Moray Firth West OWF set to Power 640,000 Homes.

Aflandshage Offshore Windfarm, situated in the Baltic Sea.

Offshore Wind Farm Client Training with Robertson Geo.

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Offshore Wind Farm issue

ROBERTSON GEO SERVICES
MARINE GEOTECHNICS

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

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 Services (RGS) have undertaken 60 OWF projects across 51 wind farms globally. 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.

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.

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Image: Shutterstock

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.

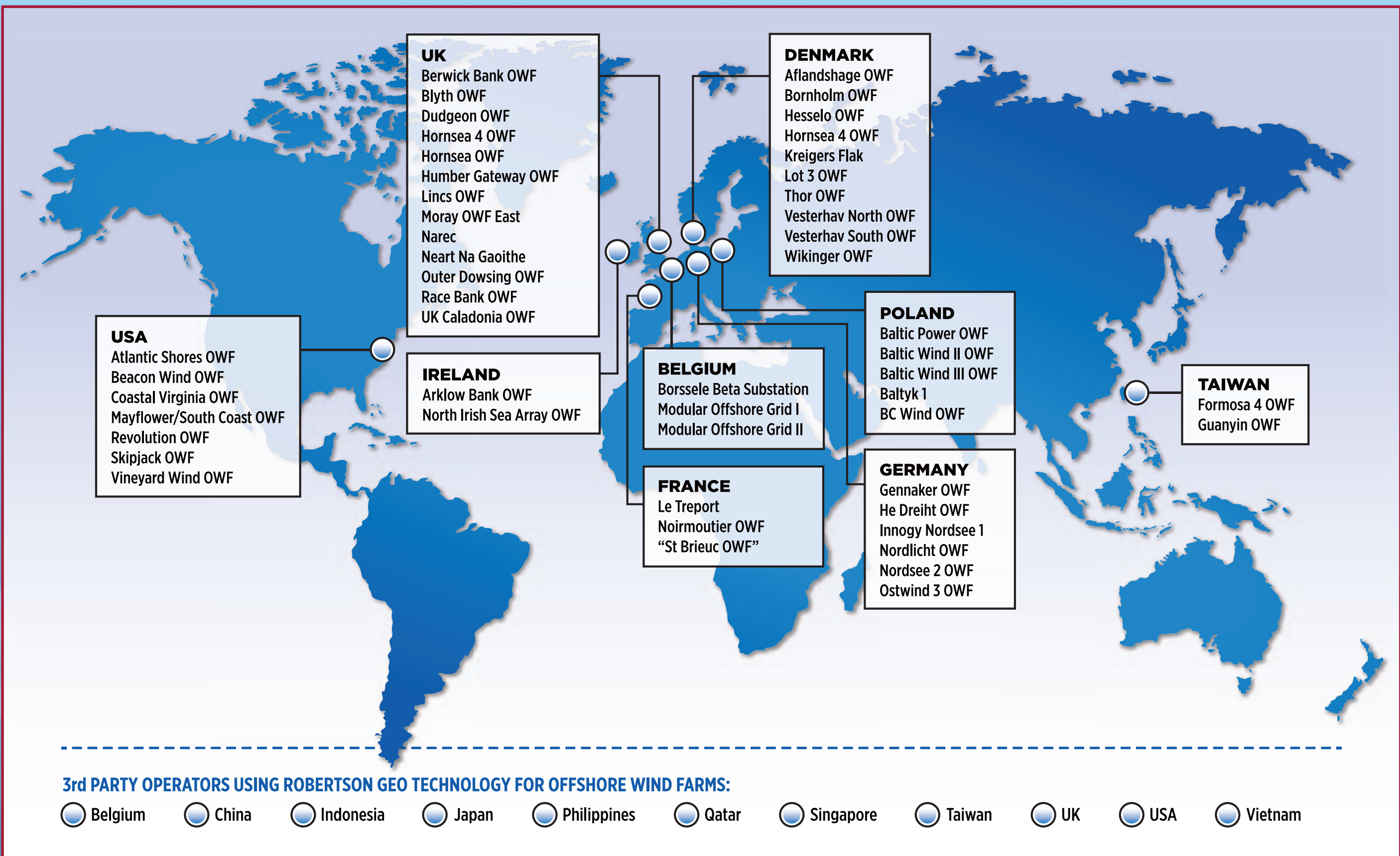
The PS Logger® has also continually evolved to better meet the needs of the OWF environment. Changes to the power system, electronics, hardware design and sensors have all been implemented alongside changes to materials whereby titanium components are now replacing stainless steel for enhanced corrosion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

Robertson Geo Services Global Offshore Experience.



Windmill park Westermeerwind, the largest offshore wind farm in the Netherlands.
The wind farm can produce 1.4 TWh of electricity, enough to provide electricity to over 400,000 households.

Global Rental Service

Robertson Geo Services (RGS) 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.

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.

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.

Global Turnkey Service

Robertson Geo 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.

Image: Shutterstock

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

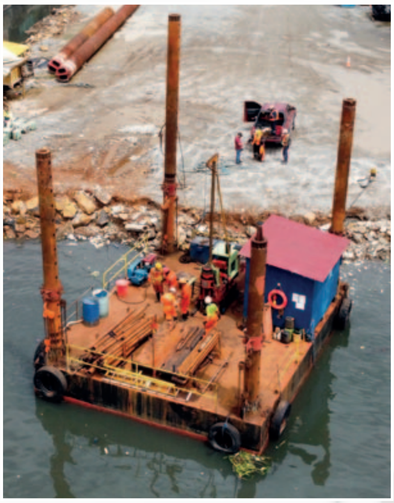
Geotechnical Adviser - Robertson Geo

> *"Logging was part of the Geotechnical Investigation package of Sol Roche Geotechnical Consultancy Corp. for the project which included boreholes and undisturbed sampling."*

SRGEC

PS Logger® testing residual soil for Reclamation Projects in Manila Bay

PHILIPPINES



The Robertson Geo PS Logger® was used in many different reclamation projects around Manila Bay, it was used to test the properties of the residual soil belonging to the Guadalupe Tuff Formation.

The logging determined the dynamic properties of the foundation soils and/or rocks. The analyses of the test was done to determine the following dynamic soil/rock properties:

- *Elastic Moduli*
- *Poisson's ratio*
- *Vp and Vs profiles*

With the site area located in a relatively shallow water environment (1 to 10m of water), Robertson Geo client Sol Roche used jack up pontoons as a stable platform in which to conduct the PS Suspension Logging. The Robertson Geo PS Logger® probe was deployed using a surface winch with the data being compiled via the Micrologger2, the surface interface system for data acquisition. The PS Logger® is a full waveform acoustic probe, designed to measure compressional and shear wave velocities in soils and rock formations. It operates using indirect excitation rather than mode conversion as in a conventional sonic.

The logging was part of the Geotechnical Investigation package of Sol Roche Geotechnical Consultancy Corporation for the project which included boreholes and undisturbed sampling, Field Vane Shear test and (seismic) Cone Penetration test.

The residual soil layer was characterised by very stiff to hard, dark brownish grey to light brown, sandy to silty clay. It is made of the in-situ weathering and alteration of volcanic ash/tuff as evidenced by the preservation of the relic vesicular texture. Some samples belonging to this layer showed altered/weathered breccia and agglomerates appearance with clasts made up mainly of scoria and glass fragments. Being residual soil in nature, transition to highly weathered and highly fractured brown to brownish grey siltstone appearing as rock fragments.

The weathered rock layers of the Guadalupe Formation is made of:

SANDSTONE (Lappillistone and Lappilli Tuff): Very weak to weak, brownish grey to dark brownish grey, mottled in some parts, silty fine to coarse sandstone. Some parts are highly weathered and highly fractured.

SILTSTONE/CLAYSTONE (altered Volcanic Tuff): Very weak to weak light brown to brown, occasionally brownish grey tuff. Highly weathered and grading to residual soil in some parts.

CONGLOMERATE (Breccia and Agglomerates): Very weak to weak, mottled light brownish grey and dark grey conglomerate. The clasts are made up of sub angular to sub rounded scoria, andesite and basalt fragments embedded in a tuffaceous matrix.

Each distinct layer represents different episodes of pyroclastic emplacement/deposition.

Sol Roche Geotechnical Consultancy Corporation: www.srgec.ph

Moray Firth West OWF set to Power 640,000 Homes in SCOTLAND

2,000m Marine Winch secured in a custom frame on the rooster box.

