DENMARK

Three new Danish offshore wind farms by 2030.

TAIWAN

Meeting targets at Guanyin Offshore Wind Farm.

SCOTLAND

Wind farm estimated to generate enough electricity for around 375,000 homes.

ROBERTSON GEO®
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Offshore Wind Farm issue

Specialist global service, equipment and technology for subsurface characterisation and investigation of Offshore Wind Farm sites.

My name is Jo, and I have been working on and offshore with Robertson Geo for just over four years. Having grown up in Zambia, completing my BSc in South Africa and after heading over to Cardiff University for my MSc in Environmental Geology, I have become one of the team of specialist onsite logging engineers.

I have worked on several different offshore windfarm projects ranging from the East coast of America to the North Sea and the Baltic. My main role is to deploy specialised wireline probes downhole to acquire detailed information regarding the ground conditions below the seabed.

The Robertson Geo PS Logger® probe is a given on Offshore Wind Farm projects, other probes regularly used include the 3-Armed Caliper and High Resolution Acoustic Televiewer. The logging set up differs depending on the vessel, with either the winch being set up in the rooster box or down on deck, and the surface system set up from either the doghouse, lab or CPT office.

Logging is done according to a plan set up either in the project specification, or after discussion with the drillers and geotechnical engineers onboard. This allows ground conditions to be closely managed to prevent borehole collapses after the drill pipe has been extracted. Logging data is processed onboard and supplied to the client within 24 hours of completing the borehole. This data is also sent back to our Senior data team for QA/QC.

Working in the offshore world has its ups and downs (literally), but it is a wonderful opportunity to meet and work with people from all over the world with such different backgrounds (still holding out hope I will find another Zambian out there one day). Robertson Geo has had an offshore presence for over 15 years now and I often come across a new face offshore who has had the experience of previously working successfully with our offshore logging team.

Joanne van Aardt
Logging Engineer - Robertson Geo

Offshore wind farm (OWF) development is now on the agenda for any nation with a coastline as the world moves inexorably away from fossil fuels toward renewable energy. The exponential growth plans for OWF, driven by the acceptance of human caused climate change and exacerbated by the recent energy crisis are now being revised upwards. Robertson Geo, with its experience gained from early involvement with OWF, will continue to play its part through supply of equipment and services.

No one is more experienced for global subsurface data acquisition for Offshore Wind Farms

The importance of product supply and training or global deployment of engineers and equipment for full-service data acquisition

Fully qualified engineers able to offer autonomous operation (globally)

PS Logger® use as tool of choice

Experience from drilling ships to gantry rig deployment

Overcoming challenging deployment circumstances

Working with offshore Geodrilling organisations

Background

Robertson Geo has been supplying equipment and services to the OWF market since 2008, most notably the PS Logger® probe, which has established itself as an essential part of OWF site geotechnical investigation. From 2008 to the present-day Robertson Geo Operational Services (RGS) have undertaken 44 OWF projects across 39 wind farms globally in nine countries. In addition, RGS has provided rental systems for OWF, with on-site training, and equipment and technologies purchased from Robertson Geo have seen action on many global OWFs *(See Figure 1 for RGS OWF statistics)*.

Wireline logging provides unique high quality in-situ data which is used in the complex design process required for OWF turbine installations. The PS Logger® is used to determine P and S wave velocities which feed into stiffness calculations for these designs. This data is complementary to that from CPT and SCPT by providing data in harder formations where CPT methods cannot penetrate. With its integral source and consistent energy delivery the PS Logger® can collect data from any depth required for geotechnical investigation.

As wind farms have, by necessity, moved ever further from shore, so the geotechnical investigation methods have had to evolve to meet these challenges. This has seen moves away from jack-up platforms, still used for near shore investigation, to complex heave compensated drill ships with dynamic positioning. The wireline method has similarly evolved to work efficiently on these complex vessels with the advantage of being able to deploy a range of probes from the same surface set-up in a single borehole.

As clients demand ever more and better cost-effective data to streamline their design processes, the wireline method and specifically the PS Logger® will continue to evolve to meet these requirements.

Equipment and Sales

For remote OWF geotechnical site investigations it is economically vital that all equipment performs reliably to eliminate costly downtime and to avoid the need to run to port due to equipment failure.

Robertson Geo designs and manufactures all its own equipment from its base in North Wales using ISO 9001 accredited processes. An integral part of this process is a strong feedback loop from customers and RGS which drives product development to improve reliability and meet the challenges from OWF.

This need has seen the development of a marine version of the popular Robertson Geo 2000m Winch which is usually mounted on the rooster box for heave compensated vessels. The marine version uses high grade stainless steel wherever possible and features plug-in sub modules for rapid field swaps and revised electronics for reliability and ease of maintenance.

The PS Logger® has also continually evolved to better meet the needs of the OWF environment. Changes to the power system, electronics, hardware design and sensors have all been implemented alongside changes to materials whereby titanium components are now replacing stainless steel for enhanced corrosion protection.

All equipment manufactured by Robertson Geo goes through an extensive testing regime prior to release. For probes this includes an ISO 9001 accredited multi-part process of calibration and borehole testing before a conformance certificate is issued.

For equipment sold for offshore environments Robertson Geo offer comprehensive pre-sales advice, based on direct experience from RGS, and can supply standardised spares packages to mitigate any problems that may arise from working in the harsh conditions on offshore vessels. Often equipment will be supplied from stock for OWF applications, always with a valid conformance certificate. Selling to over 140 countries Robertson Geo have the expertise to ensure shipping is organised efficiently and takes account of the complex import requirements found in different countries. Training and commissioning will always be offered to clients, often at their own sites, and for ongoing support a help-desk facility is provided. Specifically for the PS Logger®, a data processing service is available as well as a QC function for clients, particularly important given the critical nature of the PS Logger® data.

In addition to the PS Logger®, probes that have been used for OWF site investigation include the 3-Arm Caliper (for QC purposes and for natural gamma), the High Resolution Acoustic Televiewer (for imaging fractures and bedding in harder formations and for core depth control and orientation), the Formation Density probe (for in-situ bulk density) and for the future the Nuclear Magnetic Resonance probe is being actively considered (for detailed porosity and pore space evaluation). *See Figure 2 for OWF probe deployment statistics*.

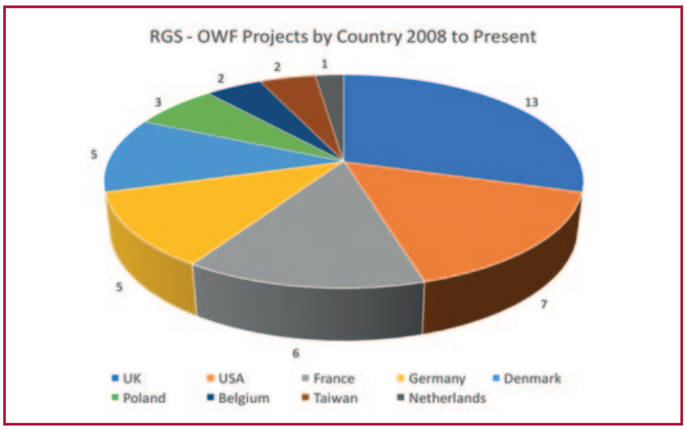


Figure 1: RGS Projects by Country

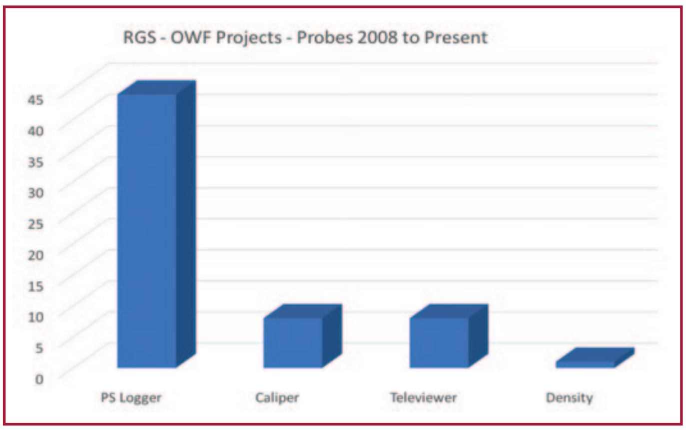


Figure 2: RGS Probe Usage

Global Rental Service

Robertson Geo Operational Services maintain a large pool of OWF equipment for their own turnkey service including Marine Winches, Microloggers, PS Loggers, 3-Arm Calipers, High Resolution Acoustic Televiewers and associated accessories and spares. This same equipment is also available for rental worldwide, generally for customers with experienced personnel or for shorter projects where buying is not economic. In all cases RGS can provide pre-contract advice, particularly important if the work is be performed on a heave compensated drill ship where the winch may be mounted on the rooster box.

From direct experience RGS understand the isolated nature and harsh conditions usually found on OWF and therefore ensure that all rental equipment undergoes stringent checking before shipping. This includes recommendations for which spares should be carried, conformance certification for probes as well as a full system check on all equipment. For the winch this includes full testing of spares including temporary fitment to the winch to guarantee they will work should they be needed.

The level of training required will vary, usually based on the experience of the engineers. In some cases, clients will send their engineers to Robertson Geo for an intensive training course. Training at the customer site is also available in many cases as well as training via a videocall, though the latter is not ideal for inexperienced engineers. For rental clients who have longer term needs but inexperienced staff, RGS would recommend that one of our engineers be present for the first "hitch" as on the job training and supervised operation is undoubtedly the preferred way to learn best practices.

RGS offer unparalleled multi-level equipment back up for all rental customers. Spare probes are strongly recommended for OWF applications as operating on heave compensated drill decks is by necessity a hazardous business even under the best H & S regimes. For inexperienced operators the drill deck is a daunting environment requiring constant vigilance especially at night in bad weather. The recommended spares have evolved to include everything that should be required to be able to keep working. If any equipment is damaged RGS can usually ship out, same day, replacements from its stock pool without disruption to vessel operations. Should RGS not have a replacement immediately available a call off can usually be made on sales stock or repairs can be fast tracked, all this from the Robertson Geo manufacturing unit without any recourse to external suppliers.

As the rental job commences it may be anticipated that there will be initial teething problems operating in the difficult OWF environment. RGS provide a hotline, manned by an experienced engineer, for the real time resolution of problems, usually most relevant to the first boreholes being logged.

The largest wind farm installation vessel in the world and the first turbine installed off the coast of Aberdeen. Balmedie, Aberdeenshire, Scotland, UK. April 11th 2018.

Due to the complex nature of recording and interpreting seismic data, experience counts, especially for the PS Logger® where P and S waves must be identified and arrival times picked. For rental clients RGS offer either a complete data processing service or can provide a QC service for already picked data. Again, this is particularly useful for customers for the initial boreholes.

Global Turnkey Service

Robertson Geo Operational Services has been providing a global turnkey wireline logging service to OWF for many years and has unsurpassed successful experience. On all these projects the PS Logger® has been deployed for P and S wave determination. Over this period RGS have developed their OWF service, with special regard to heave compensated drill ships, based on the principles of a high-quality service level throughout the contract process. This includes zero-attributable downtime, competent fully trained engineers capable of working autonomously, quickly, safely, and flexibly and finally the provision of the highest quality data possible. Together this is designed to ensure that RGS inspire confidence.

At the pre-contract stage RGS can provide information to customers regarding probe selection, winch emplacement, scheduling, equipment delivery, engineer competence, H & S matters, and data outputs. This is mostly for less experienced clients whereas for regular clients this stage is mostly an exchange of relevant information. Flexibility is key here, as equipment profiles, start dates and durations may be subject to late changes.

The provision of the equipment and engineer to the vessel at the start of a contract in a timely manner is one of the challenges RGS face. It can be difficult for clients to specify exactly when they will be departing for the OWF and even the port of departure may be subject to a late change. Delivering equipment by freight is a necessity outside of Europe whereby contingency needs to be added to cover for delays in customs and changes to flights. For European operations RGS invariably deliver the equipment directly to the port of departure as this allows a much higher degree of control over the process, effectively a just in time system. Brexit has also influenced decisions regarding how best to deliver equipment as Carnets are now required for Europe. The engineer may travel with the equipment or can fly out separately, whichever is the most cost effective.

