Conquering New Frontiers in Underwater Cone Penetration Testing

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ABSTRACT: The future poses a challenge with the need of accurate information about the bearing strength and shear strength of very soft seabed at ever greater water depths. The static cone penetration testing (CPT) method is a technique that has proven to be very suitable for obtaining reliable data in the harsh environment of the deep sea. Special requirements apply for the two main parts that make up the CPT unit: the pushing device and the measuring device. This paper deals with the aspects of designing these parts in such a way that they meet the challenges posed by the deep sea environment at 5000 m water depth and anticipates further future developments.

1 INTRODUCTION

What are extreme environments? They are merely circumstances that we are not used to. We define a depth of 5000 m below sea level as an extreme environment, but the fish that are living there would probably say, if they could talk, that we are the ones living under extreme circumstances, that is, under an extremely low pressure. So trying to work under extreme environments means nothing more than trying to broaden your horizon and to conquer new, so far unknown territory, which is what mankind has always endeavoured.

1.1 *Cone Penetration Testing*

Cone Penetration Testing is all about conquering new territory. It has been used for over 60 years in the Netherlands for the prediction of pile behaviour under loading conditions of the approximately 1 million foundation piles yearly put into practice. Without these piles it would be virtually impossible to build (lasting) structures in the Netherlands.

The geological conditions in the Netherlands make it necessary, already since several hundreds of years ago, to apply pile-foundations on a large scale. At first timber piles were used exclusively, while the driving depth was determined during the process of pile-driving. Only much later the procedure was improved in such a way that simple pile driving formulae, based on empirical data, came into use, in order to assess a relation between driving depth and bearing capacity.

Between 1930 and 1935 the CPT method came into use. It enabled the pile-length and the bearing capacity to be determined prior to pile installation. The process was also accelerated by the general trend in the building trade to erect larger structures, which are more sensitive to settlements and differential settlements. This development required a better and more accurate understanding of the behaviour of their foundations and that of the subsoil. Especially after 1945 the development of the CPT method was remarkable. The method of interpretation of the reading from CPTs in order to predict the bearing capacity of foundation piles replaced the pile driving formulae entirely, as well as the driving of test-piles. By means of a very large number of load-tests it was proven that by considering the CPT as a model test-pile, a sufficiently accurate prediction of its bearing capacity could be obtained. Nowadays it is generally considered inacceptable to design a pile-foundation in the Netherlands without having available sufficient CPT data.

1.2 *Advantages of the CPT method*

Characteristic advantages of the CPT method over other types of soil investigation are:

1 A continuous stream of information covering the full depth is obtained so that the layers of different composition or behaviour can be shown;

2 Measurement of the parameters is done in-situ, so that the actual stress conditions are influenced as little as possible, this in contrast with tests performed just below the bottom of a borehole and especially when it concerns so-called undisturbed samples for testing in the laboratory;
3 The results are very reliable because the human influence on registration of the results can be entirely excluded;
4 The method provides results, which can be interpreted on the spot;
5 The costs involved are infinitely lower than those of other kinds of soil investigations.

2 HISTORY OF OFFSHORE SOIL INVESTIGATION EQUIPMENT

2.1 *Wireline CPT: WISON-APB*

Offshore soil investigation using the static "Dutch" cone penetration testing method was started in 1970 with wire-line "down-the-hole" CPT equipment, called WISON (stands for WIreline SONdeerapparaat), built by A.P. van den Berg for Fugro. Since that time numerous units were manufactured by several different parties and many different technical developments have taken place. Nowadays the wireline equipment made by A.P. van den Berg is called WISON-APB. The CPT unit is lowered into a pre-drilled bore-hole to measure cone tip resistance, local friction and pore-water pressure over 3 m intervals up to maximum 50 kN, 1 m intervals up to maximum 100 kN and 1.6 m intervals up to maximum 150 kN.

2.2 *Seabed CPT: ROSON*

In the eighties the ROSON (stands for ROtating SONdeerapparaat) was put into use for the first time: a CPT unit that could be lowered onto the seabed for continuous penetration testing at capacities ranging from 10 kN to 200 kN. The driving force was supplied by electrically driven friction wheels, ensuring the continuous movement into the soil.

