CPT for soft sediments and deepwater investigations

R. Boggess & P.K. Robertson
Gregg Drilling & Testing Inc., Signal Hill, California, USA

ABSTRACT: As energy exploration moves into deeper water, there is a growing need for high quality in-situ testing of near surface seafloor sediments. The cone penetration test (CPT) has become the primary in-situ test for offshore site investigations, especially in deep water. This paper describes key features for improved accuracy for the CPT with particular emphasis on testing in deepwater. Recent developments in the design of cones for deepwater CPT are also described.

1 INTRODUCTION

As energy exploration moves into deeper water, there is a growing need for high quality in-situ testing of near surface seafloor sediments. In deepwater (>1,000m) the near surface seafloor sediments are often very soft fine-grained soils with low shear strength. Projects in deepwater often require a variety of structures to be placed on and in the seafloor. Hence, a detailed evaluation of the soft seafloor sediments has become increasingly important. The cone penetration test (CPT) has become the primary in-situ test for offshore site investigations, although full-flow penetrometers (T-bar and Ball-cone) have also become popular in soft sediments.

To measure the in-situ characteristics of soft near surface seafloor sediments requires careful attention to details in cone design and procedures. The following sections describe the main features that are important for accurate measurements using the CPT.

2 CONE DESIGN

Lunne et al. (1997) provided a detailed description on developments in CPT equipment, procedures, checks, corrections and standards. There are several major issues related to equipment design and procedure that are worth repeating and updating.

2.1 *Friction sleeve measurements*

Sleeve friction values can be very helpful in indentifying soil behavior type (e.g. Robertson, 1990) and aiding in interpretation (e.g. Robertson, 2009). However, it has been documented (e.g. Lunne et al., 1986) that the CPT sleeve friction is generally less accurate than the cone tip resistance. The application and use of CPT sleeve friction values in soft sediments requires accurate measurements. The perceived lack of accuracy has often meant that the CPT sleeve friction values are either ignored or underutilized. The lack of accuracy in f_s measurement is primarily due to the following factors (Lunne and Anderson, 2007);

- Pore pressure effects on the ends of the sleeve
- Tolerance in dimensions between the cone and sleeve
- Surface roughness of the sleeve
- Load cell design and calibration

All CPT standards have strict limits on dimensional tolerances and many have clear specifications on surface roughness. Hence, the main variables are pore pressure effects on the ends of the sleeve and load cell design and calibration.

2.1.1 *Pore pressure (water) effects on the ends of the sleeve*

Due to the inner geometry of the cone the ambient water pressure acts on the shoulder behind the cone and on the ends of the friction sleeve. This effect is often referred to as the unequal end area effect (Campanella et al., 1982). Figure 1 illustrates the key features for water pressure acting on the end areas of the friction sleeve. Although Campanella et al., (1982) recommended that all cones should have friction sleeves with equal end areas, it is still common for many commercial cones to have friction sleeves with unequal end areas.

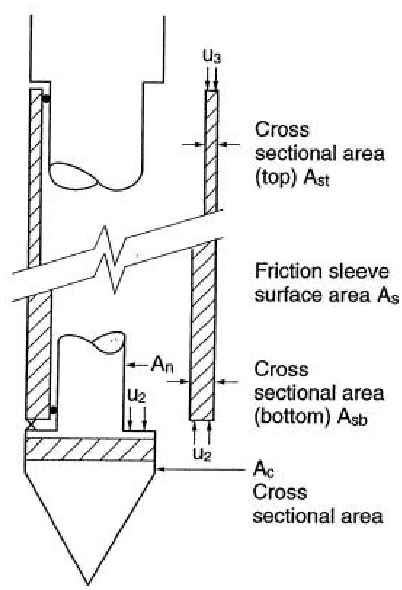

Figure 1 Unequal end area effects on friction sleeve (After Lunne et al., 1997)

Lunne et al (1997) showed that the corrected sleeve friction (f_t) can be represented by the following:

$$f_t = f_s - (u_2A_{sb} - u_3A_{st})/A_s \quad (1)$$

where: f_s = measured sleeve friction
u_2 = water pressure at base of sleeve
u_3 = water pressure at top of sleeve
A_s = surface area of sleeve
A_{sb} = cross-section area of sleeve at base
A_{st} = cross-sectional area of sleeve at top