Sunset overlooking the companion Moray Firth East OWF .

Robertson Geo Services (RGS) were contracted by Gardline to conduct PS Logging operations from their heave compensated drill ship, for the Moray Firth West OWF, managed by a joint venture between Ocean Winds, EDPR and Ignitis Group.

The Moray West OWF is located in the Moray Firth in the Northeast of Scotland. The projected power output of the 60 x 14MW turbines will be 882MW, enough to power 640,000 businesses and homes. The port of Aberdeen was used as the base of operations for the vessel during the project.

Before the project could begin for RGS, the mobilising engineer was tasked with the installation of the 2,000m Marine Winch into a custom-built frame which houses the winch during it's use on-board the vessel. All work conducted following the thorough safety practices set out before the engineer and crew on-board the vessel.

Three boreholes were logged on the project, using multiple casing pulls to mitigate the risk of borehole collapse and to maximise data recovery should any unstable zones be encountered. Before each run of the PS Logger® the engineer would run the 3-Arm Caliper probe to ensure the integrity of the borehole and to discover any potential collapses before sending the PS Logger® probe into the borehole.

The PS Logger® probe, with its integral source, measures compressional (P) and shear (S) wave velocities in a single borehole in soft and hard formations. The velocity data was used to derive Poisson's Ratio and when combined with density values can be used to calculate the small strain moduli, with Shear Modulus (G) being important for offshore wind turbine foundation design.

The logging programme was successfully completed without issue or deviation from the original logging programme.

ATLANTIC SHORES

Offshore Development

The Atlantic Seaboard region is currently leading the way in OWF development in the USA, with the Atlantic Shores developments being a key contributor.

Atlantic Shores is a 50:50 joint venture between Shell New Energies US LLC and EDF-RE Offshore Development and when complete will deliver 5+GW of energy to New Jersey and New York, enough to power 700000+ homes, with the first power scheduled for production from Atlantic Shores 1 in 2027.

Robertson Geo PS Logger® and 3-Arm Caliper probes have been on hire with Fugro USA for over 12 months for their Atlantic Shores OWF geotechnical investigations. After encountering some difficult ground conditions Robertson Geo Services engineer Mark Scarisbrick joined the team to support the existing staff for four weeks, logging some of the difficult boreholes and assisting in the training of Fugro USA engineers.

Two Fugro vessels were working in conjunction to complete borehole drilling operations with Robertson Geo engineer Mark living aboard the HOS Browning. The first two boreholes logged had PS Logger® as a deliverable, the second two boreholes required both PS Logger® and 3-Arm Caliper.

Multiple runs of the PS Logger®, using both PS Logger® filter tubes (1m and then 2m) with variable sample windows, were conducted to confirm the highly variable lithologies of the area. Unconsolidated sand beds, gravelly coarse sand and high strength clay were all observed.

Training covering the PS Logger® software, settings, data confidence and data processing was provided. Routine maintenance training, important in the harsh marine environment, was also given for the 2,000m Marine Winch, PS Logger® and 3-Arm Caliper probes.

Services Engineer Mark Scarisbrick with Fugro USA Engineers.

PS Logger®

COMMISSIONING AND TRAINING IN MANILA BAY

The client purchased a complete logging system to be deployed on board a heave compensated drill ship. A package of commissioning and training was provided by a senior logging engineer from Robertson Geo Services over a period of 10 days.

The job involved commissioning a comprehensive PS Logger® system and training six operators in its use at their chosen South East Asia location. This was in preparation for a major project in Manila Bay, Philippines, where they would be conducting ground investigations for an upcoming bridge construction project.

The training consisted of probe theory, calibration, essential maintenance (probes and surface equipment), logging procedures and data processing. The first five days of training were carried out in port, simulating logging scenarios on deck in addition to classroom training. Working on heave compensated drill ships requires the winch to be mounted on the rooster box. This requires the fabrication of a frame to mount the winch and recommendations on how to fabricate the frame were provided.

Following fabrication of the frame, the winch was mounted in it and the setup successfully tested. Once the team understood the fundamentals of logging the engineer joined them on their next short project offshore. A short section of borehole was logged as training continued, running through the setting up of their equipment, logging, safety matters, preventative maintenance and the processing of their own collected data.

Upon conclusion of the training, certificates were issued to the six operators confirming they had achieved the necessary competency.

RGS Debut on Sylur vessel for Next Geo Solutions

Robertson Geo Services (RGS) was contracted by Next Geo Solutions to conduct PS Logging operations on their heave compensated drill ship, the Sylur for the Nordlicht OWF on the Baltic Sea.

The project represented an important milestone for RGS, Next Geo Solutions and the industry in general, as the Sylur now provides much needed additional geotechnical drilling capacity to the expanding requirements of the offshore wind farm industry.

The Nordlicht project site is located north of the island of Borkum and should go online by the end of 2027, with a generation capacity of 980 MW (Nordlicht 1), enough electricity to meet the annual requirement of more than one million average German households. The Netherlands port of Eemshaven served as the vessel's base of operations for the project.

The initial challenge for the engineer was to assist with the installation of the 2,000m Marine Winch and sheave wheel arrangement onto the rooster box, to exacting safety standards, including weight testing. Once the equipment was installed and fully tested, the vessel proceeded to the Nordlicht site where PS Logging was conducted at seven locations. On each borehole the logging was split into three runs to maximise data recovery should unstable zones be encountered.

The PS Logger® probe, with its integral source, measures compressional (P) and shear (S) wave velocities in a single borehole in soft and hard formations. The velocity data is used to derive Poisson's Ratio and when combined with density values can be used to calculate the small strain moduli, with Shear Modulus (G) being important for offshore wind turbine foundation design.

The logging programme was successfully completed without any significant problems or deviations from the original logging plan.

Aflandshage Offshore Windfarm, Koge

DENMARK

The Aflandshage Offshore Wind Farm is a 286MW offshore wind power project situated in the Baltic Sea, south of Copenhagen. The windfarm project plans 26 turbines spread over an area of 44km^2 each with 11MW nameplate capacity.

The project should generate enough electricity to power up to 300,000 homes around the Øresund region and will be a major contribution to Denmark's goal to reduce CO_2 emissions by 70% by 2030.

Robertson Geo were contracted to Danish company GEO Subsurface Expertise to conduct wireline logging on the Sound Prospector jack-up vessel as part of the geotechnical survey. Mobilising from Malmo in Sweden, five 35m boreholes were logged over a two-week period. The geology encountered was mainly chalk/limestone.

The Robertson Geo probes selected for this geotechnical survey were chosen to provide structural information (High Resolution Optical Televiewer® and High Resolution Acoustic Televiewer®) and to enable stiffness parameters to be calculated (PS Logger® and Formation Density). The resulting data was processed in situ by the logging engineer and then QC checked at the Robertson Geo head office.

ROBERTSON GEO SERVICES
MARINE GEOTECHNICS

PS Logger®

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. Full waveforms are recorded digitally at acquisition time across six channels at a predetermined sample rate as low as 2.5µsec. Using the acquisition software, the waveforms can be displayed, scaled and filtered to allow for the picking of the first arrivals at each receiver.

P wave and S wave velocities are automatically calculated from the picks and, when combined with bulk density values, small strain moduli (Young's, Shear and Bulk) are calculated using simple formulae.

Formation Density

The Formation Density probe is calibrated using known density jigs and uses the principle of Compton Scattering to calculate bulk density between the calibration reference points. The Caesium 137 radioactive source emits gamma radiation into the formation surrounding the borehole. These gamma rays are scattered by electrons within the formation, some of which are returned to the probe's sodium iodide detectors.

As the electron density within the formation increases (i.e. the density) the scattering effect is increased and gamma ray counts decrease. The derived density values are seen in real time as the probe is being logged.