2.3 *Recent offshore developments*

A selection of products developed (or in development) by the R&D team in the last three years is:

Seabed sampler (development phase; since 2003)
Wireline system with a depth rating of 2000 m (development phase; since 2003)
Cones with a depth rating of 4000 m (custom made for the investigation of the oil carrier "Prestige")
Depth encoder with a depth rating of 7000 m (taken into production since 2002; 2 systems are commercially in use)
Acoustic data transmission for the Roson system with a depth rating of 2000 m (taken into production since 2000; 3 systems are commercially in use)

3 CONQUERING NEW FRONTIERS IN UNDERWATER CONE PENETRATION TESTING

The need to perform offshore soil investigations at a water depth of 5000 m requires a whole new design of the CPT equipment in order not only to survive the extreme environment at 5000 m water depth but also to obtain data with the required accuracy and reliability. The challenges encountered need to be addressed for both main parts that make up a CPT system, namely the pushing device and the measuring system. These technical challenges arise from:
6 The ambient water pressure of 50 N/mm^2;
7 Salt water;
8 The very soft seabed;
9 The accuracy of the cone to measure the soil with a nominal bearing strenght of 0.05 N/mm^2 (50 kPa) with respect to the ambient water pressure of 50 N/mm^2 (50 MPa);
10 The long way down and up, to and from the bottom of the sea.

3.1 *Considerations regarding the pushing device*

Designing offshore CPT equipment is completely different compared to the designing of onshore CPT equipment. Figure 1 gives a rough idea about the conditions to be considered when designing CPT equipment for offshore deployment. Tables 1 thru 4 show the typical groups, divided into subgroups. Below every subgroup, possible solutions are mentioned to cope with the issues posed by that specific subgroup. The conclusion should be easy: design a machine that contains all these subgroup's solutions.

But the solution for one can undo the solution for the other. And this is the challenging part for the Research & Development team.

The Research & Development team has to get the right balance between the solutions of the subgroups. A technical background, a good sense of imagination and an extensive working experience makes all the difference in creating a good working design.

3.1.1 *Handling*

In order to be able to perform soil tests up to 40 m depth, the pushing device needs a heavy weight to counter the pushing thrust and a tall frame to protect the long CPT string. A large seabed contact base for stability and minimum disturbance of the bottom adds to the heavy weight. However a sudden weather change, like hard wind and high waves will turn a heavy machine like that into an uncontrolled piece of equipment. Weight reduction will help to control the machine. It is clear that a critical balance has to be found for the opposing preconditions with respect to weight.

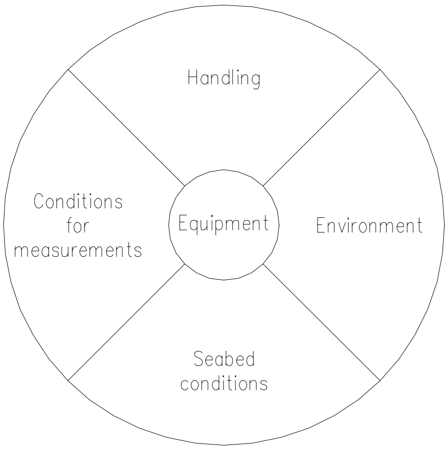

Figure 1: Mixture of groups

While lowering the equipment to the seabed the speed cannot be high otherwise it will tumble over and the CPT rod protection part will collide with the lifting cable and the umbilical with serious risk of damage. With a less tall frame and a smooth base the lowering procedure will be less risky and quicker.

To be still able to penetrate to 40 m with less weight and a smaller frame, the following modifications are needed:

11 the cross sections of the cone and the rods are reduced ($\sigma = F/A$).
12 a cartridge system with CPT rods and a manipulator to connect and disconnect the rods.

Group: Handling	
Sub-group	*Possible solutions*
Weather conditions	Light weight, small
Sea conditions	Light weight, small
Skills of the crew	Easy to operate
Long way up and down	Hydrodynamic shapes

Table 1: Considerations regarding handling

A computer with special software running on deck communicates with the submerged multiplexer on the unit and collects the CPT data. A window on the screen shows the movements of the manipulator. After a sounding depth of 40 m the manipulator disconnects the rods and put them back in the cartridge.