The error due to unequal end areas (Δf_s) is:

$$\Delta f_s = f_t - f_s = (u_2A_{sb} - u_3A_{st})/A_s \quad (2)$$

The surface areas (A_s) for 10 and 15 cm^2 cones are 150 cm^2 and 225 cm^2, respectively. To illustrate the magnitude of the error in sleeve friction when performing CPT in soft fine-grained soils, typical values can be applied to equation 2. In most normally to lightly overconsolidated, fine grained soils the average friction sleeve value is approximately, $f_s/\sigma'_{vo} = 0.1$. In sensitive clays the sleeve friction ratio (f_s/σ'_{vo}) can be as low as 0.01. Hence, at a depth of about 10m, where $\sigma'_{vo} \sim 100$ kPa, the typical value of $f_s \sim 10$ kPa. The penetration pore pressure at the u_2 location is generally $\Delta u_2/\sigma'_{vo} = 4$, hence $u_2 = 400$ kPa in soft soils. A typical ratio of u_3/u_2 in soft soils is from 0.6 to 0.8, with an average of 0.7. Therefore, a value for $u_3 = 300$ kPa can be estimated. These values apply equally to onshore CPT in soft soils.

Based on data collected in 2000 and 20001 and presented by Lunne (2006), Table 1 illustrates the important effect of unequal end areas on the accuracy of sleeve friction measurements in soft fine-grained soils, where $f_s = 10$ kPa, $u_2 = 400$ kPa, $u_3 = 300$ kPa, for various commercial CPT equipment.

Table 1. Example of error in sleeve friction due to unequal end area

Cone	cone size (cm^2)	A_{sb} (mm^2)	A_{st} (mm^2)	A_{sb}/A_{st}	Δf_s (kPa) (u_2 = 400 kPa) (u_3 = 300 kPa)	Error % (for f_s = 10 kPa)
Fugro	10	326	259	1.26	-3.51	35%
Fugro	15	388	343	1.13	-2.33	23%
v.b. Berg	10	263	263	1.00	-1.75	18%
Pagani	10	437	214	2.04	-7.37	74%
Envi	10	305	170	1.79	-4.73	47%
Gregg	15	150	150	1.00	-0.66	7%

It is clear from Table 1 that the error in measured sleeve friction can be significant when using cones with unequal end areas and testing soft fine-grained soils. The error is also larger for 10 cm^2 cones compared to 15 cm^2 cones. Ideally, pore pressures should be measured at both ends of the sleeve (i.e. at u_2 and u_3 locations). However, this complicates cone design and test procedures for commercial CPT and is not commonly done. Table 1 illustrates that for accurate measurement of sleeve friction (for both onshore and offshore CPT) cones should have equal end area friction sleeves with small cross-sectional area ends (i.e. A_{st} and A_{sb} should be as small as possible) and preferably a 15 cm^2 cross-sectional area cone. Corrections to obtain f_t, using equation 1, are recommended, even if an assumption is required of u_3/u_2.

When the CPT is carried out in deep water the water pressure acts on the ends of the sleeve before the cone penetrates the seafloor sediments. To illustrate the magnitude of this zero load off-set, the following example is provided for a water depth of 3,000m.

Table 2. Example of error in sleeve friction in 3,000m of water
(Water depth = 3,000m. $u_2 = u_3$ = 30 MPa)

Cone	cone size (cm^2)	A_{sb} (mm^2)	A_{st} (mm^2)	A_{sb}/A_{st}	Δf_s (kPa)
Fugro	10	326	259	1.26	-134
Fugro	15	388	343	1.13	-60
v.b. Berg	10	263	263	1.00	0
Pagani	10	437	214	2.04	-446
Envi	10	305	170	1.79	-270
Gregg	15	150	150	1.00	0

Table 2 shows that at a depth of 3,000m the unequal end areas on the friction sleeve can produce a significant zero-load offset. For most commercial cones that have unequal end areas the off-set is negative. Hence, the sleeve friction load cell is unloading during initial penetration into the seafloor sediments. Zero load stability becomes a major issue when measurements are made very close to zero load. Clearly, cones should have equal end area friction sleeves for deepwater CPT.

2.1.2 *Load cell design*

Penetrometers (cones, T-bar and Ball-cone) use strain gauge load cells to measure the resistance to penetration. Basic cone designs use either separate load cells or subtraction load cells to measure the tip resistance (q_c) and sleeve friction (f_s) (Lunne et al., 1997). In subtraction cones the sleeve friction is derived by 'subtracting' the tip load from the tip + friction load. Figure 2 illustrates the general principle behind load cell designs using either separated load cells or subtraction load cells.