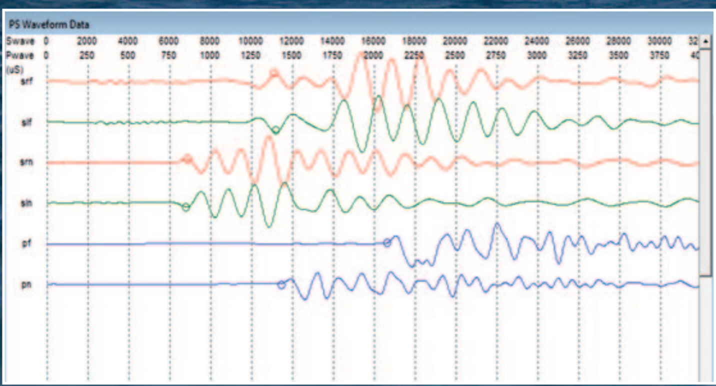
Optical and Acoustic Televiewers

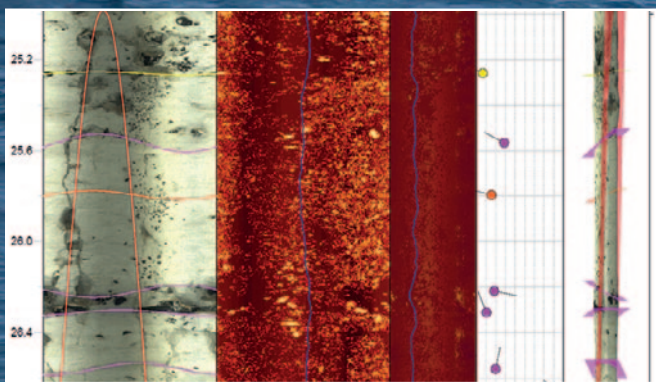
For the High Resolution Optical Televiewer® a fisheye lens is used to record a 360° slice of the borehole simultaneously, illuminated by a ring of LED lights. The borehole image data is combined with orientation data to produce an 'unwrapped' image of the borehole.

The High Resolution Acoustic Televiewer® produces a similar image but uses a high frequency sound pulse whereby the return pulse from the borehole wall is recorded as an arrival time and an amplitude.

Televiewers characterise features intersecting the borehole wall, including bedding, drilling-induced/natural fractures and faults and integrated orientation data allows the inclination and azimuth of features to be calculated.

Examples of PS Logger® and Televiewer data results.





Offshore Wind Farm Client Training TAIWAN

One of our major Offshore Wind Farm (OWF) clients in Taiwan recently purchased a comprehensive PS Logger® system for their extensive ground investigation works in the Taiwan straits.

They required in-depth 'onboard' training for their operators, and this was provided by one of Robertson Geo Services' team's highly experienced logging engineers joining them onboard their drilling vessel for eight days during drilling works on their current Formosa 4 OWF project 18 to 20 kilometres off the coast of Miaoli County in north-western Taiwan. Formosa 4 and neighbouring Formosa 5 will have a potential installed capacity of over 2.6 GW, which will be able to power up to nearly 3 million households upon completion.

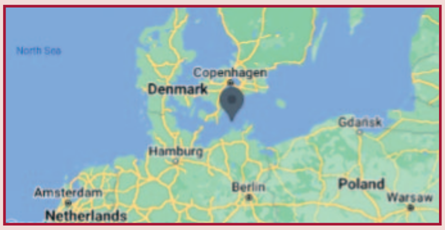
By joining the operators onboard, the Robertson Geo Services (RGS) training engineer could give them first-hand training in probe theory, probe and surface equipment maintenance, calibration and logging during a real ground investigation scenario. After collecting PS Logger® and caliper gamma data from three 100m boreholes, our engineer provided training on quality control, processing and presentation of the data acquired.

RGS training engineers' vast experience of logging in many different scenarios and conditions allows them to provide training tailored to the client's needs and teach them tips and techniques to enable operators to collect the best quality data and show ways to operate efficiently while keeping downtime to a minimum.

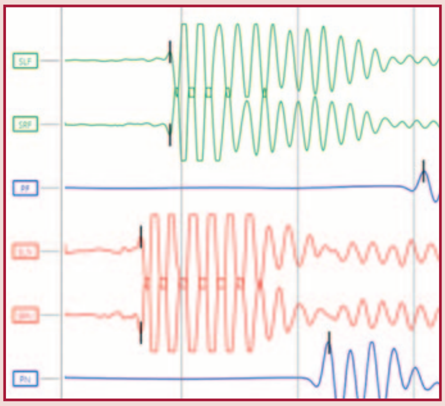
All competent trainees were given a certificate at the end of the course.

Gennaker Offshore Wind Farm will deploy 103 x 9MW turbines on monopile foundations for a total capacity of 927MW which will feed into the German electricity grid, enough clean energy to power 965,000 households from 2027.

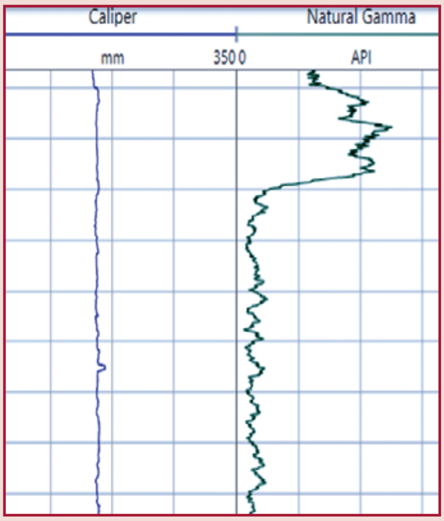
Located in the Baltic Sea some 15km off the German coast the project will be spread over an area of 185km^2.



Gennaker Offshore Wind Farm Location.



PS Logger® P and S Wave Data showing Picks.



Example of 3-Arm Caliper Data.

Gennaker OWF

The Baltic Sea's Most Powerful Windfarm

Seehorn vessel in untypically calm weather.

Robertson Geo Services were contracted by Geoquip Marine to join the geotechnical investigation, operating on the drill ship Seehorn, based out of Rostock, Germany. The PS Logger® and 3-Arm Caliper probes were required to log five boreholes, drilled using Geobor S, with depths to 60m over a period of three weeks.

Once the drilling was completed on each borehole the logging was conducted in multiple runs to minimise potential problems with borehole stability. The resulting data was processed on board the vessel by the engineer, with a fast turnaround, and finally QC checked by a Robertson Geo geophysicist back in the UK.

The Probes

The PS Logger® probe measured 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) were calculated using simple formulae.

The 3 Arm Caliper probe provides a single continuous log of the borehole diameter as recorded by three mechanically coupled arms in contact with the borehole wall. This gives a detailed profile into the integrity of the borehole wall, useful for QC when running sonic probes like the PS Logger®, as a smooth borehole wall will re-transmit a more coherent waveform. Natural Gamma was also recorded, indicating lithology changes, as radioactive elements are concentrated in some formations (clay or shale) and depleted in others (sand and chalk).

The Data

Full waveforms were recorded across six channels, two for P waves and four for S waves (left & right) at the near and far receivers. The sample rate was 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 were be displayed, scaled and filtered to allow for the picking of the first arrivals at each receiver. Once picked and the results combined with density data, small strain moduli were derived. Upon successful completion of the logging programme a final report was prepared for the client.

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.

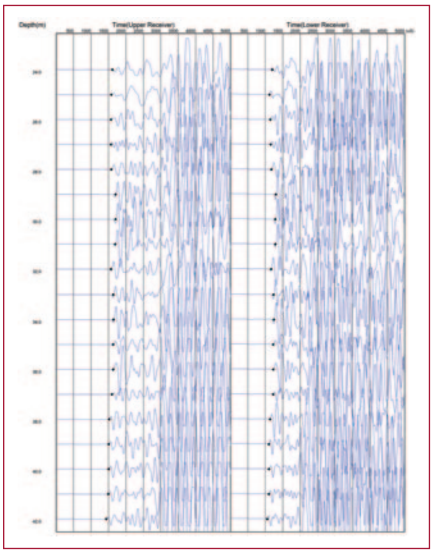
The collection of data to feed into the wind turbine design process is vital, due to the complex nature of the dynamic and cyclic loading of these structures, to characterise the soil-structure interactions. Regardless of which design approach is adopted, a marine geotechnical investigation (including 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).

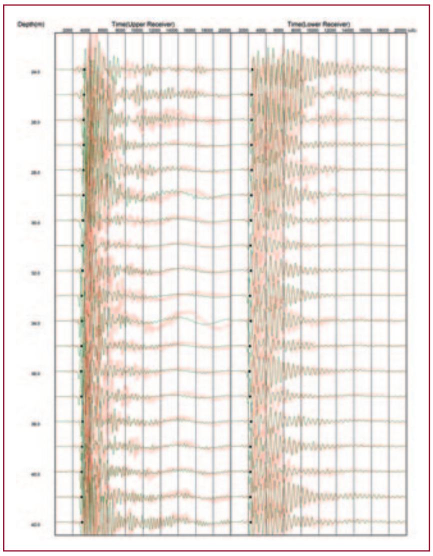
Geotechnical surveys employ invasive techniques and are usually conducted following the geophysical investigations. For shallow near-shore pilot or small-scale sites this was often carried out on small jack-up platforms where the crews were changed each shift. These arrangements also required a variety 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



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



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

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

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.