When lifting the equipment from the seabed the winch on deck will have a hard time to pull the machine upwards against the massive resistance. Hydrodynamic smooth topside will help to ease the lifting.

All in all the entire unit is made smaller, lighter, safer to handle, even in bad weather, and still able to push 40 m.

3.1.2 *Environment*

3.1.2.1 Water pressure

At 5000 m water depth the ambient water pressure will be a staggering 50 N/mm^2. While lowering the machine, a pressure compensator will be necessary to deal with the pressure difference of 50 MPa between the inside and outside of the housings.

Some chambers and housings in the unit, which need an atmospheric pressure of 0.1 MPa, like electronic chambers, have to be sealed off from the high pressure. This affects the seals and the geometry of the design. Some of the chambers or housings have to be pressure compensated otherwise the unit will be too heavy. The compensating system has to react on every change in ambient pressure otherwise the differential pressure can damage the seals and seawater will have access to important parts of the unit.

The ambient water pressure especially has effect on the cone. If a normal onshore cone is used it will be impossible to measure a value accurately because the measured value will be less than 0.1% of the ambient water pressure. A special cone design will be necessary to make accurate measurements.

Group: Environment	
Sub-group	*Possible solutions*
Seawater	Protecting coating; seawater resistant materials
Ambient pressure	Strong housing or fluid filled with compensator

Table 2: Considerations regarding the environment

3.1.2.2 Salt water

Salt water can be very aggressive to certain materials, and may therefore cause failures. Especially saltwater in combination with electricity will give corrosion problems. Next to the underwater problems, a problem can also occur on deck. When the system is used and put back on deck, the water will evaporate and the salt crystals will stay behind.

These salt crystals stick to grease and can affect the function of for example a bearing or a seal.

3.1.3 *Seabed conditions*

The very soft seabed consists of very small particles suspended in water. The challenge is to detect the border between water and seabed. When the system is lowered with a certain speed and hits the seabed, disturbance of the soil will occur. The weight of the system is also a problem if the base plate is too small. The unit will sink into the seabed. If the pushing system sinks into the soil the consequence is that the cone or vane test apparatus starts below the seabed surface. This will preload the cone during zero reading. A preloaded cone or vane test apparatus will give data biased with the preload value. Distance to seabed measurement during landing will prevent this.

Before testing measurement of the horizontality and possible correction of horizontality is necessary.

Three moveable legs with levelling plates with sufficient area answer to these issues. Before lifting the equipment after performance of the test, the legs are retracted.

Group: Seabed conditions	
Sub-group	*Possible solutions*
Slope	Adjustable support plates
Soft	Large surface of the support plates to avoid sinking in
Hard	Heavy reaction weight

Table 3: Considerations regarding seabed conditions

Group: Conditions for measurements	
Sub-group	*Possible solutions*
As little as possible disturbance of the seabed	Large surface of the support plates to avoid sinking in
No undesirable movements of the equipment	Large stable unit to lead the reaction forces to the seabed

Table 4: Considerations regarding measurements

3.2 *Considerations regarding the measuring system*

One of the most important challenges is an accurate measurement of the soil strength parameters in deep water. The main issues to be addressed with measuring soil strength in deep water are:

13 Sensitivity versus water pressure, especially for friction measurements. The friction of the “O” ring seals to the other parts increases with the water pressure and limits the free movement of for instance the friction sleeve.

14 Water pressure consuming the measuring range of the cone tip resistance q_c and pore water pressure U.

The force acting on the cone resulting from the penetration speed is passed on to the pushing rod in several ways. Only the way through the load cell is measured by the data acquisition system. Other possible ways are for instance through “O” rings, soil seals and dirt or contamination.

“O” rings for instance deform under high pressure and exert a higher force on its metal surrounding. This causes a greater part of the generated force to pass through the “O” rings, resulting in a lower measured parameter.

The area on which the water pressure U_2 acts preloads the cone load cell.

