GeoInfo

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Unlocking Your GeoData

Complementary Technologies

PS Logger®, Seismic CPT and CPT for Ground Investigation

Ground investigation for Offshore Wind Farm (OWF) development routinely employs CPT, Seismic CPT and the PS Logger® in combination to determine in-situ formation stiffness. CPT supplies parameters beyond the linear elastic limit while Seismic CPT and the PS Logger® provide stiffness parameters for very small strain elastic response.

The ongoing development of Cone Penetration Testing (CPT) techniques, now with more measurements, has evolved to the point where CPT now provides a system of testing comparable to that of conventional wireline logging.

The PS Logger® is vital to these investigations as it can provide a continuous stiffness profile through layers where CPT cones cannot penetrate (rocks, pebbles, gravels etc).

Introduction

The characterisation of soils and rocks for the design of supporting structures can involve a myriad of different tests, both in-situ and from laboratory samples. Here we will be focussing on the PS Logger®, Cone Penetration Test (CPT) and Seismic CPT and their application to ground investigation for Offshore Wind Farm (OWF) development.

CPT, which pushes a measuring cone into the formation via a rod, has now become so sophisticated and accepted that it is hard to envisage that any significant civil engineering structures would be constructed without some element of CPT. Seismic CPT (SCPT) and the PS Logger® have emerged as complementary technologies that provide additional parameters relating to the linear elastic response of formations.

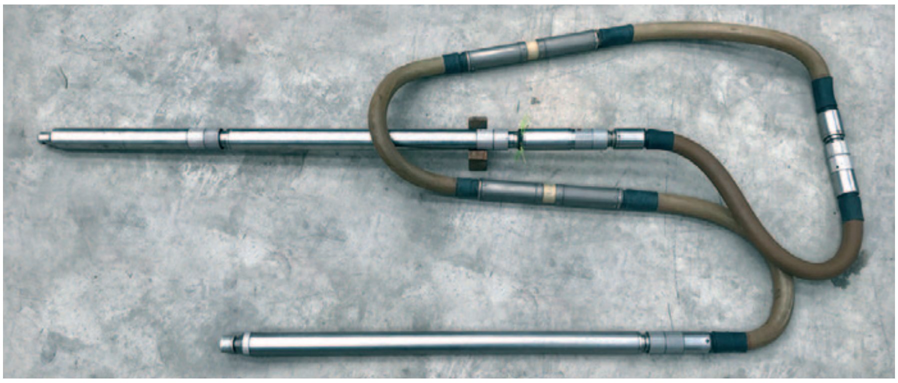
More accurate soil parameters for modelling loading response gives benefits in cost reduction due to better optimised foundation designs.

Example CPT Cone.

History

Before the advent of CPT, the Standard Penetration Test (SPT) appeared, in the early 1900's. This consisted of a tube driven into the soil by a sequence of standard hammer blows, the count of which (N count) gave a measure of penetration resistance which could be used for geotechnical design purposes. Despite concerns over disturbance of samples, the SPT method was adopted worldwide, due to its simplicity, and it remains the most frequently used subsurface exploration drilling test performed.

The CPT method was developed in the 1950's in the Netherlands to provide analogue and subsequently digital data which could be more readily related to soil parameters. Early probes measured the total penetration resistance or bearing capacity of the formation. To separate the resistance of the rod from the tip resistance, a friction sleeve was developed in the 1960's which helped quantify soil cohesive strength. The addition of a transducer to measure pore pressure then allowed for correction of tip friction values. Tip resistance, sleeve friction and pore pressure could now be considered as the standard CPT outputs. Other sensors including those for resistivity, natural gamma, temperature, inclination, video and magnetometry can also be embodied within the cone.



The Robertson Geo PS Logger®.

The addition of one or two geophone arrays in the cone, coupled with an external sound source, saw the emergence of Seismic CPT as an important additional test which can be run concurrently with standard CPT.

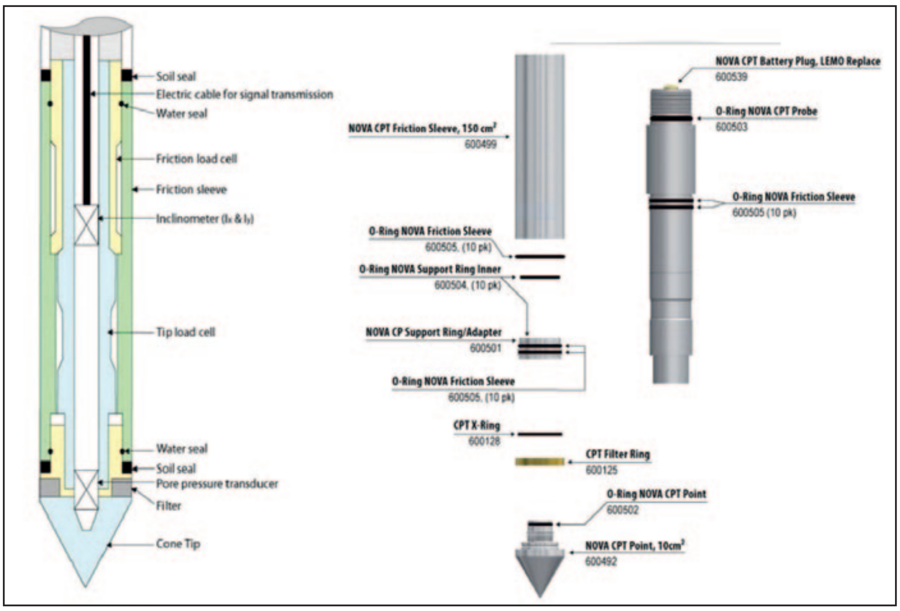
The PS Logger® (a registered Robertson Geo Trade Mark) was originally developed by the OYO Corporation in the 1970's to provide a full waveform tool that would produce reliable P and S wave velocity measurements in unconsolidated materials and rock formations, at depth, from a single borehole. The initial application was for determining earthquake susceptibility, but the probe was soon adopted for geotechnical investigation. Both on land and offshore (mainly for OWFs) the PS Logger® has become a standard means of collecting P and S wave data used for determining small strain moduli, superseding other sonic probes due to its ability to generate shear waves even in unconsolidated sediments.