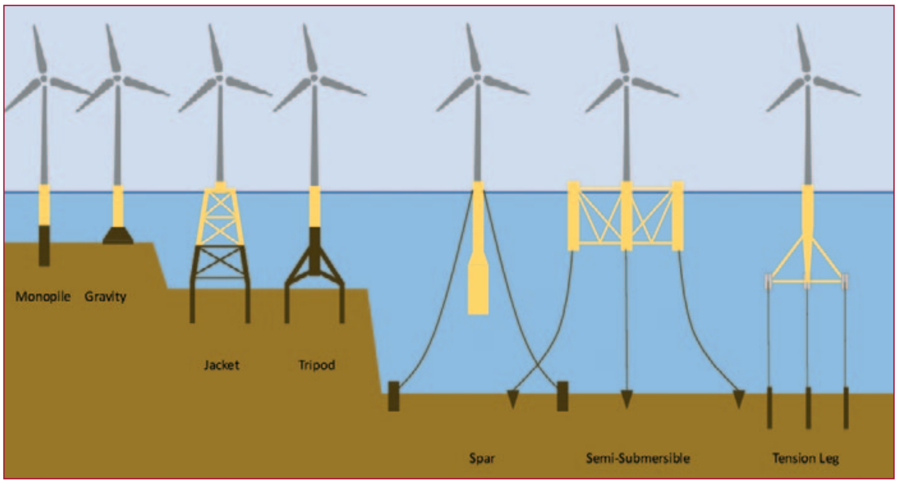
Foundation Designs

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.

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.



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

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

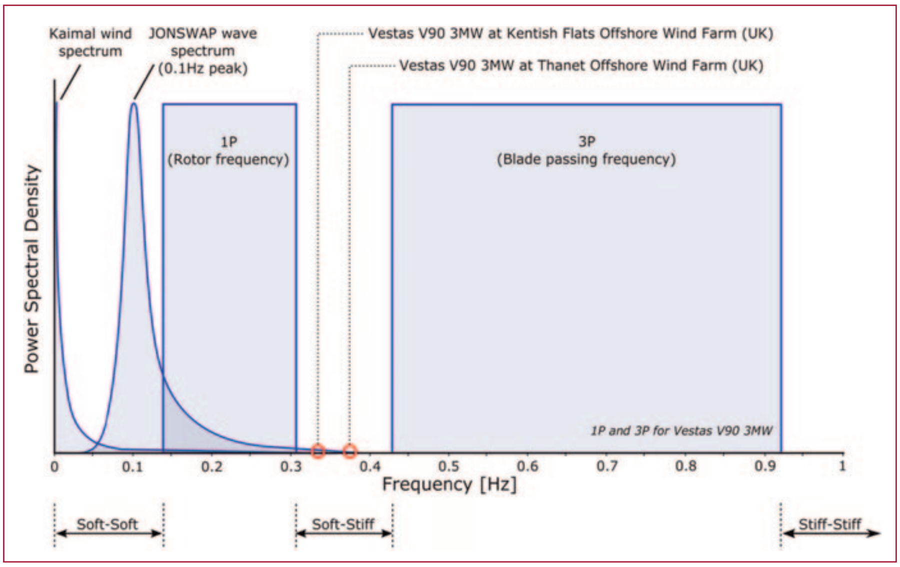
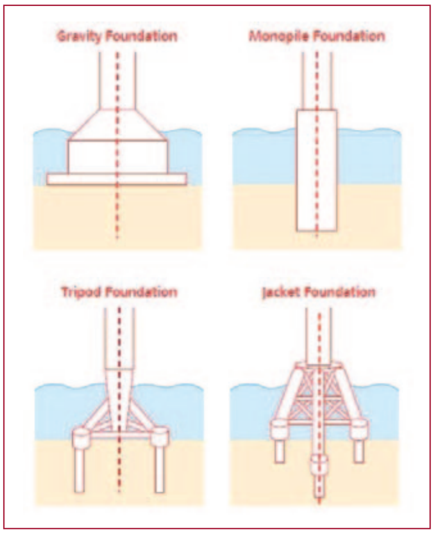


Figure 2: Example Power Spectra for OWT Design (Source: www.surrey.ac.uk).

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.

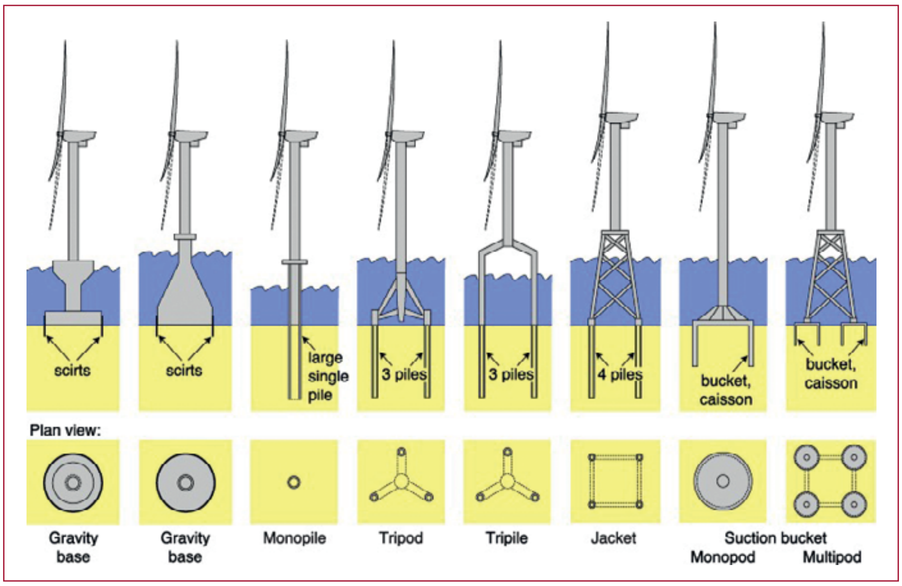
In addition to analysing stresses and determining natural frequencies there are many other factors that need to be considered for a successful design. These include turbine size, choice of foundation type, foundation installation methods, scour mitigation and supporting infrastructure, such as substations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

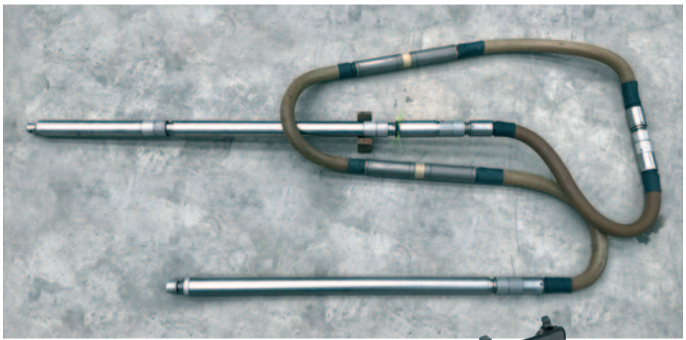
With a proven track record for reliability and data quality in the OWF market, wireline systems will continue to provide data which is difficult or impossible to collect by other means. Robertson Geo Operational Services provide turnkey solutions for the hazardous environment of drill ship operations, 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
Geotechnical Adviser - 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	Ground modelling	
	Dips and azimuths		
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

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.

