  - in clay from Larsson & Mulabdic' (1991) and Larsson & Åhnberg (2007)
  - in sulphide soils from Larsson et al. (2007);
  - in clay till according to Larsson (2007).
- Evaluation of friction angle, (ϕ')
  - in sand and in silt (if no pore pressures have been generated during sounding) from Bellotti et al. (1989) and Marchetti (1985)
  - in silt (if pore pressures have been generated during sounding) from Senneset & Janbu (1984), Sandven (1990)
- Evaluation of compression modulus or Young's modulus, (M or E), in sand from Swedish empirisism (Larsson, 2007), Lunne & Christophersen (1983), Jamiolkowski et al. (1988) or Robertson & Campanella (1988).
- Relative density (I_d) in cohesionless soil from Lancelotta (1983), Baldi et al. (1986) and Lunne & Christophersen (1983).

In Finland no self-made spreadsheet software or commercial CPT interpretation software is used for interpretation of CPT results. In Denmark, both self-made spreadsheet software and commercial software are used. The commercial software used is gINT, Datgel CPT Tool, CPeT-IT and CPT Pro.

For interpretation of CPTU data in Norway, both possibilities are used as well. Self-made spread-sheets are most popular and extensively used by companies and institutions. Available commercial CPT interpretation software includes CPT Pro (Janecki) and CONRAD (Swedish Geotechnical Institute). These software programs are also available through manufacturers of CPTU equipment. In Norwegian geotechnical practice, the recent software package GeoSuite is used for processing, presentation and administration of CPTU data, and an interpretation module may be incorporated in the near future.

In Sweden interpretation of CPTU is normally done using the software CONRAD developed at the Swedish Geotechnical Institute, and updated 2006. This program is based on the publication SGI Information 15, updated version (Larsson, 2007).

6 CPT APPLICATIONS

6.1 *Main applications*

In Finland, the CPT is used mainly for soil profiling. In Denmark the main applications are for soil profiling, evaluation of soil parameters as strength and deformation as well as for pile design. It is also used for evaluation of strength development in weak layers that are loaded stepwise and for identification of a specific thin soft soil layer.

Soil profiling and identification are usually an objective of all CPTU tests and interpretations in Norway. Parameter interpretation is usually carried out for CPTUs in clays, provided data quality is up to standard. In pile design there is also some use of CPTU data, as interpretation methods for vertical pile capacity from CPTU are included in the Norwegian Code of Practice. The use of CPT for seismic analyses has been very limited so far, but the new guidelines for earthquake design in the Eurocodes will increase the need for assessment of dynamic shear moduli and shear wave velocity values for design. Empirical interpretation methods for CPTU data are available and are being used increasingly by industry, but need to be enhanced by more direct measurement of the properties.

Soil profiling and identification are usually carried out in all CPTU tests in Sweden. Evaluation of shear strength and preconsolidation pressure are usually carried out for CPTU's in clays, provided data quality is good enough. Also evaluation of friction angle in sandy soil from CPT is carried out. Occasionally, the CPT is used for calculation of bearing capacity and settlement for shallow foundations and for calculation of bearing capacity of pile foundations. Seismic data have been used mainly for evaluation of the shear wave velocity and initial shear modulus in connection with high speed trains. Another application of the CPT is the case where CPT was performed inclined in order to investigate the overlapping zone in lime-cement column rows (Larsson 2005). However, the CPT seems to be used more frequently for control of lime-cement columns.

6.2 *Geoenvironmental applications*

In the Nordic countries there has generally been little use of the CPT for geoenvironmental applications. Conventional use of CPTU data (soil profiling, dissipation tests) may be used as supplementary information to sampling. In Denmark the CPT is not used for commercial environmental applications – only research of minor extent. In Finland CPT for environmental applications have only been used for demonstration purposes so far. In Norway CPTU probes with particular environmental sensors in the probe are not used beyond research level. Resistivity probes are becoming more popular, but the use of them in environmental investigations has so far been limited. In Sweden environmental CPT-types as the FFD-probe has been used mainly at research level for detection of organic compounds e.g. petrol, diesel and creosote, simultaneously with soil profiling and identification.