Deployment

For offshore geotechnical investigation relating to OWFs some testing will be conducted at each turbine location usually with sample boreholes being drilled at a percentage of them. In the early days, where the OWF locations were near shore, jack-up platforms were often used. As the OWFs have gradually expanded to deeper waters (20-50m) boreholes are routinely drilled from heave compensated drill ships. As the commercial development of floating wind farms starts the water depths will increase (up to 500m) which will require different designs and approaches to the ground investigation.

Offshore, CPT testing may use the drilling mode whereby the CPT system is latched into the drill string and the 'push' is provided by a hydraulic umbilical using the drill string as the resistive force. Alternatively, there are dedicated CPT systems which are contained within a seabed frame which is lowered to the seabed under control from the surface where the weight of the frame supplies the reaction mass.

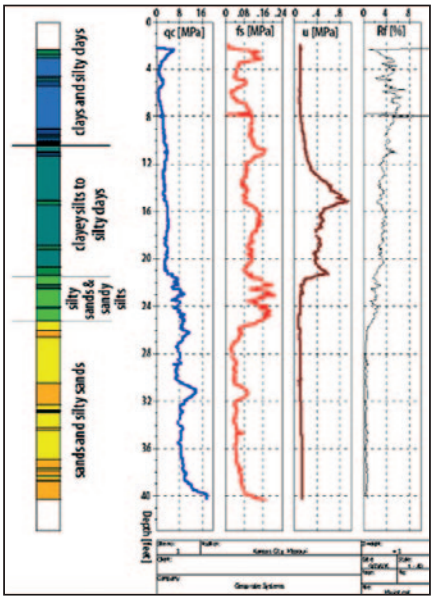
For seismic CPT an additional S wave source generator is required which is lowered into position adjacent to the borehole or may be combined in the dedicated CPT frame. In some cases, the S wave source can also produce P waves but this will usually be on a seabed frame separate from the CPT delivery system.



Cutaway of CPT cone with pore pressure transducer (CPTu).

PS logging requires a borehole to be drilled and once target depth, plus a 5m over-drill, has been reached the borehole is ready to log. The drill string stays in the borehole and is usually withdrawn in stages to expose a section of open borehole. This open section is logged and the probe withdrawn. Then more drill pipes are removed to reveal a further open section. This is logged with an overlap and the process repeats.

For onshore investigation, the CPT is usually delivered from dedicated truck mounted systems. PS logging from drilled boreholes routinely provides deeper data even through hard formations where the CPT 'refuses'.



Sample CPT Data.

Measurements

CPT

The CPT method uses a hydraulic rod fitted with a cone which is pushed vertically into the ground at a controlled speed. The sensors in the cone provide profiles, at centimetre resolution, throughout. As the cone penetrates it forces failure of the soil about 40cm ahead of the tip. The tip resistance is measured by load cells behind the tapered cone and is theoretically related to the undrained shear strength of a saturated cohesive material. Taking measurements from strain gauges, the sleeve friction is theoretically related to the friction of the formation being penetrated. Piezo cones measure pore pressure using a porous plastic insert just behind the tapered head that is made of hydrophilic polypropylene. In dense formations, like sand, pore pressure may drop and in clayey materials high pore pressures may be induced by the driving of the cone head. If pore pressures are measured that appear transient the 'push' may be halted to allow the pressure to equilibrate. The results from CPT combine to supply a soil classification and through theoretical analysis of the data produce further engineering parameters.