In the 1980's subtraction cones became popular because of the overall robustness of the penetrometer (Schaap and Zuidberg, 1982). In the 1980's cones that used separate load cells tended to have the friction sleeve load cell in tension which made construction complex and the probes somewhat less robust. In recent years cones with separate load cells are predominately compression load cells and have significantly improved in design and robustness. In soft soils, subtraction cone designs have always suffered from a lack of accuracy in the determination of sleeve friction due primarily to variable zero load stability of the two load cells. This point is illustrated in Figure 3. In subtraction cone designs, different zero load errors can produce cumulative errors in the derived sleeve friction values. For accurate sleeve friction measurements in soft sediments, it is recommended that cones have separate load cells.

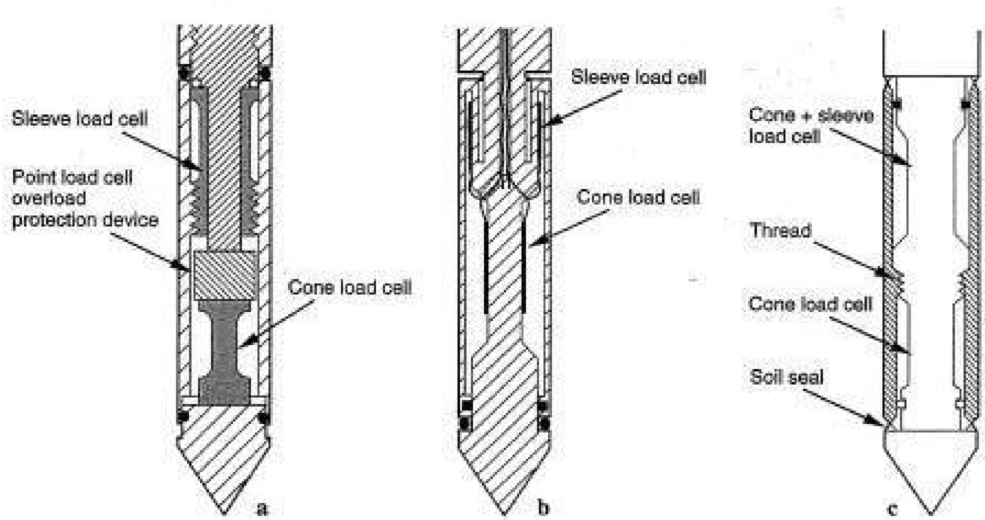

Figure 2 Designs of cone penetrometers (a) Tip and sleeve friction load cells in compression, (b) Tip load cell in compression and sleeve friction load cell in tension, (c) subtraction type load cell design (After Lunne et al., 1997)

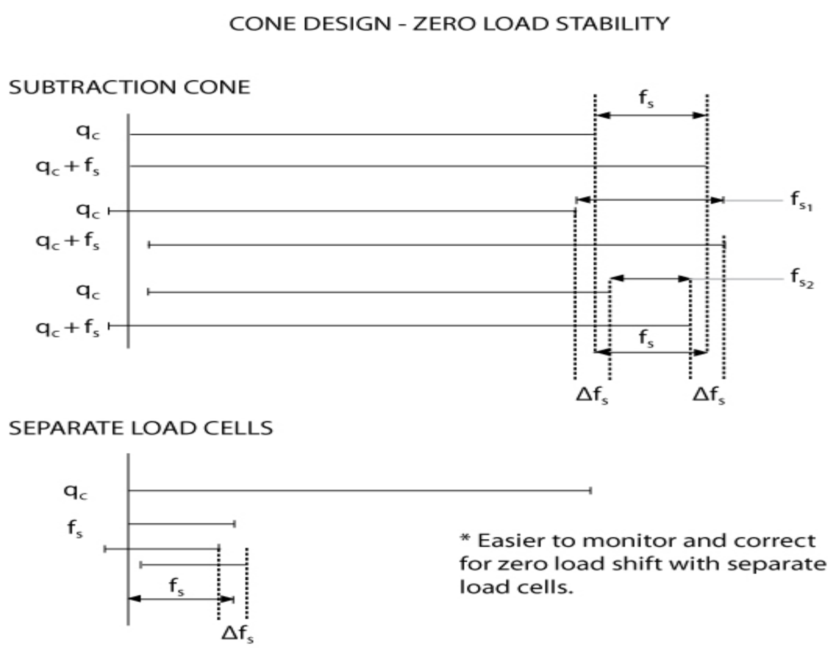

Figure 3 Influence of cone design on zero load stability. Zero load shifts for subtraction cone (above) and cone with separate load cells (below)

With good design (separate load cells, equal end area friction sleeve) and quality control (zero load measurements, tolerances and surface roughness) it is possible to obtain repeatable sleeve friction measurements. However, f_s measurements, in general, will be less accurate than tip resistance in most soft fine-grained soils.