Offshore vessels undertaking OWF geotechnical investigations naturally always strive to eliminate or at least minimise downtime. As vessels operate on a 24/7 basis any lost time has a commercial impact. There is also potentially a knock-on effect to downtime for vessels with dynamic positioning as they can only operate within specified weather limits, i.e. "weather windows". Downtime could cause an entire window to be missed given the time it takes to complete a borehole. Full system checks are performed prior to mobilisation (including spares testing), and where time allows a full system check will be conducted at the dockside once the kit is onboard. RGS fully understands the implications of downtime and have mitigated the possibility of attributable downtime by providing fully tested equipment with spares and spare probes and engineers trained to find solutions which allow them to keep working. While operational problems with shipborne equipment cannot always be avoided RGS has no recorded instances of attributable downtime across the projects undertaken and never has a vessel had to run to port due to RGS equipment failure.

Prior to the commencement of logging operations, a set of RAMS would be provided and once onboard the vessel a kick off meeting will take place covering logging operations and safety. At this meeting the important matters of winch emplacement and how a shooting plan will be conducted will be discussed, including the provision of data pertaining to depth control. Depending upon the heave compensation set-up, the winch will either be emplaced for the duration of the project or will be emplaced and removed for each borehole, the latter being the most common approach. The shooting plan meeting, before each borehole, will involve the drilling team, the geoengineers and the OPM representative whereby all available information goes toward deciding how many individual runs (or casing pulls) will be required, based on depths of any weak layers identified. Protocols for safety and toolbox talks will also be put in place and reiterated for each borehole.

Operations on a heave compensated drill deck are managed by the driller or drilling supervisor who has full responsibility for a series of complex hazardous operations. These operations take place in a limited space which contains many prime movers and a lot of heavy equipment. Operations are 24/7 which means working at night and in the windy weather conditions prevalent on wind farms. When drilling is complete, and it is time for the wireline logging, the RGS engineer takes control of the logging operation with the lead driller maintaining oversight. Client confidence is only inspired by the competency of the engineer and his ability to work together as part of the drill deck team. The engineer is responsible for setting up the winch and surface recording system and ensuring the safe ingress and egress of the probes in the borehole. Once depth has been set the engineer will lower the probe(s) into the borehole and commence logging, providing real time QC monitoring throughout. A typical wireline operation on a heave compensated drill ship should easily be completed within a single 12-hour shift, even with multiple probes. Upon completion, the equipment is rigged down and needs to be stored quickly as the drill pipes will immediately be withdrawn and the vessel prepared for the move to the next borehole.

The challenges that face the logging engineer are many and varied but include, responsibility for safe operations, correct setting of probe parameters, real time quality control of the data, dealing with the harsh weather conditions, communicating effectively with the drill crew, and solving any problems with the equipment that may arise. RGS only select engineers that are capable of this autonomous working within the team environment. A strong emphasis is also placed on the sharing of learned information and practices between team members for continuous service improvement.

Wireline Data

The provision of high-quality data safely and in a timely manner from the wireline operation is its raison d'être. This data feeds into the wider developer data set allowing design optimisation which should lead eventually to reduced costs. Confidence in the data provided is also very important, which is achieved by using the best equipment, with valid conformance certification, operated by highly trained, competent engineers.

Offshore Wind Turbine in a Wind Farm Under Construction Off The East Sea in Asia.

RGS engineers always process their own data onboard the OWF vessels, usually within 24 hours, and the data is then sent back to the RGS QC team for final checking and confirmation. The feedback loop from processing the data highlights the care and attention that must be applied by the engineer throughout the logging to achieve the best results.

The PS Logger® probe has been deployed on all RGS OWF projects to date, giving P and S wave profiles, which allow Poisson's Ratio and small strain moduli to be calculated. This data is important to characterise the ground/pile interaction of the overall turbine structure. Where CPT refusals in harder formations are encountered the PS Logger® continues to provide a stiffness profile.

In conjunction with the PS Logger® a 3-Arm Caliper probe may also be run. This gives a profile of borehole diameter and provides natural gamma data for the formation. The diameter is used to provide QC for any other probes, most importantly the PS Logger®, so that any washout zones in the borehole are identified. The natural gamma can give high vertical resolution of the bed boundaries within the formation.

The High Resolution Acoustic Televiewer probe may also be deployed, usually where harder formations are expected, to provide an unwrapped borehole wall image from which fracture and bedding dips and orientation can be easily derived. A "pseudo core" image is also produced, used for depth control and for orientation of rotary cores.

A Formation Density probe measuring in-situ bulk density is a desirable complement to the PS Logger® data for stiffness calculations. However, due to the difficulties around regulations and the impracticality of retrieving a probe lost downhole, this service is usually declined by developers.

The Future of Wireline Logging

Offshore wind farm development continues globally as the electric age replaces the fossil fuel age. The trends are toward bigger turbines for greater efficiency and a gradual move away from the shore, as the easily attainable near-shore sites are being consumed. Floating and hybrid systems are now in the early stages of commercial development which can operate in deep water beyond the range of fixed bottom designs.

Wireline logging will continue to provide data, unobtainable by other means, by adapting where necessary to the deeper water environments. New methods and technologies, such as NMR, are now being actively considered to provide data to support the design of anchorage systems, infrastructure, and cabling placements.

Graham Comber

Geophysical Services Manager
Robertson Geo
www.rgeo-services.com

Expansion of QATAR'S North Field

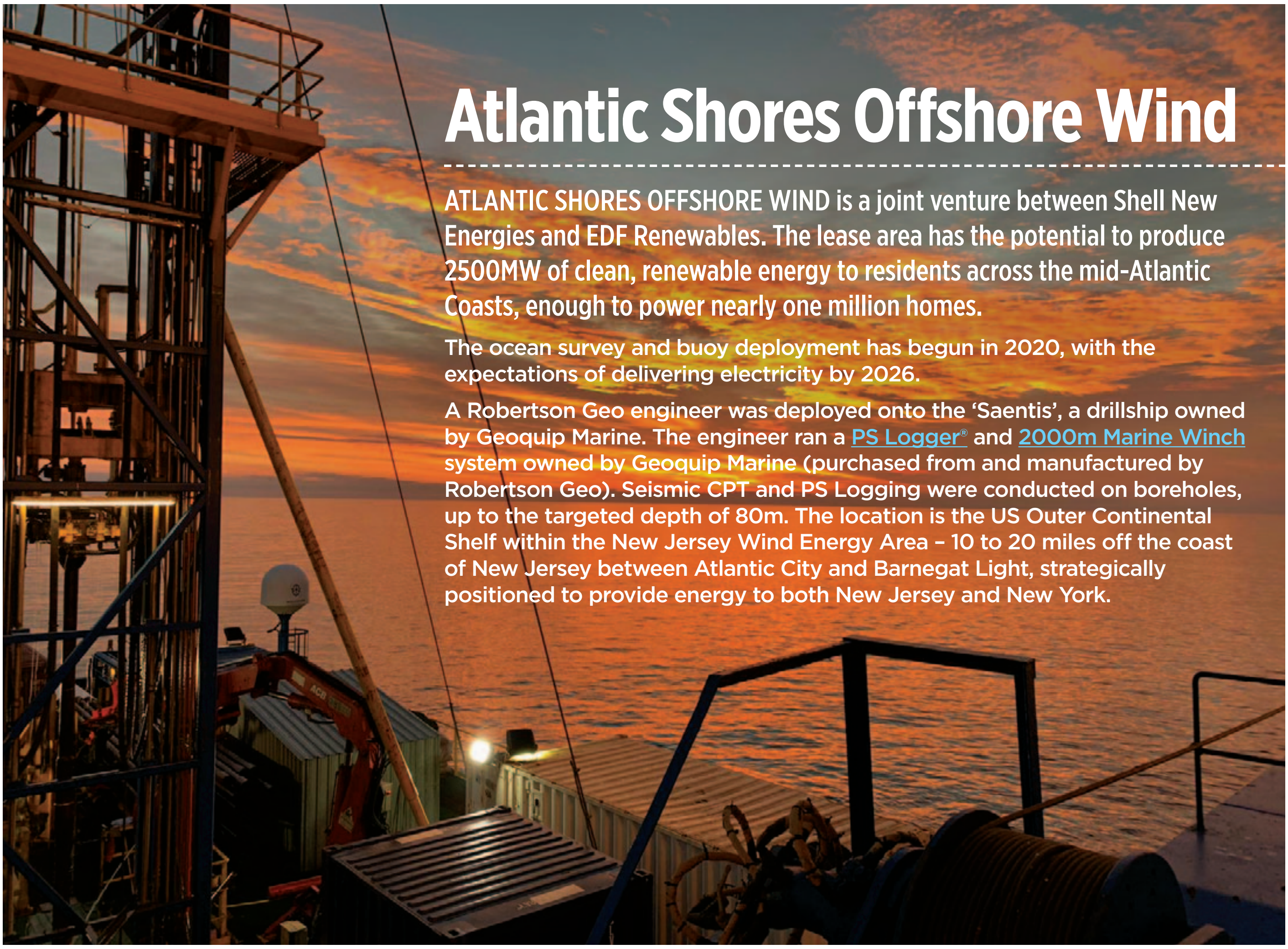
BETWEEN APRIL AND JULY 2021, Robertson Geo Operational Services conducted PS Logging in the Arabian Gulf as part of the geotechnical investigation preceding Qatar's North-Field expansion.

Qatar's North Field is the world's largest non-associated natural gas field; Qatar Gas are increasing extraction here by 43% via the installation of eight wellhead platforms. The locations for seven of these platforms have been investigated by Robertson Geo to advise on their design.

At proposed locations for the wellheads, the PS Logger® extracted data from boreholes up to 160m deep. The geology encountered consisted of intermingling layers of Sands, Clays, Silts, and Limestones, producing Lithologies such as Calcarenite and Calcisilite. This meant data quality became highly variable as depth changed, however a faster sample rate of 10µs for S-wave data ensured greater resolution (and therefore data quality) throughout.

Reprinted from GeoUnlocked issue 15

Drilling and testing was conducted onboard the Quest Horizon.



Atlantic Shores Offshore Wind

ATLANTIC SHORES OFFSHORE WIND is a joint venture between Shell New Energies and EDF Renewables. The lease area has the potential to produce 2500MW of clean, renewable energy to residents across the mid-Atlantic Coasts, enough to power nearly one million homes.

The ocean survey and buoy deployment has begun in 2020, with the expectations of delivering electricity by 2026.

A Robertson Geo engineer was deployed onto the 'Saentis', a drillship owned by Geoquip Marine. The engineer ran a PS Logger® and 2000m Marine Winch system owned by Geoquip Marine (purchased from and manufactured by Robertson Geo). Seismic CPT and PS Logging were conducted on boreholes, up to the targeted depth of 80m. The location is the US Outer Continental Shelf within the New Jersey Wind Energy Area – 10 to 20 miles off the coast of New Jersey between Atlantic City and Barnegat Light, strategically positioned to provide energy to both New Jersey and New York.

Reprinted from GeoUnlocked issue 13

Elia Mog 2 Offshore Wind power
Ostend Belgium

Above: An impression of one of the installations.

ELIA IS PLANNING to develop the Modular Offshore Grid (MOG) 2 project that includes the construction of a new offshore grid infrastructure to connect new wind farms in the Belgian part of the North Sea to the mainland.

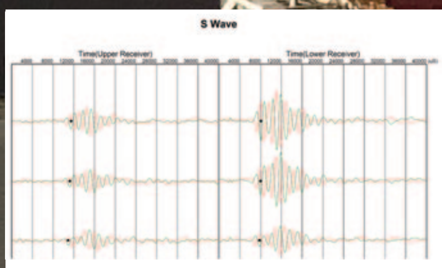
In addition to the MOG 1 project that is currently being developed and expected to bring 2.3 gigawatts (GW) offshore wind power by 2020, MOG 2 project aims to add between 1.7 GW and 2.04 GW. The project is part of Belgium's Energy Strategy to create new zones for electricity production and transmission with the objective to reach a capacity of 4 GW by 2030. The project will enhance the integration of renewables and support the country's climate goals.

The Offshore 2 (or MOG II) project is being developed to provide new grid infrastructure, including high-voltage platforms and cables, for the transmission of electricity generated by future offshore wind farms to the onshore grid.

AS PART OF the preliminary geotechnical surveys, Robertson Geo conducted PS Logger® operations on three 80m boreholes over a seven-week period. The geology encountered was moderately stiff clay for all depths surveyed.

The PS Logger® probe measures P (compression) and S (shear) wave velocities in a single borehole without the need for external energy sources, making it simple and quick to deploy. When combined with bulk density values (from sample tests conducted by the onboard laboratory) small strain moduli (Young's, Shear and Bulk) can be calculated using simple formulae.