TÜV SÜD ISO 9001
ISO 9001
Certified
Quality Management System
www.tuv-sud.com/ms-cert

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 300mm 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

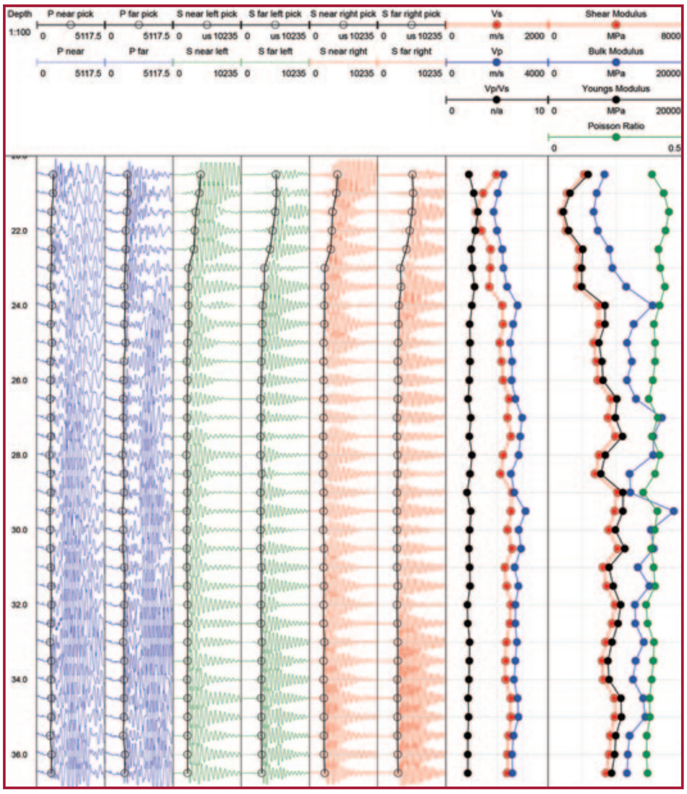
Stoneley waves are the last arrivals on the traces and are characterised by having a lower frequency than the S waves and do not exhibit the 180° phase shift as with S waves. These waves are not currently used in the analysis of PS Logger® data.

> *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.*

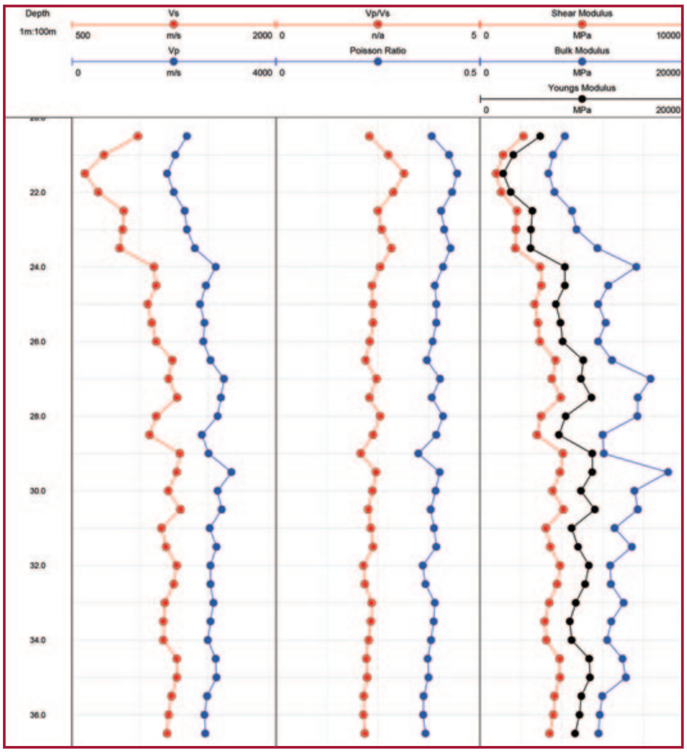
Data Processing

Full waveforms are recorded digitally at acquisition time across six 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.

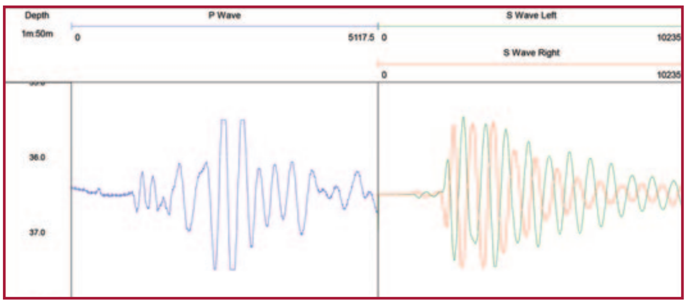
Using the acquisition software, the waveforms can be displayed, scaled and filtered to allow for the picking of the first arrivals at each receiver. Automated picking is available but in most cases the arrivals are picked manually by experienced engineers. While the P wave arrivals are generally simple 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.



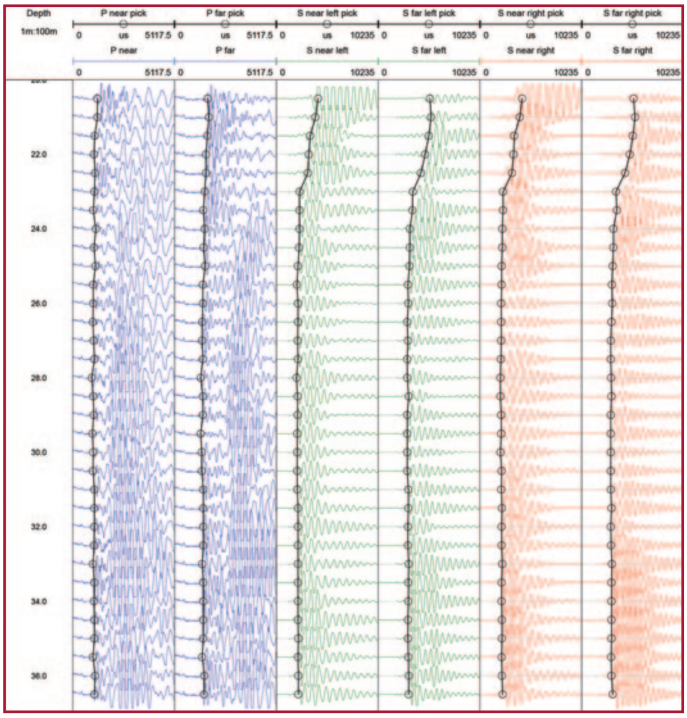
Full PS Logger® Output



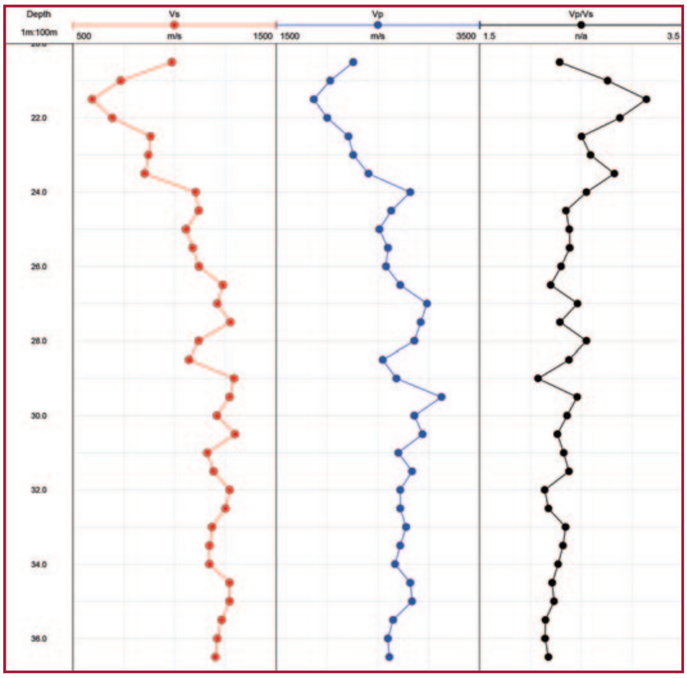
PS Logger® Derived Data



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®

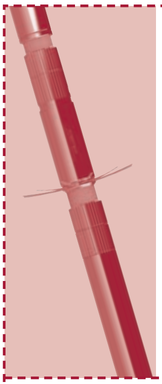
The PS Logger® is manufactured exclusively by Robertson Geo and is available as a full turnkey service, for rental or for outright purchase.

Robertson Geo 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 Robertson Geo 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.*



Developing a Standard for the PS Logger®

The PS Logger® sonic probe, since its inception in the 1970's, has seen ever increasing adoption for geotechnical investigations, with the exponential growth in Offshore Wind Farm (OWF) development being a primary driver. As with many technologies in this field the development of a standard follows behind its widespread use, such that there is currently no standard for the PS Logger®.

To address this, Robertson Geo have recently submitted a paper to the 7th International Conference on Geotechnical and Geophysical Site Characterization in Barcelona (ISC7) entitled "Towards the development of a standard for the PS suspension logger". Herein follows a brief resume of the salient points and scope of this paper.