Data Outputs

Data	PS Logger®	SCPT single array	SCPT dual array	CPT
Outputs	**Waveforms:** P near P far S left near S left far S right near S right far	**Waveforms:** Sx Sy (+ for P wave source) P	**Waveforms:** Sx near Sy near Sx far Sy far (+ for P wave source) P	Tip resistance Sleeve friction Pore pressure (Inclination) (Resistivity) (Temperature) (Natural gamma)
Derived data	Arrival times P velocity (interval) S velocity (interval) Poisson's ratio	Arrival times S velocity (P velocity) Interval velocities (Poisson's ratio)	Arrival times S velocity (P velocity) S velocity (interval) (P velocity (interval) (Poisson's ratio)	Friction ratio Friction angle Undrained shear strength ++
Additional data	...with bulk density Shear Modulus Bulk Modulus Young's Modulus	...with bulk density (Shear Modulus) (Bulk Modulus) (Young's Modulus)	...with bulk density (Shear Modulus) (Bulk Modulus) (Young's Modulus)	Many other derived parameters

Comparison of PS Logger® versus SCPT for Offshore Ground Investigation

The PS Logger® and the Seismic Cone Penetration Test both measure formation velocities but by completely different means. The PS Logger® is deployed by a conventional wireline arrangement while SCPT usually runs concurrently with standard CPT testing. The table below highlights the significant differences between the two methods.

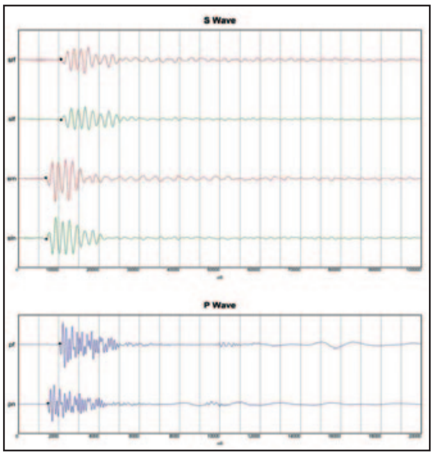
Consideration	PS Logger®	SCPT
Energy source	Bi-directional hammer - integral with probe	Separate generator on seabed frame
Source/receiver alignment	Fixed - 2 x single geophone and hydrophone array	Requires x-y polarised geophones due to uncertainty in cone orientation
Shallow Investigation 5-10m	Often not possible to test due to casing cover/noise	Proximity to source gives good S/N ratio
Deeper investigation	Performs best at depth due to consistent source energy	Below 40m may not be possible as S/N ratio diminishes
Unconsolidated deposits	Requires good borehole condition without washouts	Works well in unconsolidated sediments
Hard/dense soils and rock	Works well in hard/dense formations	May not be able to penetrate
Receiver coupling	Not required for the suspension method	Good
Waves measured	Always P and S	Always S but P waves require a separate source generator
Interval velocities	Measured directly	For single geophone array must be derived from source to receiver arrival times
Depth control	Accurate and consistent	Heave and tides can give problems
Data Formats	Proprietary and SEG Y	Flexible – variety of formats available
Ship borne noise	Can be problematic when probe is near seabed	Generally, quite resilient to ship borne noise
Weather effects	Can be significant when near surface	Mostly unaffected
Set up issues	Winch usually mounted on the 'rooster box' for heave compensation	Requires energy source to be deployed on a seabed frame
Operational issues	5m over-drill is needed to achieve data at target depth	Placement of seabed source can be difficult
Borehole requirements	100-200mm diameter, single borehole preferably with low rugosity and little washout	None – cone is pushed in front of the drill bit

Seismic CPT

Seismic CPT records waveforms at one or two receivers in the cone which are strongly coupled to the formation. The energy source comes from a separate generator placed on the seabed next to the borehole. Readings are taken statically with each receiver station using orthogonally mounted geophones. Data from the best orientation (x or y) are then processed and the arrival times picked. From the source-receiver distance and arrival times, velocities and interval velocities may then be calculated. With the addition of bulk density readings small strain moduli may also be calculated if P waves have been recorded.

PS Logger®

The PS Logger® is run in a borehole with a conventional wireline system and records P and S waveforms at two positions from a powerful integral energy source. Unlike other sonic probes the PS Logger® takes readings statically, usually at 0.5m or 1.0m intervals and at each depth position 3 shots are taken, one for P waves and two for S waves (left and right). The distance between the two receiver stations is fixed at 1.0m and interval velocities are calculated once arrival times are picked. Poisson's Ratio, and with the addition of bulk density data, small strain moduli are then calculated.



PS Logger® Waveforms.

Seismic CPT Cone.

Conclusion

Ground investigation for OWF foundation design has developed over the past decade, now collecting a wealth of data at specific turbine and infrastructure locations. Core sampling and subsequent laboratory analysis provide a multitude of parameters which feed into the design process. In-situ data is also vital, and this is provided mainly through CPT and wireline techniques in drilled boreholes.

While CPT provides a wealth of parameters beyond the linear elastic limit, Seismic CPT and the PS Logger® can provide small strain moduli inside the elastic limit (when combined with a bulk density).

In general, the PS Logger® method is faster than SCPT as the latter requires careful placement of a separate seabed source which can be time consuming and can have an impact on the routine CPT technique. For this reason, the Seismic CPT method is often used only for measuring near surface velocities while the PS Logger® is used for deeper sections (10m+).

Where hard formations, impenetrable to CPT methods, are encountered, only the PS Logger® can provide the required data.

PS Logger®, Seismic CPT and CPT should be seen as complementary technologies which together can supply in-situ stiffness parameters at all depths and in all formations.