Data is logged and processed on site by the Engineer. Full waveforms are recorded digitally at acquisition time across 6 channels (P wave, S wave left & S wave right at the near and far receivers) at a predetermined sample rate as low as 2.5µsec. The sample rate is carefully selected to be as small as possible to provide the best resolution but high enough to capture the arrivals within the listening window. Using the acquisition software, the waveforms can be displayed, scaled and filtered to allow for the picking of the first arrivals at each receiver.



Example of shear wave data.

Reprinted from GeoUnlocked issue 11

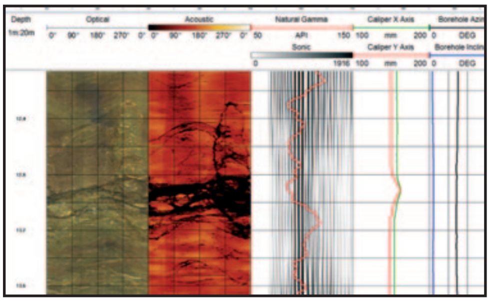
BOREHOLE INVESTIGATION SEAWATER TIDAL

THE CUSTOMER REQUIRED information to assist with constraining parameters for modelling a development and planning of a proposed sea wall and port.

This required logging a framework to investigate boreholes in a shallow water tidal area where the proposed sea wall and marine offloading facility would be constructed off the north coast of Anglesey.

Borehole depth was 10-80m - a suite of probes was used to identify fractures, fault patterns and ground stability, including Optical Televiewer, High Resolution Acoustic Televiewer, Full Waveform Sonic and Borehole Geometry with inbuilt X and Y calliper. Surface equipment was a 2,000m winch with 3/16" core cable, connected to a Micrologger system.

Logging of 26 holes was successfully completed over a period of two months. The Robertson Geo team supported two jack-up rigs, with Engineers on 24 hours availability over the duration of the project. The jack-up rigs were accessed from a small rib boat that docked at nearby Cemaes Bay.



Engineers working on the project were required to undertake an offshore training course.

Offshore in CHILE

THE OUTER PORT project, known as the Puerto de Gran Escala is envisaged to be a major expansion of the existing port infrastructure of Puerto San Antonio, Chile. The proposal involves staged development over a 19-year time span, with an estimated overall cost of $3.4 billion.

When fully completed, San Antonio's outer port will have a breakwater of over 3.9 km long. The design includes an access channel and dredging of the turning basin and the interior harbour to ensure accessibility for E-class container ships, including under unfavourable weather conditions.

Work on the breakwater could begin by 2020, and the geophysical analysis of the immediate subsurface is under way.

Roberston Geo customer Geo Marine commissioned the use of the PS Logger® to collect data from six 40m offshore boreholes; the probe was deployed by a 2000m marine winch. The location was 100m from the shoreline and the MV Investigator was a ship that did not have a dp2 system unlike most drill ships. In the continuous heavy weather four anchors were used to aid the stability of the ship during the logging process.

The data successfully collected was good given the sea state.

Three new Danish OFFSHORE WIND FARMS by 2030

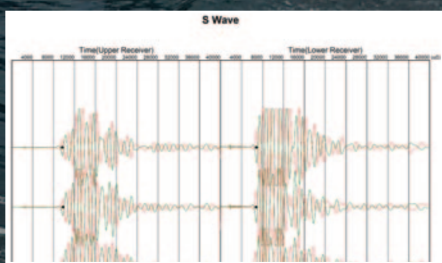
Robertson Geo's 2,000m marine winch secured to the drilling deck with the PS Logger® laid out to its left and ready to be deployed.

BY CONSENSUS OF political parties in the Danish Parliament and as part of the Energy Agreement of June 29, 2018 three new offshore wind farms are to be established before 2030.

Fred Olsen Windcarrier's jack-up vessel Jill is nearing completion of the preliminary geotechnical surveys at the Thor offshore wind project. The wind farm is planned to have a capacity of minimum 800 MW and maximum 1,000 MW and planned to be in full operation no later than 2027. The offshore wind farm will be established in the North Sea, west of Nissum Fjord, some 20 km from shore and will be named "Thor" after the name of the town "Thorsminde".

As part of the preliminary geotechnical surveys, Robertson Geo conducted PS Logger® operations on four 70m boreholes over a two-week period. The geology encountered was mainly moderate to stiff clay with some dense sands, predominately producing excellent data from the PS Logger® with both the compression and shear waves being well defined.

The PS Logger® probe measures P (compression) and S (shear) wave velocities in a single borehole without the need for external energy sources, making it simple and quick to deploy. When combined with bulk density values (from a density log or in this case from core sample tests) small strain moduli (Young's, Shear and Bulk) can be calculated using simple formulae. The data is logged and processed onboard by the Robertson Geo service engineer and further assessed at the HQ by a senior engineer.



Reprinted from GeoUnlocked issue 09

BUSY TIMES OFFSHORE

Atlantic Shores Offshore Wind, US

The versatile 2000m marine winch comes on board the Saentis to deploy subsurface probes at Atlantic Shores.

ATLANTIC SHORES OFFSHORE Wind is a joint venture between Shell New Energies and EDF Renewables.

The lease area has the potential to produce 2500MW of clean, renewable energy to residents across the mid-Atlantic Coats, enough to power nearly one million homes.

The ocean survey and buoy deployment has begun in 2020, with the expectations of delivering electricity by 2026.

The project is located on the US Outer Continental Shelf within the New Jersey Wind Energy Area – 10 to 20 miles off the coast of New Jersey between Atlantic City and Barnegat Light, strategically positioned to provide energy to both New Jersey and New York.

Robertson Geo engineers were deployed onto the 'Saentis', a drillship owned by Geoquip Marine. The engineers ran a PS Logger® and 2,000m marine winch system owned by Geoquip Marine but purchased from and manufactured by Robertson Geo. Seismic CPT and PS Logging were conducted on various boreholes, up to the targeted depth of 80m.

Due to the current pandemic, Covid-19 tests and isolation after testing, were conducted on each individual who was to embark on the ship. Daily temperature checks were also carried out while on-board the vessel and rapid Covid tests were made available on the ship should there be any potential suspected cases.

Coastal Virginia Offshore Wind (CVOW), US

THE CVOW PROJECT is currently the second offshore wind project in the US and is the first project to be installed in federal waters under the Bureau of Ocean Energy Management (BOEM) process.

The project proposal is a three-phase deployment of approximately 880 MW each, with the total capacity of 2640 MW in the commercial lease area. This would make it the largest single offshore wind project in the United States and aims to generate enough clean energy to supply power to 650,000 households at peak wind.

Pending approval, this wind project is scheduled to being construction in 2024 and be completed by 2026. The exact number of wind turbines being deployed is subject to design layout and site conditions but is estimated at 180 turbines. Norfolk, Virginia – 27 miles off the coast of Virginia Beach, site spanning 2135 acres.

The Robertson Geo PS Logger®, 2,000m marine winch, Micrologger 2 and winch controller units were used on this project. Boreholes were logged between the depths of 90m to 120m.

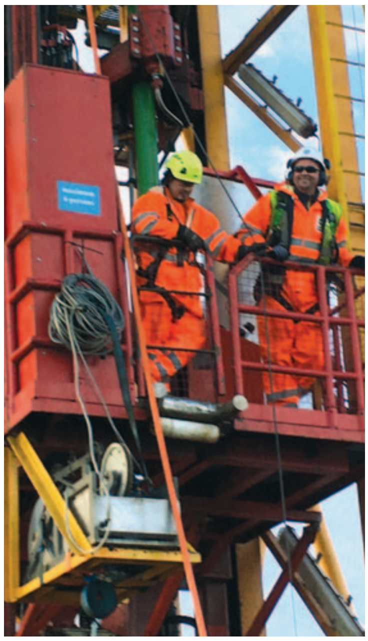
The PS Logger® is a static tool which takes shots at designated depths in order to measure the P and S wave velocities at each targeted depth. Where the ground conditions were deemed stable by the on-board engineers and drillers, data was collected at half meter intervals. In zones of potential instability data was collected at one meter intervals, with sands and clays being predominant across the site. This equipment was deployed from the Geoquip Marine vessel, the 'Dina Polaris' for the initial boreholes. Following which the Robertson Geo engineer was transferred to a second vessel, the 'Saentis' where the remaining boreholes were logged. This was done using a similar system of Robertson Geo equipment, previously purchased by Geoquip Marine.

Hornsea Two Windfarm, Yorkshire, UK

DUE TO BE fully operational in 2022, Hornsea Two will span an offshore area of 462km^2.

Its location is 89 km off the Yorkshire Coast in the North Sea, its proposed 165 Siemens Gamesa 8mw turbines will have the capacity of 1.4GW providing power to well over 1.3 million homes.

Field logging operations were conducted with the winch mounted under the rooster box. The Robertson Geo marine winch remained in this position throughout this phase of the project. Three Arm Caliper, High Resolution Acoustic Televiewer, PS Logger® and Formation Density probes were successfully deployed at multiple locations for sea bed investigation.



TAIWAN

Guanyin Offshore Wind Farm

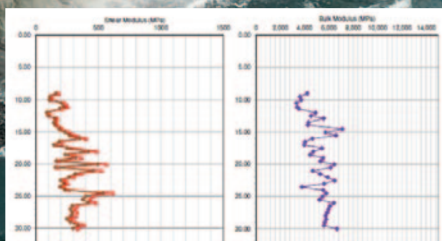
Right: "All aboard" - Kyle Owen, Robertson Geo Logging Engineer, transferring from rig to the jackup vessel on the crew transport basket - that's Kyle on the left!

Taiwan is due to meet its target of renewable energy providing at least 20% of the country's electricity generation by 2025, with 20GW of solar PV and 5.7GW of offshore wind online by the middle of the decade.

THE GUANYIN OFFSHORE wind farm project is planned two kilometers off the coast of the Taoyuan district in the north of the island state, with commissioning planned for 2021/2022.

Robertson Geo was contracted by Horizon Geosciences for the logging of multiple boreholes of 35m depth. The nine week project at the site of the 350MW wind farm was for the deployment of the PS Logger® probe via a 2000m marine winch.

The seabed geology proved to be 0-10/20m conglomerate with 10/20m-35m of sand and clays. For the logging operation between the mud line and 10/20m below (this varied between boreholes) the layer of conglomerate (gravels and cobbles) frequently caused the borehole to collapse. To minimise this and in an effort to obtain as much data as possible the casing string was removed/pulled in 0.5m sections (this would typically be done in 6m sections) with the actual logging



duration taking up to 12-15 hours on some boreholes. This approach was rewarded with the hole staying open for longer than expected in the conglomerate zone.

The acquired data was successfully processed on site by the Robertson Geo engineer, producing small strain moduli when combined with the density values given by the onboard lab on the jackup vessel.

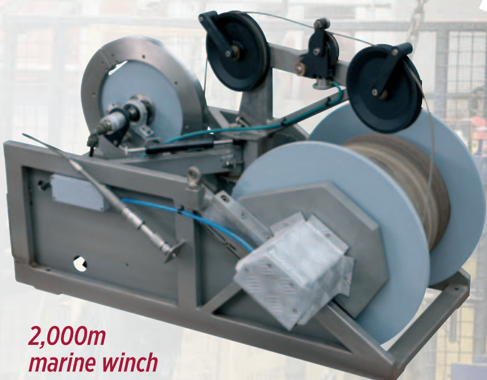
Reprinted from GeoUnlocked issue 08

GETTING THE JOB DONE

ROBERTSON GEO SERVICE engineers are highly trained and fully certified for offshore work.

Logging on offshore locations demand versatility of both crews and equipment to get the job done. Here, the 2,000m marine winch has been suspended in the gantry to deploy geophysical probes for offshore subsurface investigation near New Bedford, Massachusetts, USA.

If you look carefully you can just about see the Robertson Geo logging crew behind the marine winch in this image of the set up prior to logging.



2,000m marine winch

Working experience by Robertson Geo offshore logging crews has led to the introduction of the 2,000m marine winch, designed to resist corrosive and saline conditions. Precision engineered for reliable use in the most challenging offshore applications, the marine winch is fully compatible with the Micrologger2 surface data acquisition system and the full range of probes to depths of 2,000m.

The Horizon Geosciences ship 'Horizon Geobay'.

New Bedford Massachusetts Wind Farm

First large-scale offshore wind energy project in the USA

ROBERTSON GEO IS contracted by Horizon Geosciences for this important project managed by Vineyard Wind LLC.