Why the PS Logger® is Increasingly Adopted

The PS Logger® probe measures compressional (P) wave velocity and shear (S) wave velocity from a single borehole using a standard wireline logging setup. Unlike other sonic probes the PS Logger® can measure S wave velocity across the spectrum of formations from the hardest of rocks to unconsolidated sediments. From the resulting velocities small strain moduli can be easily derived with G_{max} being of particular relevance for OWF turbine foundation design, given the complex nature of the forces acting on the structure. Other in situ measurements routinely collected offshore include the Cone Penetration Test (CPT), the Seismic Cone Penetration Test (SCPT) and the Standard Penetration Test (SPT). PS Logger® data is a natural complement to these methods as it can provide strength parameter data through hard rocks where CPT cannot penetrate, with data quality generally improving with depth. For OWF ground investigations the operational simplicity of the PS Logger® is key as the source is integral with the probe avoiding the need for operationally challenging seabed sources. By mounting the winch on the rooster box, for heave compensated drillships, excellent depth registration can be easily maintained.

Current Standards Relating to Soil Strength Determination Methods

The most relevant standards organisation applicable for soil strength determination is ASTM International (formerly the American Society for Testing and Materials). Other professional bodies involved include ISO (international Standards Organisation), BSI (British Standards Institution), AGS (Association of Geotechnical and Geoenvironmental Specialists), and OSIG (Offshore Site Investigation and Geotechnics Committee). Any standards produced by these bodies are technically voluntary until specified in a contract.

There are many laboratory based methods for measuring the strength of core samples with some specific tests being covered by applicable standards including ISO, ASTM and BSI.

For in-situ testing there are some general standards which apply to the PS Logger® such as ASTM D5753-18 (Standard Guide for Planning and Conducting Geotechnical Borehole Geophysical Logging) and BS7022:1988 (Guide for geophysical logging of boreholes for hydrogeological purposes). Both of these covers acoustic velocity logging but are very generic in nature with no details of PS Logging methodology. CPT and SPT methods are well served by ASTM standards such as ASTM D5778-20 and ASTM D1586M-18 respectively. SCPT is less well covered by applicable standards but is referenced in ASTM D5778-20 and ASTM D7400M-19.

Why is a Standard Important?

A relevant standard can form a bridge between client requirements and the purveyor of the service, detailing what the client requires and what is expected from the service provider. Conversely the lack of a standard leaves the specification of requirements and deliverables in the hands of individual clients, manufacturers and contractors with predictably variable results.

Proposed Framework for a Standard for the PS Logger®

Section	Sub-Section	Content
General Information		Scope, overview of method, principle of measurement, significance and use, terminology, units, significant digits, symbology, referenced documents.
Borehole Specifications	General	Separation between boreholes, open versus cased boreholes, necessity for fluid filled boreholes. Suggested drilling method.
	Geometry	Depth limits, borehole diameter, depth point, probe geometry.
	Grouting and Casing	Casing material requirements (PVC), importance of proper installation and grouting, best practice for grouting procedure, grout density specifications. Explanation of problems caused by improper grouting/casing.
Apparatus	Overview	Schematic of the PS logger®, showing all probe sections and components.
	Energy Source	Specification of dipole source: uni-axial force applied indirectly via borehole fluid, exciting flexural borehole mode. Recommended operating frequency range for avoiding dispersion corrections. Description of typical solenoid-operated hammer, merit of capacity to record measurements 180° out of phase.
	Receivers	Two receiver stations for measurement of difference in seismic arrival times, hydrophones and geophones for measurement of compressional and flexural waves, respectively.
	Acoustic Filter Tubes	Explanation of role of acoustic filter tubes, material and geometry specifications.
	Additional	Telemetry, recording system, winch and software.
Test Method	Calibration	Conformance, free pipe test
	Planning	Guidelines for planning a borehole run, starting at the deepest measurement location. Required information including datum level, typical depth interval. Liaison with other practitioners, potentially unstable subsurface conditions, logging in sections, guidelines for planning multiple runs.
	Test Instructions	Selection of appropriate test parameters by initial borehole testing, including sample rates, gains and filters. Detailed instructions of all aspects of the test procedure. Safety considerations.
	Offshore Considerations	Heave compensation, rooster box based operations, borehole instability, external noise factors.
Data Interpretation	Guidelines	Schematics of typical waveforms, compressional and flexural arrivals, picking methods.
	Deliverables	List of standard deliverables

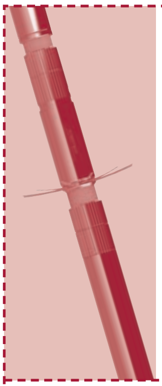
Client contractor understanding is aided by a relevant standard and this simplifies and standardises the specification process on contracts. Both standard and survey specific parameters required from the client by the contractor are better defined upfront by application of a standard. Borehole and operational matters that need to be addressed are also more easily specified by reference to a standard. Details of deliverables and their timescales can also be covered by a standard.

Scope and Content for a PS Logger® Standard

The PS Logger® is now routine deployed in both offshore and onshore ground investigations and any relevant standard must cover both environments. Operations pertaining to the Oil and Gas industry are considered out of scope as this industry is already highly developed with its own methodologies and specific safety concerns. The above framework for a PS Logger® standard is loosely based on similar ASTM standard formats.

Discussion and Conclusions

As can be seen in the above table, which is not exhaustive, there are many important factors that need to be considered when engaging with a PS Logger® service, especially for offshore deployment. Over time, Robertson Geo, as manufacturer of the PS Logger® and the world's largest purveyor of PS Logger® services, have successfully dealt with all the factors involved thus providing reliable and safe operations while achieving the highest possible data quality. For less experienced organisations having all the necessary specifications and methodologies encapsulated in a standard would undoubtably be of benefit, by providing a framework whereby consistency and better data quality could be achieved.



Aspects of the Science Behind the PS Logger®

The science involved in acoustic wave propagation in boreholes is surprisingly complex and has been subject to considerable theoretical and experimental analysis over many years. This is especially true when considering shear waves and in particular the flexural mode resulting from dipole probes such as the PS Logger®.

Overview

The velocities of compressional waves (V_p) and shear waves (V_s), derived from sonic logging, are inherent material properties of formations, important in determining strength within the elastic limit. The theoretical basis behind borehole based methods for sonic logging has been widely described in important papers through the 1970's and 1980's and work continues to this day. The PS Logger®, operating in a single borehole, uses the "suspension method" whereby the source and receivers are suspended in the borehole fluid, connected only by a flexible tube. A cylindrical dipole source is employed that creates pressure waves in the borehole fluid which in turn excite the formation at the borehole wall in different modes. Energy is transmitted along the borehole wall to two receivers, each comprising a hydrophone (for P waves) and a geophone, aligned to the source, (for S waves).

Wave Propagation

The velocities at which waves propagate in a geological formation are inherent material properties, independent of the tool used for measurement. These velocities are a complex function of several factors, including density, porosity and mineralogy. Sonic logs measure velocities by activating a source in the borehole with a specific frequency spectrum (S_f) which excites waves in the surrounding formation at wavelength λ with frequency f travelling at velocity V. Two main forms of waves exist, body waves which travel through the formation itself and surface waves which travel along an interface between two media. The equation $V = f\ \lambda$ applies to both types. Body waves may be generally described as compressional (P waves), where particle motion is in the direction of propagation, or shear (S waves) where particle motion is perpendicular to the direction of propagation and may be horizontally (SH) or vertically (SV) polarised. Surface waves may exhibit more complex particle motion and for sonic logging are assumed to exist only at the borehole fluid/borehole wall interface.

Frequency Spectra

When a bell is struck with a hammer, it is distorted and subsequently vibrates in a highly complex manner, which can be described in terms of a linear combination of many normal modes of vibration as in *Figure 1*. The frequency spectrum of the bell is the summation of these modes.