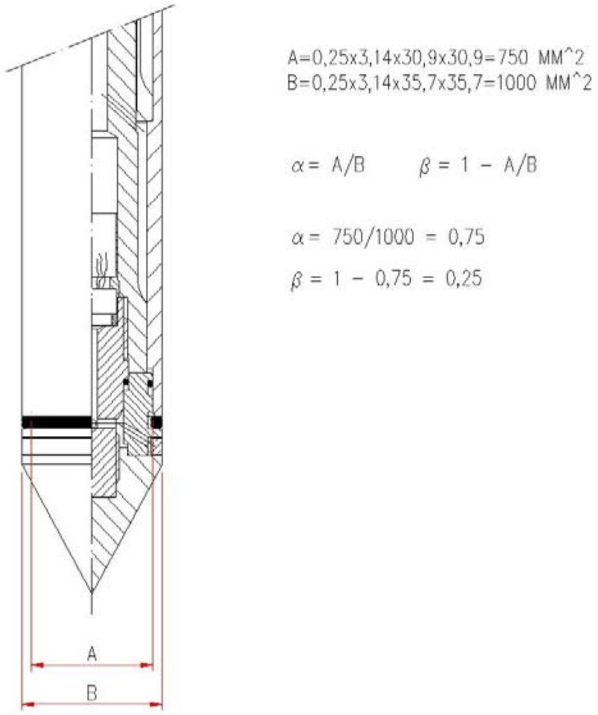

Figure 2: Standard AP van den Berg cone dimensions

$$F_h = \rho g h_z A$$

Where;

F_h is the force on the load cell

ρ is the unit weight of (sea)water

g is the earth gravity at the location

h_z is the water column

A is the area on which the water pressure acts. In the case of AP van den Berg 10cm² cones this is 7.5cm² (α=0.75).

Per 1000 m water depth this results in a force in the tip load cell of approximately 750 kN. This equals 7.5 MPa tip load. When measuring soft clays the preloading of the cone exceeds a measured value of the clay by far (a typical value measured in soft clays is 50 kPa).

3.2.1 *Possible solutions*

3.2.1.1 Hydrostatically compensated cone.

In a hydrostatically compensated cone the soil seals and seals for water tightness can be avoided when a subtraction design is chosen. The strain gauges can then be fitted on the inside of the two load cells while the outside is exposed to the surrounding water. This eliminates the problem mentioned under 3.2. sub 13 but ads the problems associated with subtraction cones like inaccuracy of the local friction.

In the hydrostatically compensated cone the preload caused by the water pressure due to area affects is grossly avoided. However the problem of calibration is introduced.

The surrounding water pressure is now present on all sides of the load cell in the cone leading to a three dimensional deformation of the material of the loadcell and the strain gauges. This deformation of the material of the cone differs from the deformation caused by the force from the soil. The IKS institute of the University of Siegen, Germany found a deviation of 1% in span when testing torque load cells under 40 MPa pressure.

A hydrostatically compensated cone needs to be calibrated under the same pressure as it is used under, which makes the calibration procedure technically very challenging and only valid at the calibrated pressure.

3.2.1.2 Specially designed “normal” cone

The ambient water pressure now only acts on the outside of the cone. The deformation of the material on the outside of the cone can be calculated and taken into consideration in the cone design.

The load cell is at atmospheric pressure and normal calibration data applies.

The inaccuracy due to the problems mentioned in 3.2 sub 13 and 3.2, sub 14 need to be addressed to see if the problems can either be avoided or be known so accurately that the effects can be adjusted.

At 3.2, sub 13

Measuring the friction of the “O” rings under pressure is determined by applying a small accurately known force to the friction sleeve of a normal cone at various pressures. For this purpose AP van den Berg designed a high-pressure vessel that is hinged in the middle. By turning the vessel upside down the known weight of the friction sleeve can be applied to the load cell or not. Mounting a friction sleeve with defined weight onto the cone and turning the vessel enables measurement of the friction of the “O” rings.