The objective is to build the first large-scale offshore wind energy project in the USA. The project is divided into two sections, with Vineyard Wind 1 functioning at a capacity of 800MW, enough to generate sufficient energy for one million homes. Vineyard Wind 2, further south is proposed to generate 400MW with the potential to develop a further 800MW at this location.

The Robertson Geo PS Logger® probe has been used for characterisation of the marine subsurface along with a 2,000m Marine Winch, Micrologger2 (the surface interface system for data acquisition) and winch controller system. The equipment was deployed from the Horizon Geosciences drill ship, the 'Horizon Geobay'; a total of six boreholes were completed in May/June 2018, with a further 10 completed in July/August 2019, with depths ranging from 50m to 70m.

Passive Acoustic Monitoring (PAM) in combination with 24/7 visual monitoring for marine mammals is ongoing throughout the project to minimise the disturbance of ongoing drilling and surveying activities on the surrounding marine species. This is especially important off the coast of New Bedford as it is nicknamed 'The Whaling City' as it was one of the most important whaling ports in the world during the 19th century.

THE ROBERTSON GEO 2,000m Marine Winch was securely welded into a steel frame at the beginning of the project. This frame was then strapped to railing on the drill deck when not in use.

Before PS Logging of each borehole, the frame and winch unit is systematically lifted and secured onto the rooster box, and the cable head released down to the drill deck to connect to the probe.

After logging is completed, the frame and winch unit is then lowered back down to the drill deck, where it is secured until the next PS Logging opportunity.

Reprinted from GeoUnlocked issue 07

OFFSHORE WIND FARM DENMARK

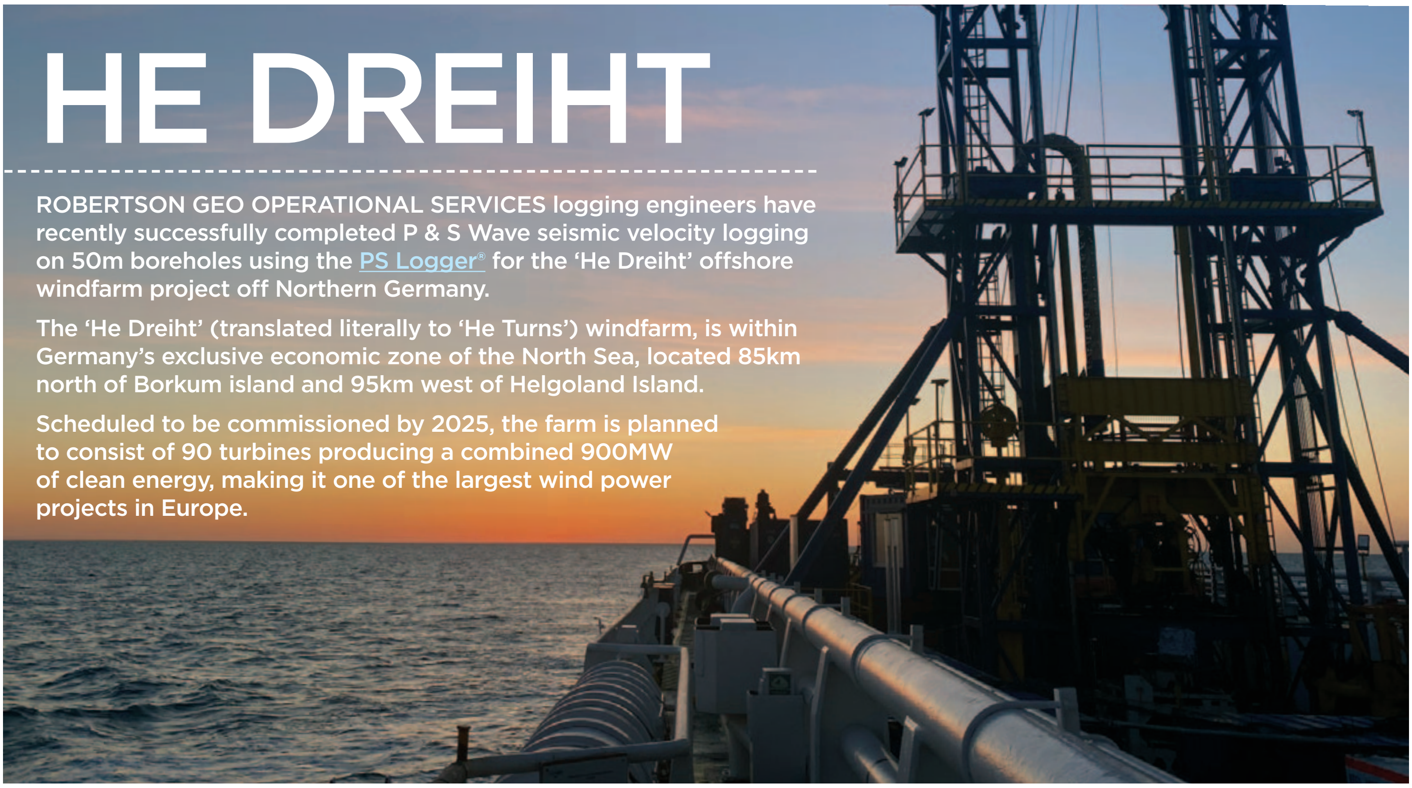
THE PROJECT WAS to investigate the small strain moduli of the sea bed down to 45m using the Robertson Geo PS Logger®. The acquired data would then be used to calculate the parameters for constructing the Vesterhav offshore wind farm off the North West coast of Denmark. The geologic formations were typically sands, clays and mudstone.

Logging was conducted from the support vessel Freja, which has a compensated drilling platform. The PS Logger® provided high resolution, shear wave and compressional velocity data in rock and soils at depths up to 500m, from measurements within a single borehole. Often it proves technically superior and more cost effective than a downhole or cross-hole seismic survey.

Thirteen boreholes were logged over a period of 10 weeks to obtain the P and S wave velocities of the sea bed down to approximately 45m at 1m intervals. These velocities were then applied to the small strain moduli equations with the addition of density, to give Shear, Bulk and Youngs modulus.

The logging probe was successfully deployed with 100% reliability; boreholes were logged from approximately 45m up to the overburden casing. Following logging operations, the operator would quickly process the data acquired. Robertson Geo Engineers were on-board the Freja throughout the project and available for logging through 24 hours each day.

Reprinted from GeoUnlocked issue 01



HE DREIHT

ROBERTSON GEO OPERATIONAL SERVICES logging engineers have recently successfully completed P & S Wave seismic velocity logging on 50m boreholes using the PS Logger® for the 'He Dreiht' offshore windfarm project off Northern Germany.

The 'He Dreiht' (translated literally to 'He Turns') windfarm, is within Germany's exclusive economic zone of the North Sea, located 85km north of Borkum island and 95km west of Helgoland Island.

Scheduled to be commissioned by 2025, the farm is planned to consist of 90 turbines producing a combined 900MW of clean energy, making it one of the largest wind power projects in Europe.

Reprinted from GeoUnlocked issue 12

The versatile Robertson Geo 2,000m marine winch is lifted on board the Omalius prior to it being fixed into its location frame and probe deployment.

This windfarm is *15.5km* off the FIFE COAST of Scotland

The windfarm is estimated to generate on completion 450 megawatts of clean energy, enough electricity for around 375,000 homes (all the homes in a city the size of Edinburgh) and displace 400,000 tonnes of carbon dioxide annually.

It is estimated that over the project's 25-year lifespan, it will contribute 0.6% of GDP (£827m) to the Scottish economy and create thousands of jobs during the construction phase as well as operations and maintenance jobs over its lifetime.

Initial work on the project began in September 2018 on a jack-up rig called the Apollo, where a total of four boreholes were logged using a suite of Robertson Geo specialised probes. The probes involved included the 3-Armed Caliper (3ACS), High Resolution Acoustic Televiewer (HRAT) and PS Logger®, the latter being the most commonly used probe for offshore work. These tools were used for characterisation of lithology, locating fractures and to determine rock strength.

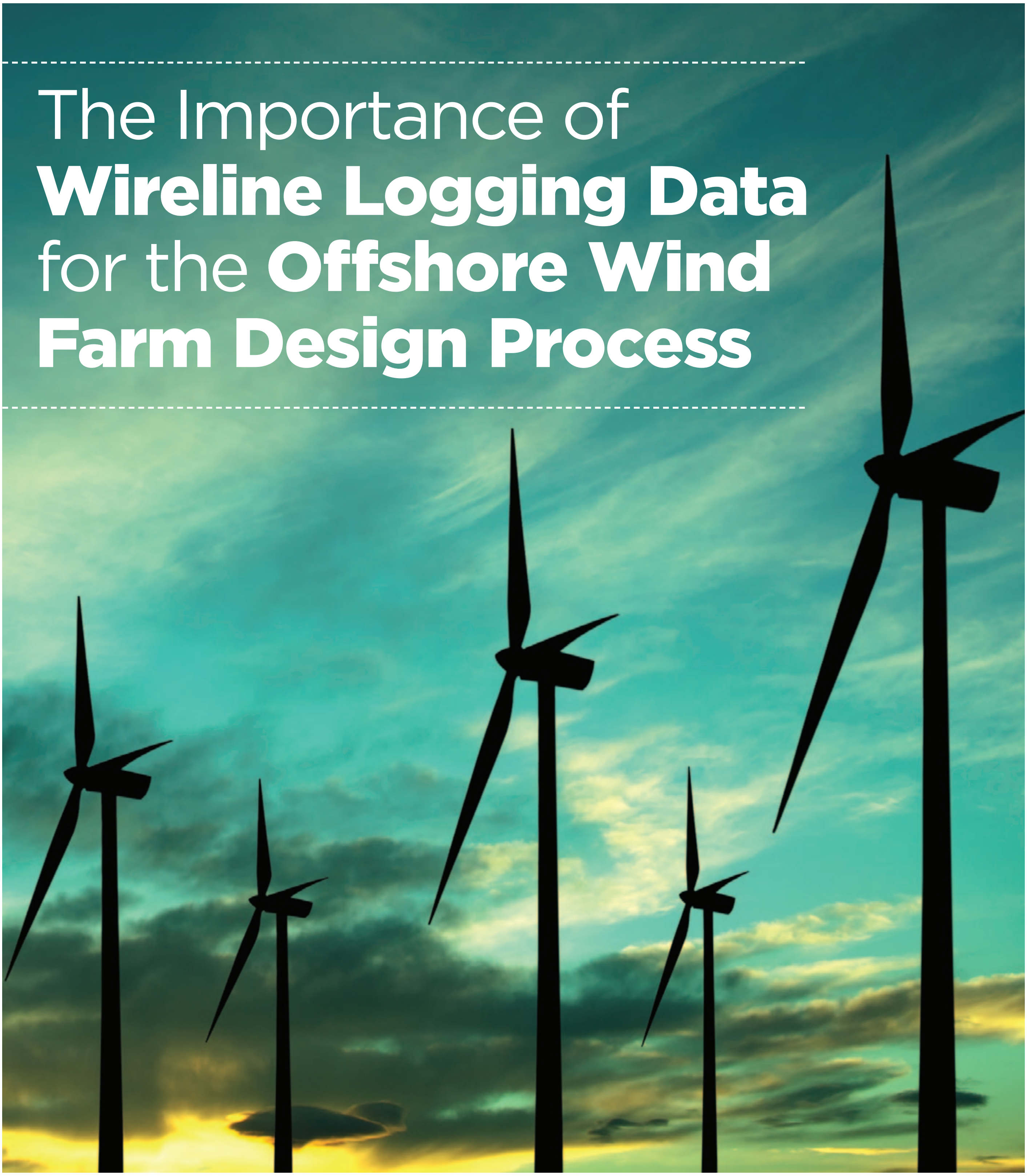
The Robertson Geo 2,000m marine winch, along with the probes and accompanying equipment was then transferred from the jack-up to a drill ship called the Omalius. A further five boreholes were successfully logged on this vessel.

For the Omalius logging application the winch was bolted into a steel frame which was mounted on the underside of the rooster box. The depth cable and data cable were connected to the winch and stored on the rooster box, along with the sheave wheel to reduce the risk of leaning out of the rooster box to reach the winch below. These cables were carefully lowered and fed into a container on deck, where the Robertson Geo Micrologger2, winch controller and laptop system was set up for logging.

Robertson Geo's engineers were actively involved in the project for around two months. Total depth of each hole drilled was 45m.