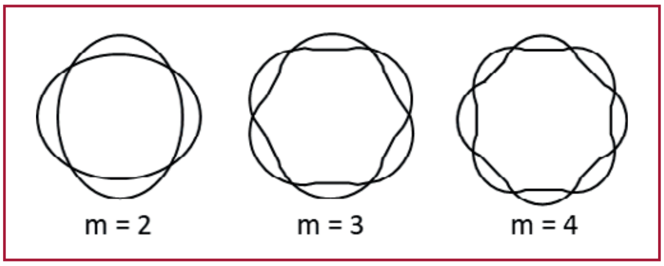


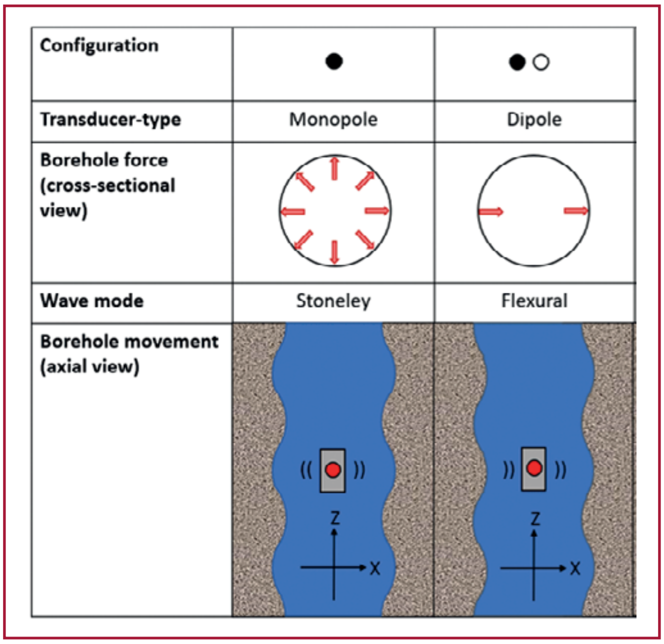
Figure 1: Bell - First Three Modes of Vibration.

Any acoustic source has an associated frequency spectrum which, when activated in the ground, causes the surrounding formation to vibrate within that frequency spectrum. The response of the ground to the signal from the source is dependent on the ground material properties and manifests itself in terms of a varying amplitude of vibration at the frequencies within the excited spectrum. Modes of propagation may also be dispersive in that different frequency components may travel at different velocities. The frequency spectra pertaining to the PS Logger® is of particular importance due to the mechanism by which shear wave velocities are derived.

Monopole and Dipole Tools

The fundamental modes shown in *Figure 2*. describe the lowest-order surface modes of monopole and dipole transducers in a borehole, exciting the Stoneley mode for a monopole and the flexural mode for a dipole.

Figure 2: Monopole and Dipole Wave Modes.



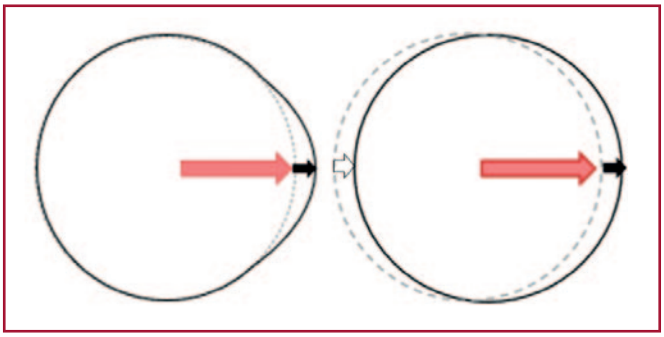


Figure 3: PS Logger® Source - Stoneley Mode (left) and Flexural Mode (right).

These modes are generated directly by the force applied to the borehole wall and are therefore present in both fast and slow formations, propagating away from the acoustic source, in both vertical directions. Traditional sonic probes use only a monopole source and therefore only excite the Stoneley mode. In fast formations, where the shear velocity is higher than the fluid velocity, a monopole tool can produce shear waves by mode conversion which are critically refracted along the borehole wall.

For the PS Logger® the source comprises a steel cylinder which is struck on the inside surface by a solenoid operated shuttle under operator control, with the direction of motion of the shuttle being reversible between shots. This source operates in both modes as shown in the planar view in *Figure 3*. The Stoneley mode occurs as an initial imbalance or bulge is produced in the cylinder which acts as a monopole source, exciting P and Stoneley waves. As the opposite side reacts, a pressure doublet is set up, such that a pressure increase in the fluid on one side of the cylinder is matched by a pressure decrease in the fluid on the other side exciting the flexural mode, generating dipole P waves and flexural waves. The PS logger is fitted with hydrophones and geophones, which are configured to measure P and Sf (flexural) wave velocities, respectively. Shear wave measurements are made in two horizontal directions (left and right), producing flexural modes 180˚ out of phase, a key indicator when identifying the flexural/shear wave components of recorded waveforms.

The Flexural Mode

The flexural mode excited by a dipole tool propagates along the borehole wall in both fast and slow formations causing it to bend. It is highly dispersive and is bound at the upper frequency limit by the Scholte wave velocity, and at the lower frequency limit by the formation shear wave velocity. The dispersive behaviour of flexural waves applies only to a specific frequency bandwidth (see *Figure 4*) where propagation velocity varies asymptotically with frequency. Below a critical frequency (the cutoff frequency), there is no dispersion and the flexural wave travels at the formation shear velocity. The PS Logger® is a low frequency tool which operates at a suitably low frequency bandwidth such that the flexural mode is non-dispersive and propagates at the formation shear velocity, precluding the need for dispersion correction. As the flexural mode exists only along the borehole wall, it is not a body wave mode, and therefore the flexural wave is technically separate from the shear wave, although it travels with the same velocity at low frequencies. The PS Logger® source centre frequency is typically 1.5kHz or below.

Applicability to the PS Logger®

The flexural mode of wave propagation in boreholes is perhaps the least understood aspect of the PS Logger® in the wider geotechnical community. An understanding of the basis of this mode, as described above, is useful when discussing the applicability of the PS Logger® across a wide variety of borehole conditions and formations. Robertson Geo have accumulated a repository of PS Logger® data from more than a thousand borehole runs over 15 years which clearly demonstrates how well it can work in practice.

P wave velocity determination is invariably straightforward as these are always the first arrivals and are characterised by a sharp peak in the waveform on the P channel (hydrophone). The S waves, or rather flexural waves, measured on the geophone channels, arrive somewhat later and tend to exhibit a slower rise time. These later arrivals may be superimposed on other waves, such as the decaying P waves making arrival time picking more difficult. As they are recorded twice (left and right shots) the characteristic 180° reversal between them is a key indicator for correct identification. In all cases velocities are derived from the time difference between the near and far channel arrivals which eliminates any difficult to quantify borehole effects.

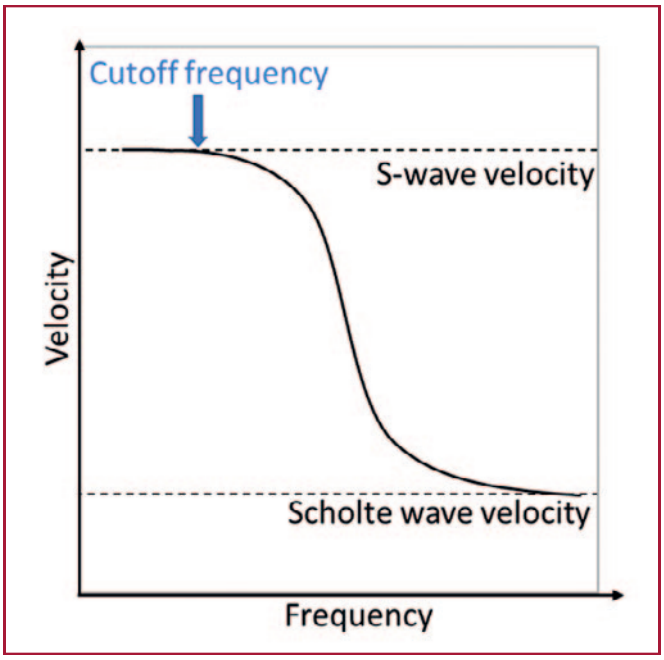
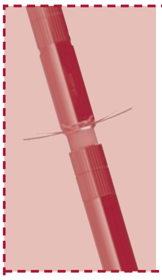


Figure 4: Flexural Wave Velocity Dispersion versus Frequency.

Conclusion

The theory behind the operation of the PS Logger® is important to understand as it needs to explain why the probe works so well across a spectrum of logging conditions. Excellent velocity data can be obtained in fast and slow formations, in borehole diameters from 75mm to 300mm and in open and cased boreholes. Robertson Geo have recently undertaken an exhaustive review of the theory supporting the probe to ensure the demonstrably good results routinely obtained in the real world are also put on a firm theoretical basis.



PS Logging in Large Diameter Boreholes

Borehole diameter, at least up to 300mm, is not in itself a limiting factor for extracting high quality shear wave (S) and compressional wave (P) data from the PS Logger®. This conclusion was reached by collating numerous data examples, where borehole diameter was explicitly known, and reviewing the science behind the PS Logger®. "Textbook" quality waveforms, and hence highly accurate shear wave velocities, were in evidence for diameters from 76mm to 300mm and can be fully supported by established PS Logger® theory.