2.2 *Compensated cone*

When the CPT is carried out in deepwater the high water pressure generates a significant tip resistance before the cone penetrates the seafloor sediments. In 3,000m of water the water pressure is equivalent to a tip stress of 30 MPa. Hence, the corrected tip stress, q_t, at the sea floor is 30 MPa. For a 10 cm^2 cone this represents a tip load of 30 kN. This tip stress (and load) is significantly higher than the expected tip stress (and load) in soft sediments that can be in the order of only 20 to 100 kPa (i.e. tip load from 0.02 to 0.10 kN). Clearly, accurate measurement of soft sediments in deepwater is difficult due to the very high initial tip stress. This is partly the reason for the development of full-flow penetrometers where the cross-section area is often 10 times larger (i.e. 100 cm^2), with a penetration load 10 times larger than a typical cone. However, even with a load 10 times larger, there is still an issue of accuracy in very deepwater due to the large initial load.

To overcome this high initial tip stress in deepwater it is possible to compensate the cone by filling the inside of the cone with oil and connecting the inner oil with the seawater outside the cone. However, for conventional load cell designs, the very high hydrostatic stress around the load cell produces an apparent load due to the elongation of the load cell.

A new load cell has been developed and patented by Gregg Drilling & Testing Inc. where the load cell acts as a shear load cell that is uninfluenced by hydrostatic confining pressure. A schematic of the shear load cell design is shown in Figure 4.

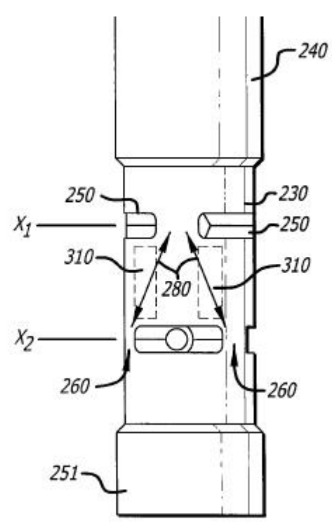

Figure 4 Compensated shear load cell design (After Gregg Drilling & Testing Inc., patent)

The fully compensated (shear) cone records zero at the sea floor regardless of water depth. Hence, low capacity load cells can be used to provide higher accuracy in very soft sea floor sediments. The new (shear) cone has been successfully used in over 2,000m of water and showed excellent repeatability and accuracy in soft sediments.

3 DEEPWATER CPT SYSTEM

Gregg Drilling & Testing Inc., have recently developed and built a new Seabed CPT System that is capable of pushing full-size (either 10 cm^2 or 15 cm^2) cones as well as T-bar tests in water depths of up to 3,000m. The Seabed CPT System incorporates Schilling Telemetry and high-quality robotic components to ensure efficient operation and exact placement on the seafloor. The control systems include three underwater cameras to monitor all aspects of the operation. It has a submerged weight of up to 100 kN (10 tons) but can achieve a reaction force of up to 200 kN (20 tons) using a suction anchor base. Continuous pushing is achieved using semi-circular griper plates that provide a large contact area with the push rods to minimize stresses on the rods. Figure 5 (a) shows the Seabed CPT System and Launch and Recovery System (LARS) and Figure 5 (b) shows a close-up of the continuous push gripper plate system.