Reprinted from GeoUnlocked issue 04

The Importance of **Wireline Logging Data** for the **Offshore Wind Farm Design Process**



Introduction

Offshore Wind Farm (OWF) development is set on an unstoppable exponential growth curve as the world moves away from fossil fuel dependency toward zero-carbon targets. The scale of wind farms and the size of their individual turbines are increasing as is the distance from shorelines. Fixed bottom designs, predominantly monopiles, have dominated to date, but as suitable near shore locations are filled future trends will include various other designs including floating systems.

Wireline logging data has been routinely collected for OWF ground investigation on jack-up platforms and drill ships for over 15 years, feeding into the complex design processes necessary for these ever-larger structures.

Specifically, velocity data from the **Robertson Geo PS Logger®** has become a standard component of the geotechnical site investigation.

Offshore wind capacity is expected to grow by at least 235 GW over the next eight to 10 years (Courtesy: ABB).

Histories

The wireline logging technique dates to the 1920's whence the Schlumberger brothers demonstrated the first commercial electric log probe. Analog systems developed for the next 40 or 50 years notably being adopted for oil and gas exploration, with an increased diversity of probes. Robertson Geo entered the slim hole tool market in the 1980's developing digital systems for geotechnical, mineral and water applications. The advantage of this digital system being the plug compatibility of probes using a common winch/acquisition unit set-up.

Although wind power has been harnessed by man for millennia it was in 1978 that the Danish developed the world's first modern multi-megawatt wind turbine at Tvind. Capable of delivering 2MW, it had a nacelle, tubular tower, pitch-controlled wings and three blades and is still running today. All commercial wind turbines resemble this Danish model, a three-blade horizontal axis design, now all rotating clockwise. Denmark also developed the worlds first commercial OWF in shallow waters at Windby in 1991. OWF development has since accelerated through many pilot and small scale schemes to the giant OWF that are common today. UK, Germany and now China are currently leading the way in terms of installed OWF capacity.

OWF Site Investigation Techniques

For any OWF, investigation of the site is essential for all aspects of the development, from wind characterisation through geophysical and bathymetric surveys to sub-surface investigation. In addition to turbine locations there will be cable runs and infrastructure locations to be considered. For a large OWF it may take two seasons (years) to complete the geophysical and geotechnical investigations as they are best conducted separately to avoid interaction.

The collection of data to feed into the wind turbine design process is vital, due to the complex nature of the dynamic and cyclic loading of these structures, to characterise the soil-structure interactions. Regardless of which design approach is adopted, a marine geotechnical investigation (including in-situ and laboratory testing) is essential for a successful design. *See Figure 1.*

The geophysical survey phase of investigation will usually be conducted first and may include unexploded ordnance (UXO) detection from a magnetometer survey. Bottom profiling techniques such as Sonar and LiDAR will be used to map further sea bottom obstacles such as rock outcrops, boulders, and maritime wrecks. With the bottom profiling complete non-invasive investigation of the subsurface can begin using shallow reflection or refraction techniques. These usually require large slow moving vessels towing hydrophone arrays and consideration of the effect of the energy sources on marine mammals will have to be considered. For seismic reflection surveys the P wave velocity profiles from the PS Logger® probe can be used in the conversion of arrival times to depths (for stacking and migration velocities).

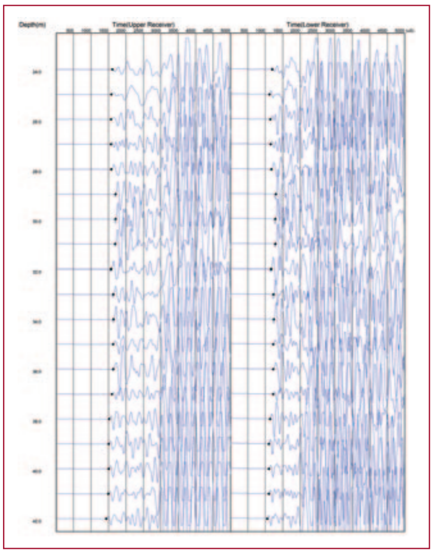
Geotechnical surveys employ invasive techniques and are usually conducted following the geophysical investigations. For shallow near-shore pilot or small-scale sites this was often carried out on small jack-up platforms where the crews were changed each shift. These arrangements also required a variety of support vessels such as tugs for platform movements, safety vessels on standby and crew transfer boats. As distances from shore increased it became impractical to change crews twice daily and larger more expensive accommodation platforms were then deployed, again with support vessels. The use of jack-ups is now mostly confined to areas where draughts are too shallow for drill ships or where tidal runs render their positioning difficult.

Heave-compensated, dynamically positioned drill ships now dominate the OWF geotechnical investigation market. These can operate, relatively economically, without assistance for long periods of time with the main constraint being the weather operating limits. These vessels employ sophisticated drilling systems which combine core sampling and CPT operations with the drilling process. Some testing of the cores may take place onboard, but the samples collected are subsequently sent for laboratory analysis where a plethora of tests may be conducted. The CPT testing provides data on tip resistance, sleeve friction and pore pressure from which many useful design parameters are derived. In addition, seismic CPT (SCPT) tests may also be conducted, involving the use of a separate seabed frame, as well as SPT or pressure meter tests.

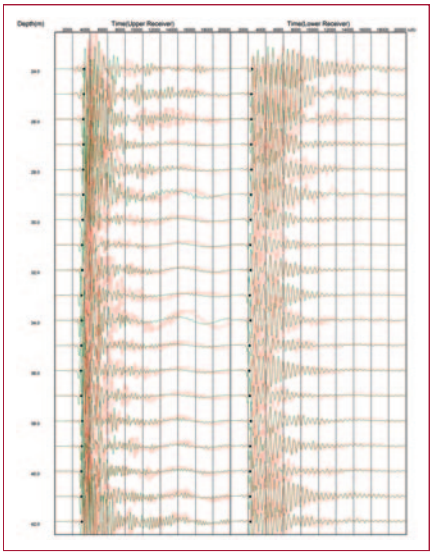
Once the borehole has reached target depth wireline logging is performed on the completed borehole, usually in stages to ensure maximum coverage. The PS Logger®, now a standard requirement for European and USA OWF, is run to provide P wave and S wave velocity profiles, often in conjunction with a caliper for QC purposes. The benefits of the PS Logger® are that it provides high quality data at the deeper sections of the borehole due to its integral energy source and provides information in rocks, pebbles, and gravels where CPT cannot penetrate. Where more competent

Type	Survey	Method	Deployment	Data Density Coverage
Non-invasive	UXO	Magnetometry	Shipborne / towed buoy	Areal
	Bathymetric	Sonar	Shipborne / towed buoy	Areal
	Bottom profiling	LiDAR	Shipborne / towed buoy	Areal
	Seismic	Shallow reflection/ refraction	Shipborne / towed array	Grid
Invasive	Sub-surface	Push CPT	Ship + seabed frame	Turbine/Infrastructure sites
	Borehole	Sampling, CPT, SCPT, PS Logger®	Jack-up / drill ship	Selected % of sites

Figure 1: Example OWF Site Investigation Programme



P waves logging example (Source: PS Logger®).



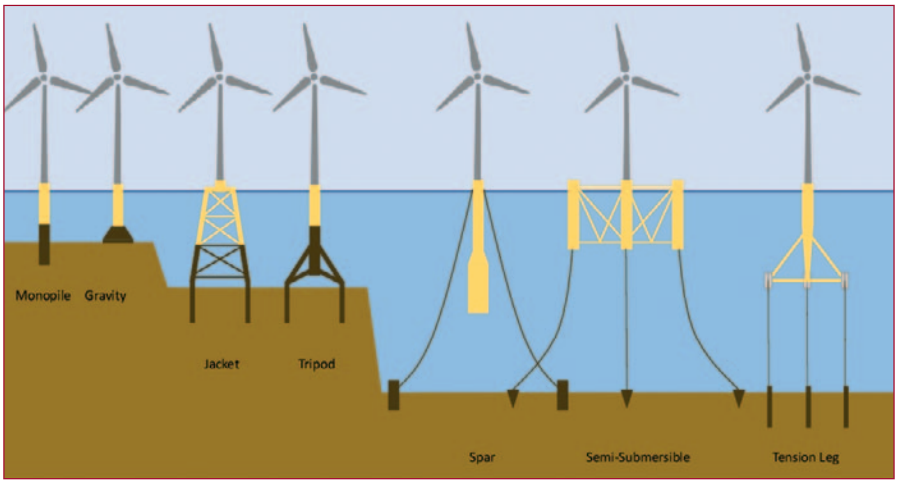
S waves logging example (Source: PS Logger®).

rocks are found an acoustic televiewer may also be deployed to provide borehole wall images showing bedding and fractures. This information is also used to provide core sample depth control and orientation for input into ground models.

As drilling is often only conducted at a percentage of turbine locations it is vital that as much data as possible is extracted by wireline means from each borehole.

Foundation Designs

Practically all commercial scale OWF to date have been of the fixed bottom design, though the transition toward floating systems is underway, in terms of pilot programmes, small scale developments and aggressive future plans.



Types of support structure concepts (left to right): monopile, gravity based, jacket, tripod, spar, semi-submersible platform and tension-leg platform.

The fixed bottom designs come in a variety of types but are to date dominated by monopile systems. Monopiles are a well proven and relatively simple concept with low manufacturing costs and well-tried installation methods. They can be constructed in soft and stiff soils equally, but the local soil conditions need to be tested and understood. Monopiles with their high mass to stiffness ratio exhibit large modal deflections in the submerged zone, attract large wave forces and are prone to scour. Nonetheless, these issues, along with challenges in manufacturing, transport, installation and maintenance have largely been addressed leading to a fabulously successful design paradigm that is a leading light in the drive towards a zero-carbon future.

As water depths increase and turbine sizes grow the monopile design has had to scale up to ever larger diameters to support the ever-taller structures. As the limits of scalability are reached it becomes economic to consider other designs such as suction bucket foundations, tripods and jacket systems. These compound designs currently represent a small proportion of installed turbines when compared to monopiles but are increasing in popularity. With turbine outputs currently approaching 15MW and with plans already in place for up to 20MW turbines the sheer scale and impracticality of single monopiles to support these structures is already driving designs toward these more modular concepts. It should be noted that tripod and jacket structures place completely different loading characteristics on their multiple foundations when compared to monopiles. Whereas lateral forces on monopiles result in bending and overturning moments in subsurface structures, tripods and jackets convert much of the lateral forces into vertical push-pull effects on the foundations.

Whatever the design paradigm, data from wireline techniques is invaluable for designers to model the soil-structure interactions.

Unique Characteristics of Fixed Bottom Wind Turbine Design

Offshore wind turbine foundation design presents many unique challenges for designers, manufacturers and installers. Large offshore wind turbines (OWT) are tall, have high rotor nacelle masses (RNA mass), are relatively flexible and are subject to a variety of dynamic and cyclic loads. Issues of scalability are also important as loading characteristics change as diameters (and therefore stiffness) increase whereby the significance of flexural bending modes may be diminished relative to overturning moments. The main purpose of a foundation is to transfer loads safely without excessive deformation to the surrounding soil. The behaviour of saturated soil under cyclic and dynamic loading is very complex and therefore the design of the foundations for these structures is challenging.

The loading characteristics on OWT includes dynamic components from aerodynamics, waves and current and soil interaction as well as cyclic loads from the blade rotation. This loading profile results in lateral loads, bending moments, rotational moments/overturning moments and sway and rocking modes of vibration.

The design of the overall OWT must ensure that the natural frequency of the structure avoids the frequencies of the cyclic loading and therefore avoids resonance. Analysis of the spectra of the dynamic and cyclic loading shows wind having the lowest frequency range, waves next lowest, then rotor frequency (1P) and finally blade passing frequency (3P – for 3 blade turbines), *see Figure 2*. Bending modes of the tower together with the top RNA mass allow the sway-bending modes of the system to be determined. The foundation is very stiff axially when compared with the tower and effectively the tower vibrates, and the foundation provides stiffness and damping. The overall design frequency of the system should avoid the blade rotor frequencies and can be in the Soft-Soft, Soft-Stiff or Stiff-Stiff zones with many designs using the Soft-Stiff region.