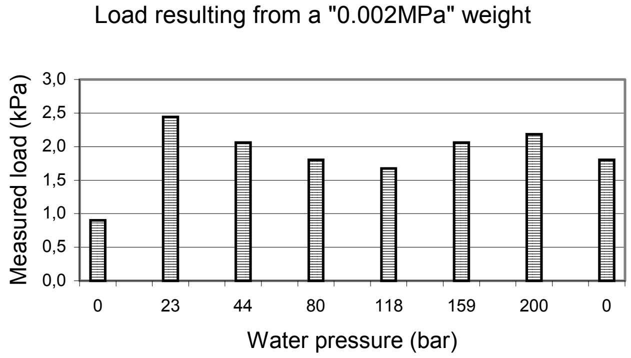

Figure 3: Relation between water pressure and measured load.

A.P. van den Berg used this method to test her cones for deep water. Having a reliable measuring method resulted in small design changes that minimizes the effects of “O” ring friction as is shown in figure 3.

At 3.2, sub 14

With only a small part of the range used for measuring the soil data special care needs to be taken with cone calibration. The cone is usually specified as 0.1% accurate. The overall accuracy depends further on the data acquisition system, the cabling in between and force bypass effects as mentioned before.

The repeatability or precision of the load cell itself is much better than 0.1%. When only a small part of the full measuring range is used the calibration procedure must be adjusted to this. Modern software packages are well capable of comparing accurate 100-point calibration data with acquired soil data eliminating non-linearity effects of the load cell.

In a calibration procedure the cone load cell is compared to a standard. Two points (zero and full load) are used to determine a straight line. This trend line is used to calculate the actual load from the loadcell output. Accuracy is the deviation of the actual load on the loadcell from the calculated load (see figure 4).

A different situation occurs when only a small part of the measuring range is used and the zero reading is recorded at the start of the test and used as the reference for testing.

The trend line differs from reality in two ways: an absolute distance between the lines and a deviation in angle.

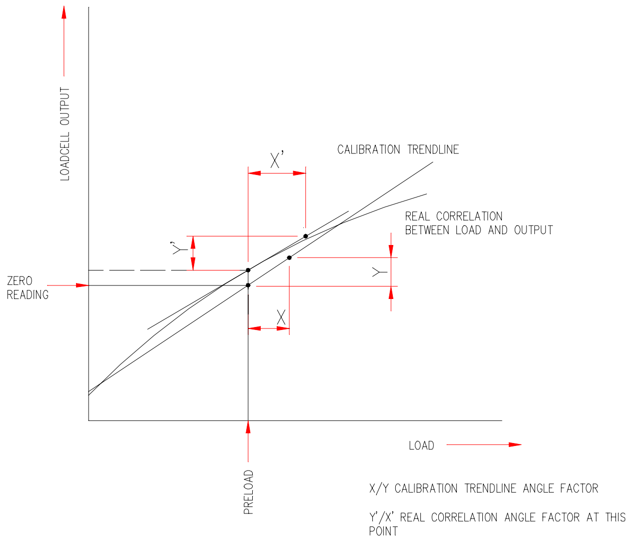

Figure 4: Calibration trend lines

Taking zero readings close to the measured value eliminates the inaccuracy due to the absolute distance between the lines. The inaccuracy due to the difference in angle however is exaggerated.

By determining the real correlation for instance at 100 points divided over the range the correlation between load and load cell output is accurately known and the software can calculate the load on the loadcell accurately from the loadcell output.

Now repeatability has become accuracy. This brings deepwater CPT data well within the required accuracy with an atmospheric cone. This led Thales-Geosolutions to choose AP van den Berg as manufacturer of the cones to CPT around the Prestige at 3800 m water depth with excellent results. Figure 5 shows one of the cones used in the Prestige project.

Figure 5: 2.6 cm^2 cone, depth rated 4000 m.

4 CONCLUSIONS

What does the future hold in store for us? The ever-growing demand of energy and living space leads to the exploration of areas in ever more extreme environments. At the same time higher demands are set to environmental concerns, reliability, safety and costs. The CPT method has proven to be the best solution so far in the reliable and accurate collection of soil data under extreme environments, at the same time meeting these other demands. Challenges to construction and technical performance posed by the environment of deep seas have been successfully met up to a water depth of about 4000 m and further designs for investigations of the soil at 5000 m water depth are very real, with an anticipated 0.5% accuracy of the measuring results. The challenges we are facing are leading us to a higher level of technology which may eventually even help us conquer the threshold of extraterrestrial soil investigation.

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