7 RESEARCH AND FUTURE TRENDS

7.1 *Research on CPT*

In the Nordic countries there has been little research in the field of geotechnical sounding methods in resent years. The main reason is the difficulty to get funding for research projects focusing on field methods, as well as laboratory methods. However, there is some recent and ongoing research in the area. In Denmark, Aalborg University is doing research in the interpretation of CPT in Danish soils (silt). In Finland there is no research in the near future. In Norway, research is currently undertaken on the following topics:

- Use of resistivity CPTU (CPTU-R) in mapping of quick clay deposits. Combination with surface resistivity measurements.
- Combination of block sampling and CPTU in clays as basis for correlations between CPTU data and soil parameters.
- Use of full flow penetrometers (T-bar, ball) for interpretation of undrained shear strength and sensitivity in clays and silts.
- Use of miniature CPTU for detailed interpretation of soil stratigraphy and inspection purposes on laboratory block samples.
- Use of CPTU data for direct interpretation of vertical pile capacity.

The most recent research in Sweden includes evaluation of undrained shear strength and preconsolidation pressure in sulphide soils (see Section 5.2, Larsson et al., 2007) as well as classification. Sulphide soils in this context refer to sulphide soils in the coastal areas around the Gulf of Bothnia often referred to as "Svartmocka", which should have an organic content of at least 1 to 2%. Contrary to other Swedish fine-grained soils, the gradual transition from silt, silty clay, clay, organic clay to organic soil that is reflected by the liquid limit, w_L, is not valid for sulphide soils, which affect the empirical evaluation of different parameters and test results that often rely on the coupling between liquid limit and soil composition. Other recent research in Sweden concerns a study on the influence of stress conditions on the undrained shear strength evaluated from CPTU. In this study the influence of horizontal stresses was studied by model tests with a miniature CPT in large triaxial cells. In addition, the undrained shear strength at the toe of a slope has been predicted based on the results of the model tests together with CPTU tests above the crest of the slope (Löfroth, 2008a, 2010).

7.2 *Future trends in the use of CPT*

Future trends in Denmark include an increase in the use and need of CPT in the western parts of Denmark. In Finland the Static-dynamic penetration test is spreading. The static phase is very close to a mechanical CPT, but a special cone and a rod diameter of 32 mm is used.

In Norway, CPTU is during the last decade or so consolidated as an important investigation method, particularly in fine-grained soils. It is believed that CPTU will strengthen its position in the future, as experience increases and the equipment is further developed to improve accuracy and quality. Use of CPTU will expand, for example by the combination of resistivity CPTU and surface resistivity measurements.

With further improvement of data interpretation and processing quality, this may represent an important development in mapping of quick clay layers in marine clay deposits. It is further believed that use of full flow penetrometers like the T-bar and ball penetrometers may find application in soft soil deposits, even in conventional site investigation programmes.

With the latest relations for interpretation of undrained shear strength and preconsolidation pressure in sulphide soil and the refined relations for clay to also include overconsolidated clay, together with an updated version of the software for interpretation of CPTU results, it is believed that the use of CPTU for classification and parameter evaluation in all types of Swedish soft soils will increase. Other trends in the use of CPTU are towards combining the classical CPTU with other types of measurements, as the resistivity CPTU and the seismic CPTU, or using the CPTU for calibration of other sounding methods. An example is the use of the CPT for identification of quick clay and estimation of the relative sensitivity. This can be done by evaluation of the friction along the perimeter of the whole equipment from an accurate measurement of the total penetration force of the CPT (Rankka et al., 2004). Measurement of the total penetration force is also about to be included as an additional parameter in some data acquisition systems. In the near future, this method for identification of areas with quick clay may be complemented by measurement of resistivity, using the resistivity CPTU, in combination with surface resistivity measurements. Some initial work on CPTU-R has so far been carried out as master theses research. Another example includes using the CPTU as a calibration method for sounding methods with better penetration capacity than the CPTU. So far, comparisons of measured net tip resistance from the CPTU and calculated tip resistance from total penetration force from soil-rock total sounding (an adaption of Norwegian total sounding for Swedish conditions) has been carried out in sand (Nilsson & Löfroth, 2009). The results from two test sites indicate a correlation between normalised net tip resistances measured with the CPTU and calculated tip resistance from the soil-rock total sounding (Figure 6).