The design of OWT foundations is based on many design tasks and analyses of design criterions in order to ensure that the relevant design limits are not exceeded, and the allowable turbine specific natural frequency ranges are maintained. Multibody Dynamics and the Finite Element Method are popular tools employed in the design process with data from the ground investigation

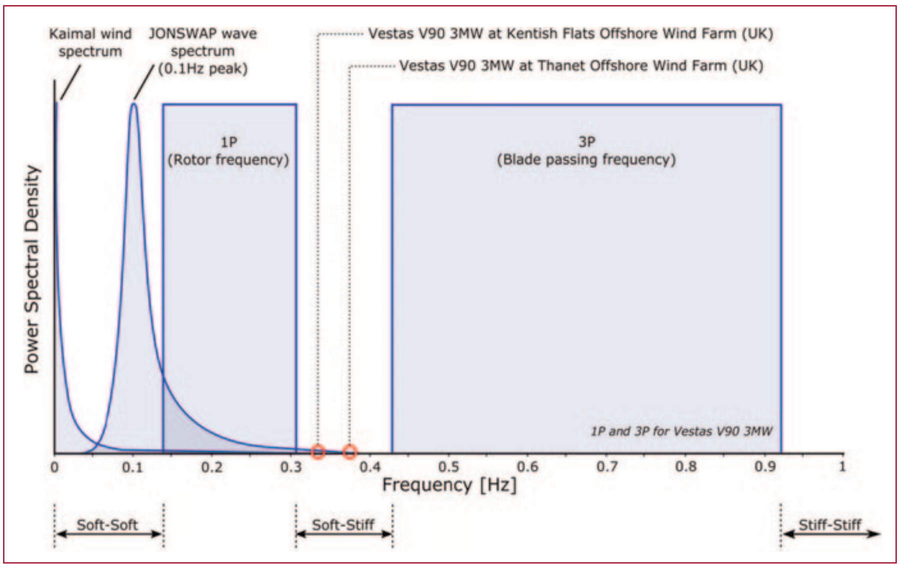
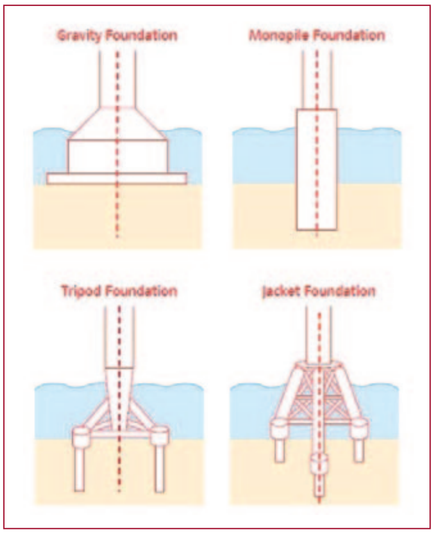


Figure 2: Example Power Spectra for OWT Design (Source: www.surrey.ac.uk).

being essential for analysing the soil-structure interactions. The modes of vibration will dictate the interaction of the foundations with the supporting soil. Furthermore, if the soil-structure interaction is understood, the long-term behaviour of the foundation can be predicted.

In European waters the PISA system has been adopted which provides a computational model for the analysis and design of laterally loaded monopile foundations for offshore wind turbines. The PISA system gives P-Y curves which simulate the soil resistance as predefined nonlinear springs. PISA provides a series of nonlinear P-Y curves that vary with depth and soil type giving pile deflection (Y) for a given soil pressure (P) per unit length of pile. For a monopile, the main interaction is lateral pile-soil interaction due to the overturning moment and the lateral load. Conversely, for a jacket, the main interaction is the axial load transfer. Therefore, the soil-structure interactions depend on the choice of foundation and how the soil surrounding the pile is loaded. The provision of sufficient damping is critical for offshore turbines to prevent excessive fatigue damage over the lifetime of the structure.

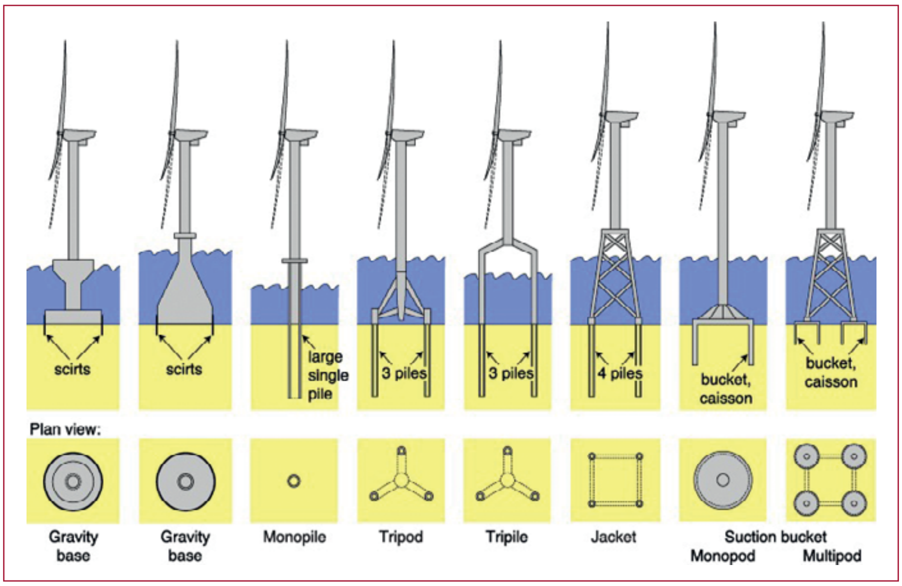
In addition to analysing stresses and determining natural frequencies there are many other factors that need to be considered for a successful design. These include turbine size, choice of foundation type, foundation installation methods, scour mitigation and supporting infrastructure, such as substations and cable runs, and environmental considerations.



Offshore wind turbines foundation types.

Wireline Data

The collection of wireline data now forms an integral part of the overall geotechnical investigation for OWF. The PS Logger® is now considered to be invaluable due to its ability to provide high quality velocity profiles for foundation design and has been adopted across UK, Europe, USA and Asia. Ease of deployment, reliability and the ability to collect data through formations that are impenetrable to CPT make it a go to technology for many OWF developers.



Fixed Bottom Designs.

Caliper logs are now commonplace to provide quality control for the PS Logger® when borehole conditions are less than ideal.

Where more competent formations are encountered the acoustic televiewer has been deployed to provide core orientation and depth control and for input into ground models. For the future, NMR technology is being considered as it gives detailed hydrogeological information, not easily obtained by other means, and raises the possibly for the derivation of in-situ density profiles. A notable benefit of the wireline system is that the same surface set-up can be used for a variety of probes, important for drill ship operation in the adverse environmental conditions encountered far from shore. *See Figure 3*.

The Future

With a proven track record for reliability and data quality in the OWF market, wireline systems will continue to provide data which is difficult or impossible to collect by other means. Robertson Geo Operational Services provide turnkey solutions for the hazardous environment of drill ship operations, all but eliminating attributable lost time. As offshore wind farms grow in size and move ever further out to sea, eventually embracing floating structures, wireline logging can continue to provide invaluable data for turbine locations, infrastructure sites and anchorage points.

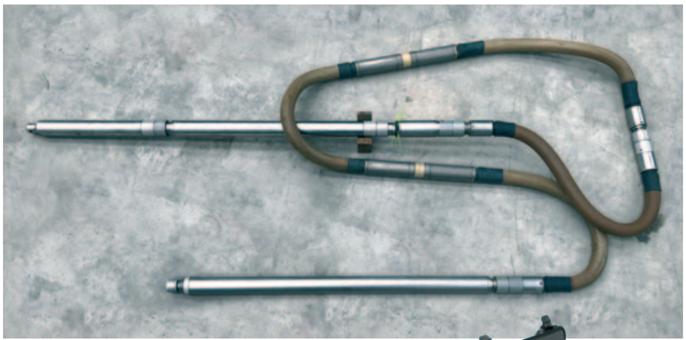
Graham Comber
Geophysical Services Manager - Robertson Geo

Probe	Outputs	Example Usage	Comment
PS Logger®	P wave velocity	Conversion of reflection data times to depths	
	S wave velocity	(+ P) Calculation of Poisson's ratio	
	Poisson's ratio	Soil type classification Elastic modelling	
	Shear modulus	Small strain moduli for elastic modelling	Requires density
	Young's modulus	Calculation of damping ratios	
	Bulk modulus	Calculation of settlement and rigidity	
Caliper	Borehole diameter	QC for PS Logger data	
		Identification of weak layers	
	Natural gamma	Bed delineation	
Acoustic Televiewer	Unwrapped image	Core orientation and depth control	Mainly for competent rocks
	Bedding and fracture Dips and azimuths	Ground modelling	
NMR	Porosity	Hydrogeological modelling	Proposed usage
	Pore size distribution		
	Mobile water content		
	Capillary water content		
	Clay based water content		
	Permeability		
	Transmissivity		

Figure 3: Example Wireline Data Outputs

PSLogger® since 79

Today the PS Logger® is routinely deployed for major civil engineering and offshore projects as the industry reference go to probe for determination of soil and rock strength.



PS Logger® is a registered trademark of Robertson Geologging Ltd.

Industry Reference P & S Wave Velocity Determination from a Single Borehole

The PS Logger® is a unique sonic probe that determines P and S wave velocities from a single borehole without the need for an external source. Excellent data can be achieved across the spectrum of strata from unconsolidated sediments to the hardest of rocks. With minimal borehole preparation required and a high tolerance to surface noise the system has become the industry reference method for subsurface stiffness determination for many large civil engineering projects.

> *Since 2010 and especially within the last 5 years the PS Logger® has been increasingly adopted for many civil and linear infrastructure projects, in preference to a conventional sonic probe.*

History

The PS Logger® was developed in the 1970's by the OYO Corporation to provide a full waveform tool that would produce reliable P and S wave velocity measurements in unconsolidated materials and rock formations at depth. The initial application was micro zonation, to characterise earthquake-prone zones with respect to geological and geophysical characteristics. From this beginning, the probe found applications for civil engineering projects in Japan and Asia.

In the 1980's the probe was introduced to the USA and was soon adopted for use in research projects, and since 1990 has seen ever-increasing use for bridges and dams, linear infrastructure, and power plants. The nascent Offshore Wind Farm (OWF) industry in NE USA has also adopted the PS Logger® as its preferred method for velocity determination.

In the late 1990's Robertson Geo began to promote the technology in Asia and the emerging Gulf markets for their growing and ambitious infrastructure projects, both onshore and offshore. This led to Robertson Geo updating the older OYO analogue technology and launching the first generation digital PS Suspension Logger 2003. Some of the major Gulf operators then adopted the technology for projects globally, including Europe and the developing OWF industry.

By 2010 Robertson Geo took over the manufacture and future developments of the PS Logger® from OYO and followed increasing global adoption. The PS Logger® method could be easily accommodated on jack-ups and drill-ships, so the tool became the method of choice in the OWF industry. On land, applications were initially confined to only the largest civil engineering projects such as nuclear power plants. In recent years the PS Logger® has been increasingly adopted for many civil and linear infrastructure projects, in preference to a conventional sonic probe.

Advantages over Other Methods

There are numerous alternative methods and variants thereof for determining in-situ P and S wave velocities for stiffness determination including: refraction survey, reflection survey, surface wave methods, crosshole method, downhole method and seismic CPT. While each method may have its place depending upon the data required, site constraints and budget considerations, the PS Logger® provides a simple cost-effective alternative.

Purely surface based methods obviate the need for any boreholes but may be limited by noisy environments and site constraints. The crosshole method requires multiple boreholes to be drilled and cased as well as a verticality survey to determine borehole orientation.

The PS Logger® requires only a single borehole with minimal borehole preparation and can be run in tandem with the full range of slimline probes. The PS Logger® source has roughly twenty times the power of a conventional full waveform sonic and provides consistent energy delivery at all depths, resulting in a good tolerance to external noise. The frequency spectrum of the source covers 50Hz to 1kHz with 300Hz being the dominant frequency. This allows for high resolution while also providing enough energy to generate shear waves in unconsolidated sediments.

The ray paths used for velocity determination are all vertically polarised giving vertical stiffness and avoiding any complications with anisotropy. The high vertical resolution (0.5m typical) allows for measurement of thin layers and the method is not affected by high velocity layers above low velocity layers.

While eminently suitable for land-based surveys the PS Logger® method with no external source is ideally suited to deployment offshore on barges, jack-ups and drill ships and continues to dominate the OWF market.

Probe Architecture

The PS Logger® comprises a powerful hammer source and two receivers, separated by acoustic damping tubes. To acquire data, the probe is stopped at the required depth and the source is fired under surface command. Known as indirect excitation (conventional sonics use mode conversion), the resultant fluid motion produces a flexural wave at the borehole wall which propagates up the borehole wall.

There are five active sections to the PS Logger® - telemetry, receivers, filter, source and driver.

The telemetry section provides for all communications to the surface unit together with the logic circuitry for probe operation.