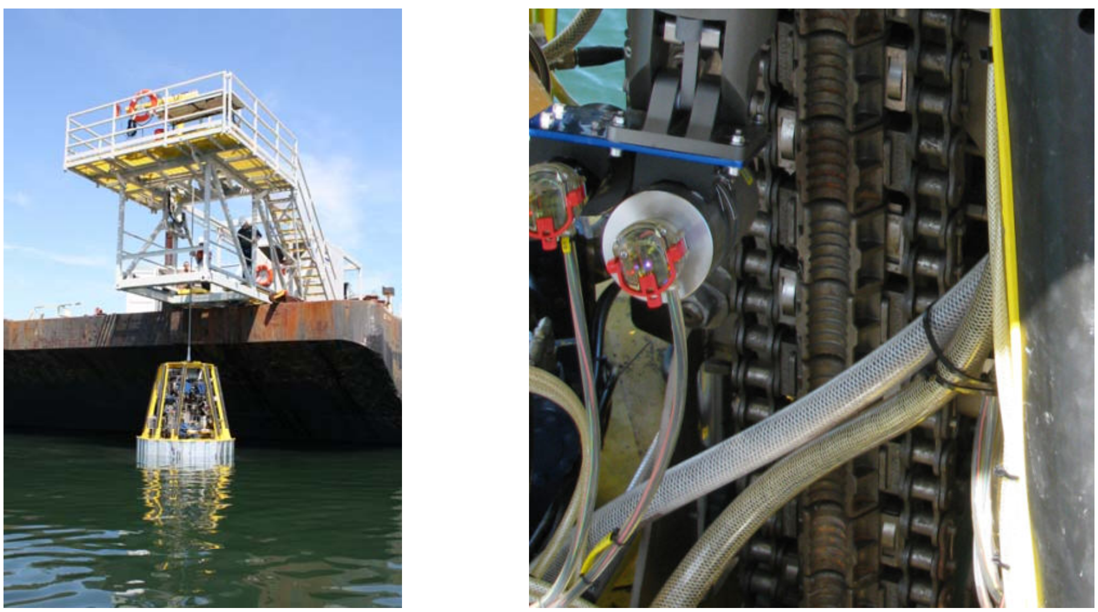

Figure 5 (a) Gregg Drilling & Testing Seabed CPT System, (b) continuous push grip plates

4 SUMMARY

Accurate measurement of CPT parameters in soft soils requires careful attention to cone design. It is recommended to use a cone design with separate load cells to measure the tip and friction sleeve independently and a friction sleeve with equal and small end areas. Careful monitoring of the zero load readings is also required.

A new load cell design has been developed that enables zero load to be recorded when a cone is lowered into very deep water. This new load cell design significantly improves accuracy of CPT (and T-bar) measurements in deep water, since lower capacity load cells can be utilized. A new seabed CPT System has also been developed to improve operational efficiency and accuracy for penetration testing in deep water.

5 REFERENCES

ASTM D5778-95(2007). Standard Test Method for Performing Electronic Friction Cone and Piezocone Penetration Testing of Soils, ASTM International. www.astm.org.

Campanella, R.G., Gillespie, D., and Robertson, P.K., 1982. Pore pressures during cone penetration testing. *In* Proceedings of the 2nd European Symposium on Penetration Testing, ESPOT II. Amsterdam. A.A. Balkema, pp. 507-512.

IRTP, 1999. International Reference Test Procedure for Cone Penetration Test (CPT). Report of the ISSMFE Technical Committee on Penetration Testing of Soils, TC 16, Swedish Geotechnical Institute, Linkoping, Information, 7: 6-16.

Lunne, T., 2006. Can we measure remolded strength or sensitivity with CPTU sleeve friction and friction ratio. Annex A, NGI Technical Note. Report number 20041618-3.

Lunne, T., Eidsmoen, T., Gillespie, D., and Howland, J.D., 1986. Laboratory and field evaluation on cone penetrometers. Proceedings of ASCE Specialty Conference In Situ'86: Use of In Situ Tests in Geotechnical Engineering. GSP 6, Blacksburg, ASCE, 714-729.

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

Lunne, T., Robertson, P.K., and Powell, J.J.M., 1997. Cone penetration testing in geotechnical practice. Blackie Academic, EF Spon/Routledge Publ., New York, 1997, 312 pp.

Robertson, P.K., 1990. Soil classification using the cone penetration test. Canadian Geotechnical Journal, **27**(1): 151-158.

Robertson, P.K., (2009), CPT interpretation – a unified approach, *Canadian Geotechnical Journal*, **49** (11): 1337-1355.

Schaap, L.H.J. and Zuidberg, H.M., 1982. Mechanical and electrical aspects of the electric cone penetrometer tip. Proceedings of 2nd European Symposium on Penetration Testing, ESOPT-2, Amsterdam, Balkema Pub., Rotterdam, 2: 841-51.