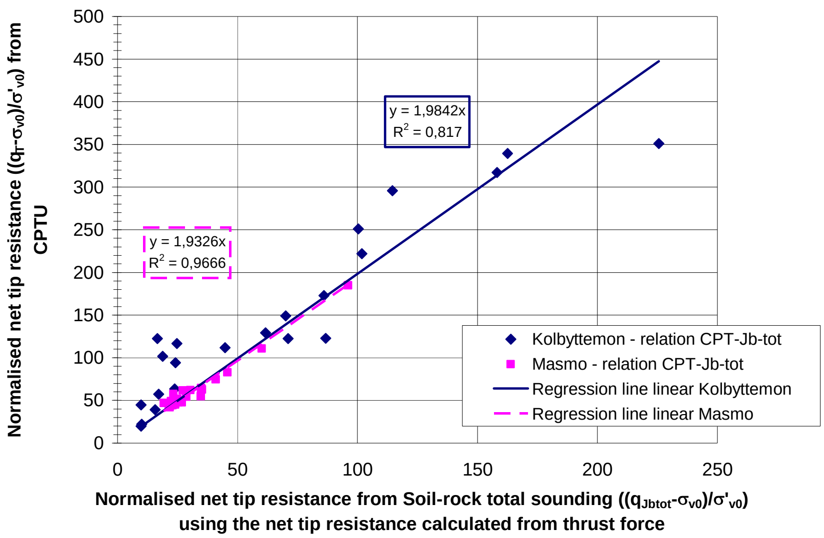

Figure 6: Relation between normalised net tip resistance from the CPT and normalised net tip resistance from soil-rock total sounding with net tip resistance calculated from thrust force for two sites (Nilsson & Löfroth, 2009).

8 SUMMARY

It can be concluded that there is a rather large difference in ground conditions between the Nordic countries, as well as within each country. The largest part of the area consists of bedrock or moraine as uppermost layer. However, the most populated areas are those with very soft ground, as marine, glacial and post glacial clays and silts. Within the Nordic countries there are also areas with coarse grained sediments, as sand and gravel, as well as soft organic deposits such as peat.

Sweden is the only Nordic country that has manufacturers of CPT equipment based within the country. The use of CPT in the Nordic countries is dominated by products from these two manufacturers. All four countries use caterpillar driven drill rigs and all countries except Denmark have a national standard or guideline.

In the Nordic countries CPTU is nearly always used, i.e. it is common to measure pore pressure together with tip resistance and sleeve friction. The use of CPT in ground investigations is more frequent in Norway and Sweden than in the other countries. The CPT is also used for offshore investigations in Denmark and Norway. Within the region there is a variation in the use and interpretation of data from the CPT. In all the Nordic countries CPT is used for identification of soil type. However, in Finland it is the only interpretation, whereas in the other three countries also evaluation of undrained shear strength, friction angle, preconsolidation pressure and deformation moduli is done. The interpretation methods used varies between the countries. The use of CPT for environmental applications is limited in all the Nordic countries.

There has been limited research in the field of CPT in recent years within the Nordic countries. However, there has been extensive research on interpretation of CPT in Danish, Norwegian and Swedish soils. In Norway and Sweden some research is carried out in the use of resistivity CPTU (CPTU-R) and seismic CPTU (CPTU-S), and in Norway also full flow penetrometers. The use of resistivity in combination with CPTU has a potential for mapping of quick clay areas in Norway and Sweden.

To sum up, an attempt is made to point out some trends and developments at the time of CPT'10, and to compare with some trends and developments at the time of CPT'95. In 1995, the then present trends and developments within the Nordic countries could be summarized as follows:

- Improved accuracy in manufacturing of electrical CPTU probes.
- National standardization of CPTU.
- Improved understanding of factors that influence the quality of CPT measurements.
- Increased use of CPTU providing improved experience and increase in local databases for interpretation of the results.
- Development of user friendly interpretation software.
- Implementation of inventive sensors to broaden the CPT measurement repertoire, particularly for environmental testing.

The developments since 1995 and current trends at the time of CPT'10 within the Nordic countries are:

- Improvement of electrical CPTU probes, e.g. to include tilt sensor for monitoring of the deviation from the vertical of the probe and temperature sensor so that erroneous readings from the channels due to temperature drift can be avoided.

- Implementation of an international standard for CPTU (however, not yet approved).
- Elaboration of existing interpretation methods to include other types of soil, as clay till and sulphide clay, or refinement of existing methods, e.g. correction of undrained shear strength for overconsolidation in soft clay.
- Research on the use of a combination of the classical CPT probes with other types of measurements, as the resistivity CPTU or the seismic CPTU, for certain purposes.

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