The receiver section has two receivers separated by 1m comprising two detectors each, held within a flexible damping tube. As the waves propagate parallel to the borehole axis, they set up corresponding fluid movements that are detected by the two-receiver combination (neutral-buoyancy 3D hydrophone for P waves and horizontally aligned geophone for S waves).

A 1m or 2m filter flexible filter tube separates the source from the receiver section and is designed to eliminate direct arrivals travelling up the probe body.

The source section contains a solenoid-operated shuttle aligned across the borehole axis to strike a cylinder on opposite sides of the probe in turn, setting up a pressure doublet in the surrounding fluid. To allow the correct frequency output, the strike cylinder is engineered so that it is suspended between a pair of 'O' rings and not in direct contact with the main source body. For the same reason the source body is held away from the borehole wall by an arrangement of whiskers.

The driver section contains the electronics necessary to drive the solenoid operated shuttle. For each shot a capacitor connected to the solenoid coil is charged up and then discharged producing a back EMF which drives the hammer. Due to the energy requirement this charging cycle takes several seconds. The process is reversible to be able to drive the hammer in opposite directions.

It is vital that the source and the receivers are aligned to detect the S waves. This alignment is pre-set at time of manufacture with alignment marks being evident on the source and receivers.

Calibration

To ensure that the PS Logger® is conforming to specification a multi-part calibration process is applied, principally at time of manufacture and thereafter at regular intervals.

Firstly, the probe undergoes a physical check including hanging the probe to check source-receiver alignment. Thereafter the communications and electronic functionality are checked through the acquisition software.

Secondly, the probe is run in a test borehole section where there is free standing steel casing of a known reference velocity and the results are checked.

Thirdly, the probe logs the open extent of the test borehole using a predetermined set of varying parameters and the resulting data is picked and compared to standard reference logs.

If all tests are passed satisfactorily then a conformance certificate will be issued.

Probe Deployment

The PS Logger® is plug compatible with the full Robertson Geo range of slimhole probes and can be deployed in fluid filled boreholes to 600m depth from a standard Robertson Geo winch. The probe dissembles into five sections which are packaged in two waterproof cases for transportation.

Once assembled, the probe is inserted in the borehole via a sheave or tripod and the depth reference is set. Unlike most conventional probes the PS Logger® takes its readings statically. At each depth point a series of three shots is conducted, one for P waves and two for S waves. Sample rates, gains, low pass and digital filters are optimised to produce the full required waveforms in the listening window. Readings are taken typically every 1.0m or 0.5m and where external noise is present shots may be stacked to improve signal to noise ratio. The result is velocity profiles for the borehole which can later be combined with a bulk density profile to provide small strain moduli.

"Robertson Geo has an ongoing commitment to certified quality management and is ISO 9001 certified by TÜV. It is the only ISO certified logging services provider, and the only company which comprehensively calibrates all of its logging systems."

Borehole Considerations

The PS Logger® is typically operated in open fluid filled boreholes, though good data can also be obtained in PVC cased boreholes provided they are well grouted. A specification for the grouting can be supplied.

Borehole conditions can dictate data quality with rotary drilled boreholes providing the best data due to low rugosity. Diameter wise, the PS Logger® can produce good data in boreholes from 65mm to 400mm with the optimum range being from 75mm to 200mm. Inclined boreholes can also be logged providing the deviation is no more than 30° from vertical.

Where borehole stability is a consideration, the logging is often split into separate runs whereby the drill string is retrieved in stages. Liaison with the drillers, geologists and geotechnical personnel is required to confirm where the potentially unstable layers are (e.g. gravel beds). A shooting plan can then be drawn up whereby the drill string is withdrawn in stages to provide some open borehole while providing protection for the problematic zones.

Due to the PS Logger®'s tolerance to borehole muds, there is often no preparation required on the borehole. Polymer or Bentonite based muds can be extremely viscous with the limiting factor being the buoyancy of the probe. Where the use of thick mud fails to provide sufficient borehole stability the borehole can be PVC lined and grouted.

PS Logger® Waves

The hammer and strike cylinder arrangement provides what is essentially an impulse source. As the source is suspended in the borehole fluid with no direct contact to the borehole wall, all the energy is transferred to the fluid. The resulting wavefront, on contact with the borehole wall, produces a variety of waves which propagate along the borehole axis. Although all waves will be evident at all receivers to some extent, the receivers are designed to isolate the waves of interest. Low band pass filters are used to allow the desired waves through on each channel.

P Waves or compression waves vibrate along the axis of propagation of the wave energy

P waves are always the first arrival and for the PS Logger® the characteristic frequency is 8-12kHz. As the borehole is fluid filled and the surrounding formation generally saturated, the velocity of the compression wave will always exceed any direct fluid arrivals. The arrival of the P wave is characterised by a sharp onset and the arrival times are usually easy to pick.

S Waves propagate perpendicular to the wave oscillation

S waves are considerably slower than the P waves with a characteristic frequency around 1kHz. These waves exhibit a slow rise time which if superimposed with the decaying P waves means that they are often picked on the first identifiable maxima rather than the onset. For the PS Logger®, S waves are generated in left and right pairs which produces a 180° phase shift between the trace pair aiding unambiguous identification.

Stoneley Waves are wave guided along the fluid/wall interface

Stoneley waves are the last arrivals on the traces and are characterised by having a lower frequency than the S waves and do not exhibit the 180° phase shift as with S waves. These waves are not currently used in the analysis of PS Logger® data.

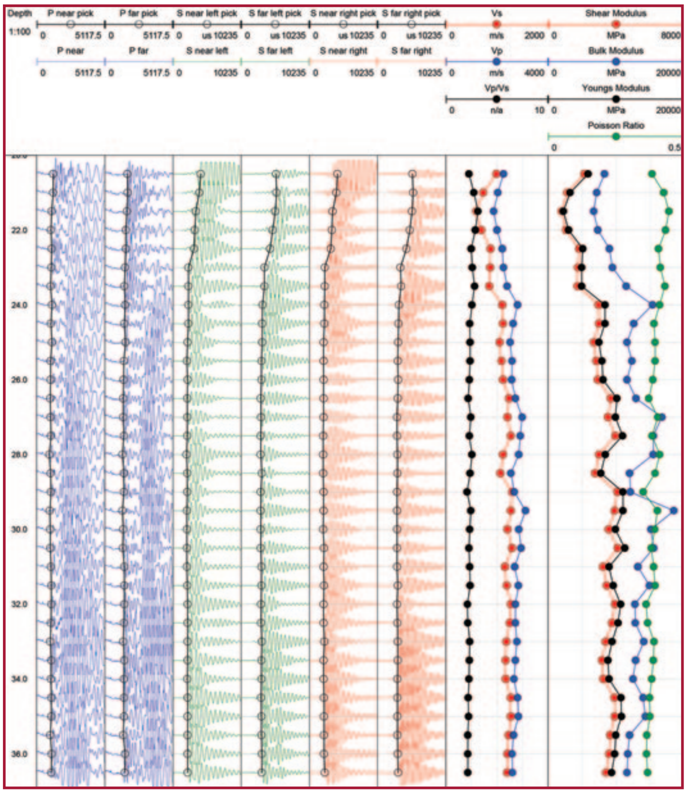
P waves are always the first arrival and for the PS Logger® the characteristic frequency is 8-12kHz.

S waves are considerably slower than the P waves with a characteristic frequency around 1kHz.

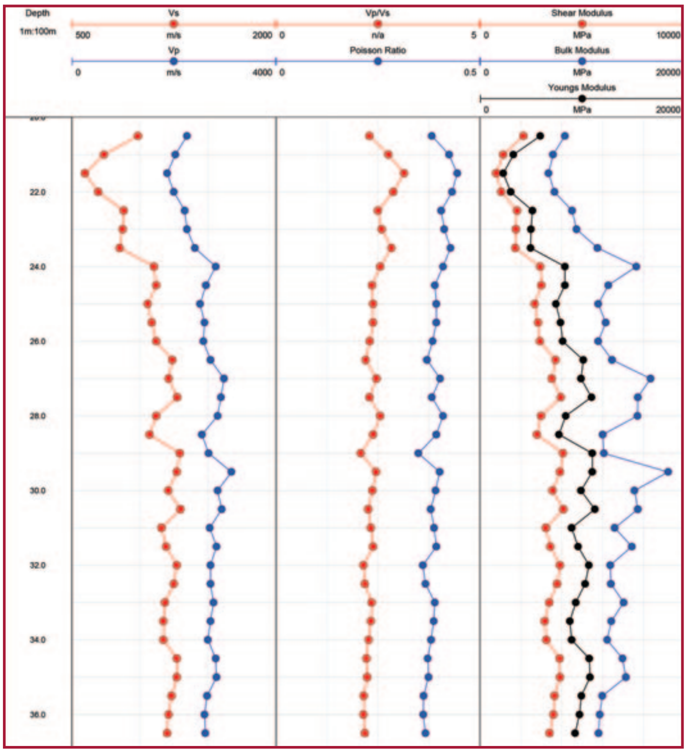
Data Processing

Full waveforms are recorded digitally at acquisition time across 6 channels (P wave, S wave left & S wave right at the near and far receivers) at a predetermined sample rate as low as 2.5µsec. The sample rate is carefully selected to be as small as possible to provide the best resolution but high enough to capture the arrivals within the listening window. Low pass filters can be applied at acquisition time and digital filters can be applied during or post acquisition.

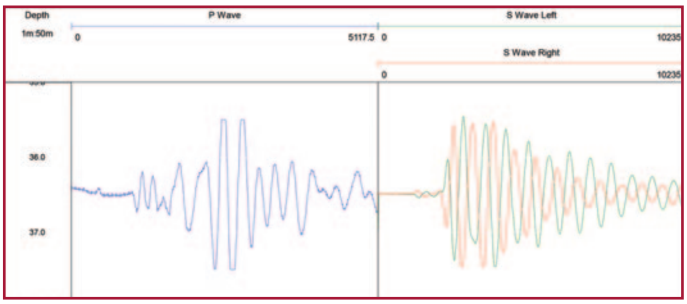
Using the acquisition software, the waveforms can be displayed, scaled and filtered to allow for the picking of the first arrivals at each receiver. Automated picking is available but in most cases the arrivals are picked manually by experienced engineers. While the P wave arrivals are generally simple to pick, the S waves with their typically slow onset and possible superposition over the decaying P waves benefit from an experienced eye to avoid 'cycle skipping'. From the receiver separation (1 metre) and the arrival times the velocities are automatically calculated. An option to output the data in SEGY format is also available.



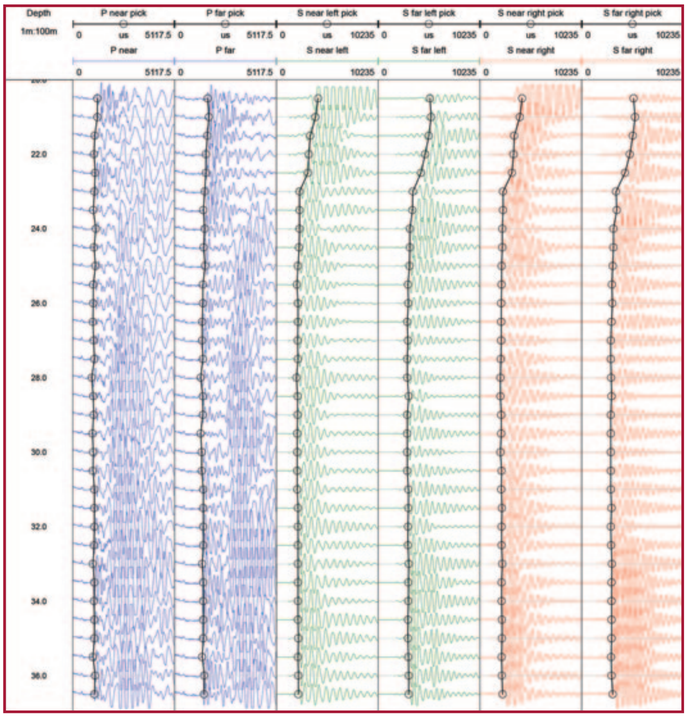
Full PS Logger® Output



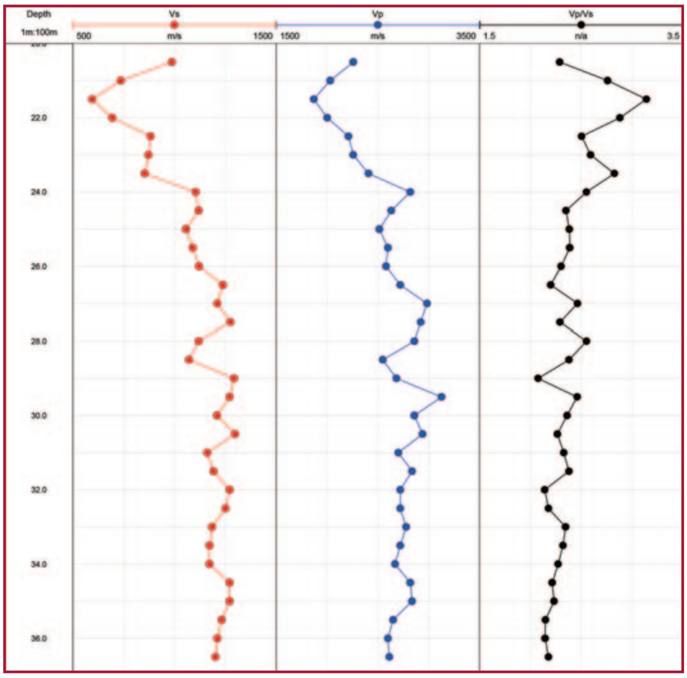
PS Logger® Derived Data



PS Logger® Single Waveforms



PS Logger® Waveforms



PS Logger® Velocities

Once the arrival times and velocities have been determined, the data is opened in a second program (also supplied with all PS Logger® systems) that creates and manipulates logs of the data. If a bulk density profile by depth is available it can be combined with velocities to give the small strain moduli and Poisson's ratio. Finally, all data can be outputted in industry standard LAS format.

Small Strain Moduli Calculations	
Given: P wave velocity Vp, Shear wave velocity Vs and bulk density ρ	
Poisson's Ratio	v = ((Vp/Vs)^2 – 2) / (2*(Vp/Vs)^2 – 2)
Shear Modulus	G = ρ*Vs^2
Young's Modulus	E = 2*G*(1 + v)
Bulk Modulus	K = E / ((3*(1 - 2*v))

PS Logger® Development

Robertson Geo is investing significantly into further development of the PS Logger®, drawing on over 40 years of experience in manufacturing and global field operations. The application of this knowledge and know how will ensure the technology is continuously evolving and delivering high value and proven geodata for some of the biggest projects in the world, and is the default trusted technology of choice for offshore wind developments.

In addition to direct development of the PS Logger® Robertson Geo have also developed a marine resistant winch and associated components in response to the demands for PS Logging on offshore wind farms.

How to Engage with the PS Logger®

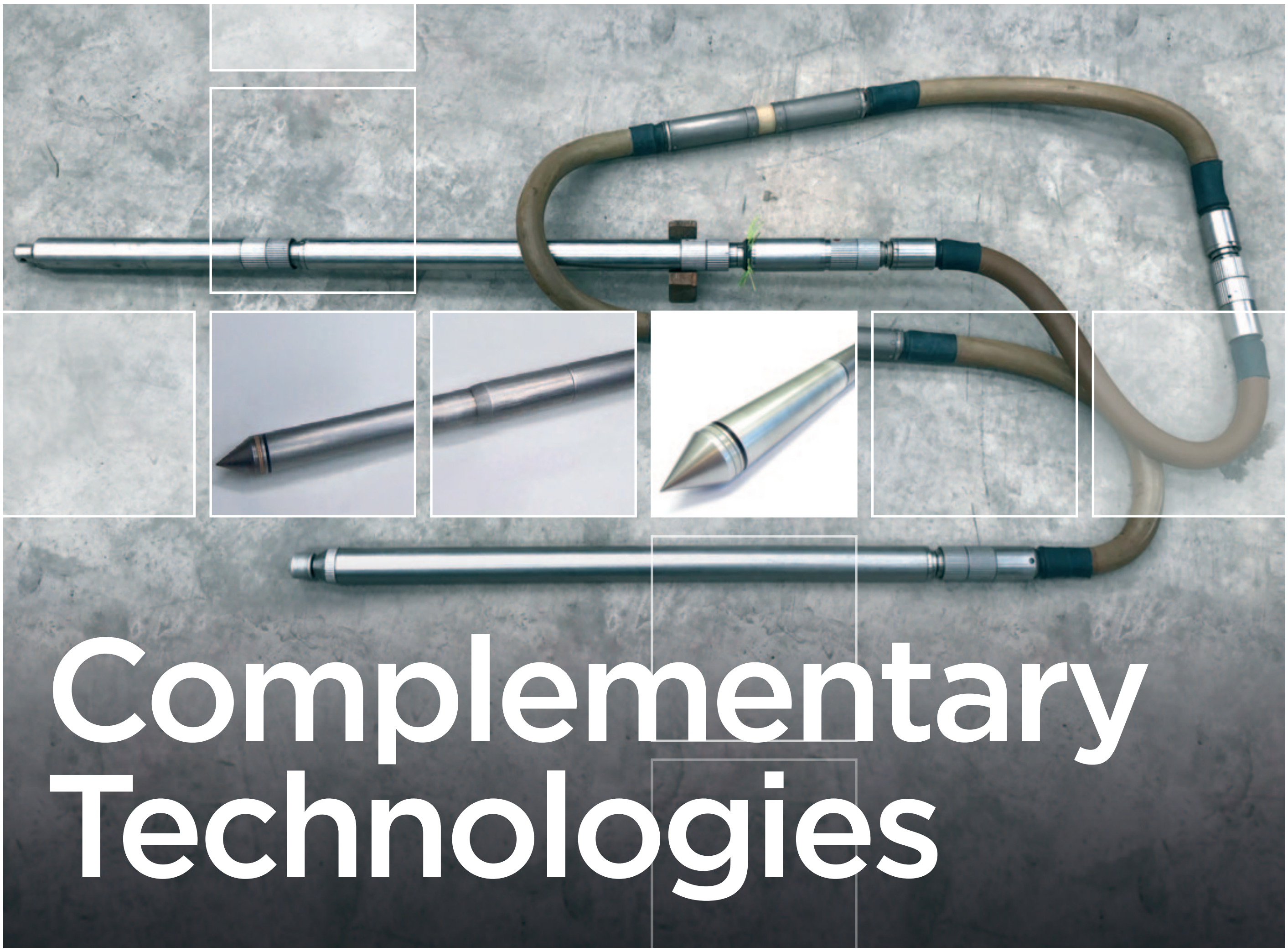
The PS Logger® is manufactured exclusively by Robertson Geo and is available as a full turnkey service, for rental or for outright purchase.

RGeo Operational Services have a team of ten engineers available to provide a full turnkey service anywhere in the world, in any environment, including deployment on heave compensated drill ships and jack-ups. A full range of slim-hole tools is also available which will run on the same surface system. From planning thorough mobilisation to acquisition and processing our experienced professionals will deliver a project that is fully certified together with full back-up and support.

PS Logger® systems are also available for rental from RGeo Operational Services to those clients who have the required in-house expertise. Full training programmes can also be arranged for client staff.

PS Logger® systems are available for purchase from our sales divisions based in UK, USA and Asia.

> *From planning thorough mobilisation to data acquisition and processing our experienced professionals will deliver a project that is fully certified from any global location, together with full back-up and support.*



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.

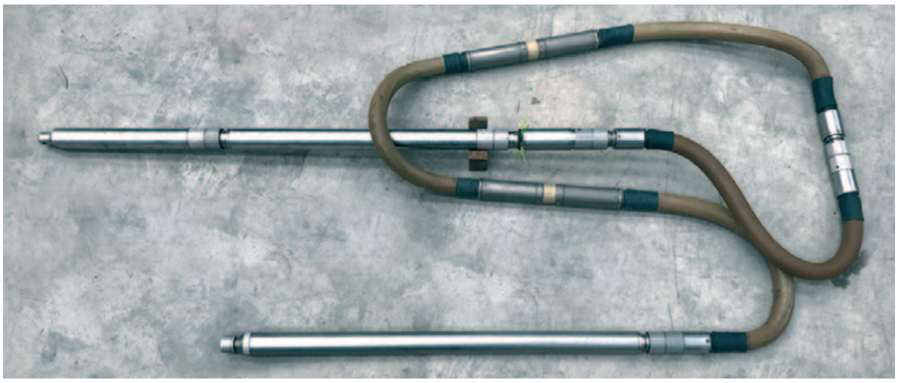
More accurate soil parameters for modelling loading response gives benefits in cost reduction due to better optimised foundation designs.

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 cohesion 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,



The Robertson Geo PS Logger®.

inclination, video and magnetometry can also be embodied within the cone.

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.

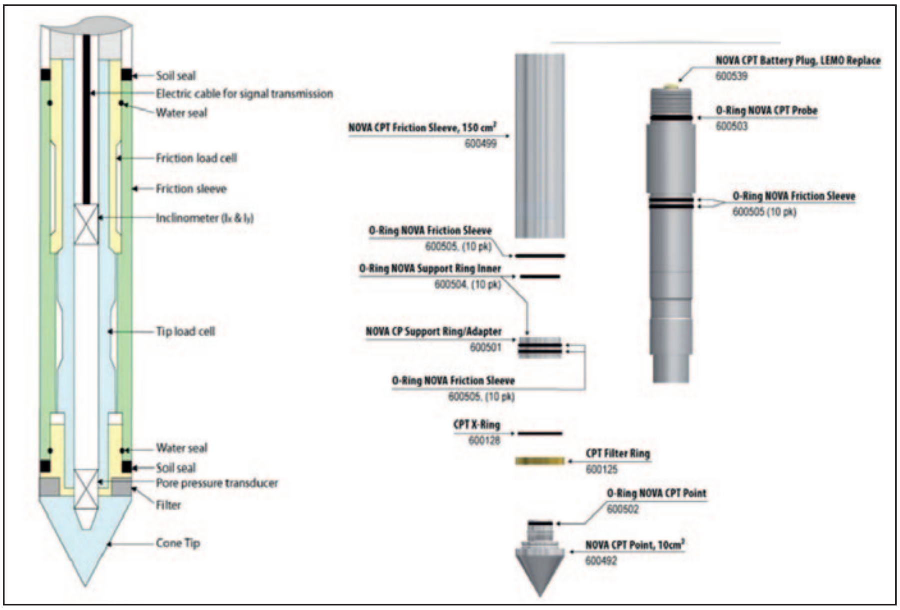
The PS Logger® (a registered Robertson Geo Trade Mark) was originally developed by the OYO Corporation in the 1970's to provide a full waveform tool that would produce reliable P and S wave velocity measurements in unconsolidated materials and rock formations, at depth, from a single borehole. The initial 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).

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

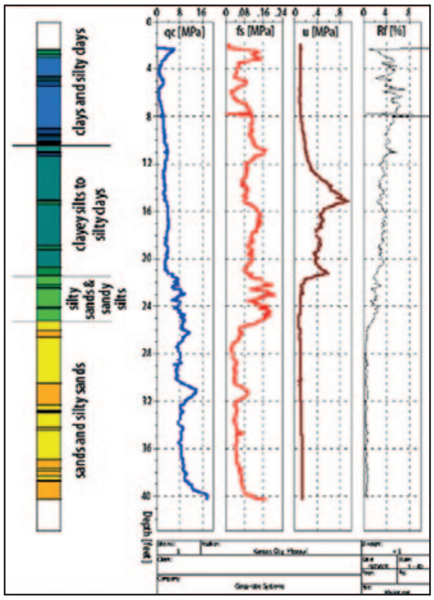
Comparison of PS Logger® versus SCPT for Offshore Ground Investigation

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

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

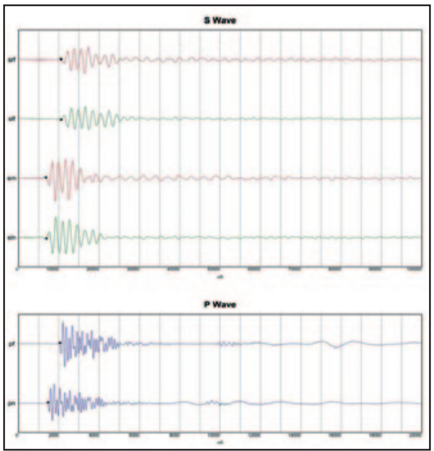
The CPT method uses a hydraulic rod fitted with a cone which is pushed vertically into the ground at a controlled speed. The sensors in the cone provide profiles, at centimetre resolution, throughout. As the cone penetrates it forces failure of the soil about 40cm ahead of the tip. The tip resistance 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.

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.

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