Background

The initial application for the PS Logger® was to provide compression (P) and shear (S) wave velocities for earthquake susceptibility. With the widespread adoption for geotechnical investigations borehole diameters between 75mm and 150mm became common, well within the "normal" range for the PS Logger®. It was only when the PS Logger® was increasingly deployed for geotechnical investigations on offshore wind farms (OWF) that significantly larger borehole diameters were routinely encountered. The reason was not necessarily that larger diameters (over 200mm) were being drilled but rather was from "washout" of loose granular sediments especially nearer to the mud line. Despite the widespread use of drilling muds, the complex drilling environment used on heave compensated drill ships means some washout will usually be present by the time the PS Logger® is run, as this is invariably the final test before the borehole is completed.

Real World Data

The increasing use of the 3-Arm Caliper probe on OWFs to provide QC information to assess the confidence in the PS Logger® results also provided the opportunity to determine the effect of borehole diameter, amongst other factors, on the final data quality.

For the PS Logger®, when considering the ray paths of interest, the effective vertical distance of travel for the waves is 3.125m (when using the 1m filter tube), the distance from the source to the far receiver. If the borehole is washed out reasonably consistently and smoothly over this extent this effectively presents the PS Logger® with a large diameter borehole. Sections of boreholes with consistently large diameters, up to 300mm, were seen to still be able to produce top quality shear waveforms *as shown in Figure 1.*

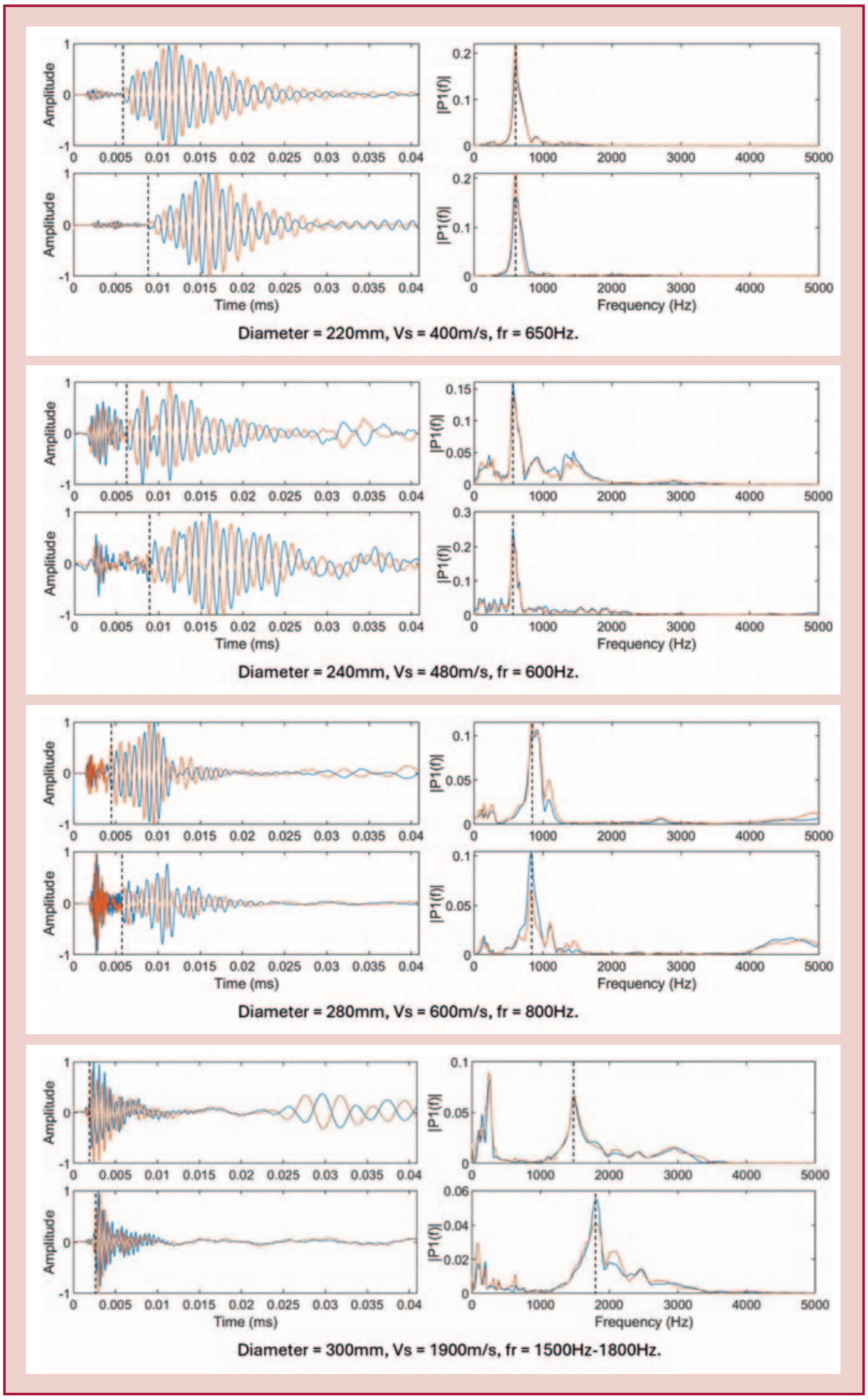


Figure 1: Shear Waveforms in Large Diameter Boreholes.

There are many other factors that affect the transmission of shear wave energy from the seismic source along the borehole wall including, rugosity, cavitation, compaction, fractures and the presence of noise from the drilling platform. Like many geophysical probes the theory of operation for the PS Logger® is predicated on the borehole presenting as a smooth cylinder. To record its waveforms, all energy from the PS Logger® "suspension" method is transmitted to the borehole fluid first. The pressure waves in the fluid then transmit energy into the borehole wall, some of which travels up the borehole toward the receivers where the energy is re-transmitted back into the borehole fluid to the receivers. As rugosity or roughness of the borehole wall increases the irregularity can cause the waveforms to become less coherent. Cavities in the borehole also adversely affect the coherence of the recorded shear waves especially if the source or receiver is adjacent to the cavity. Fractures, especially open fractures, at or near the borehole wall can introduce multiples or reduce the energy in the desired waveforms. For unconsolidated formations, the level of compaction is also significant with highly compacted sediments able to produce high quality waveforms. Data quality also tends to improve with depth as non-source generated noise from the drilling platform decreases.

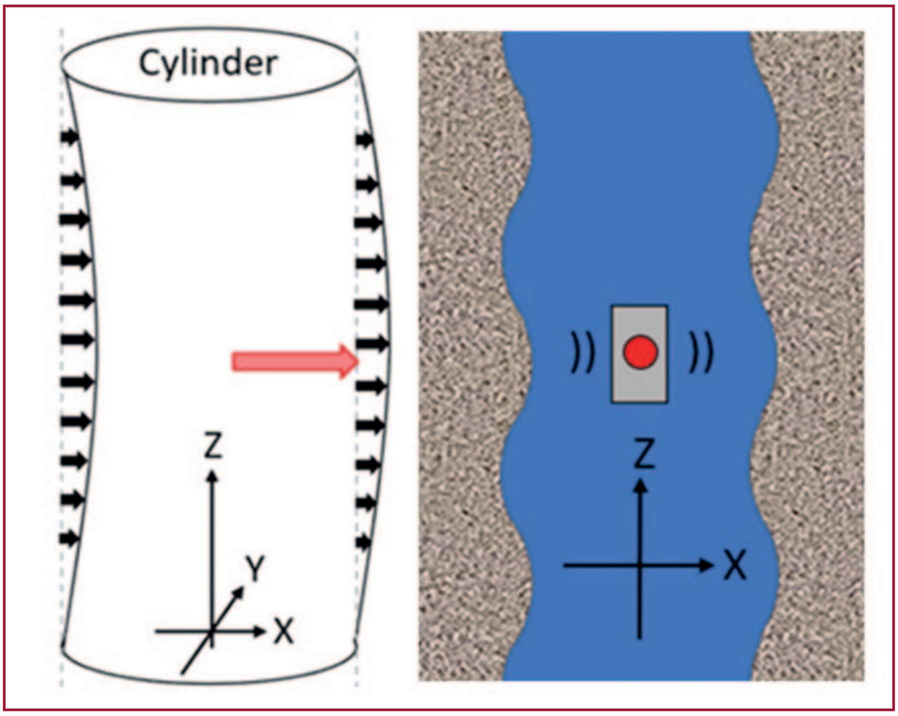


Figure 2: Fundamental Flexural Mode (reverses between shots).

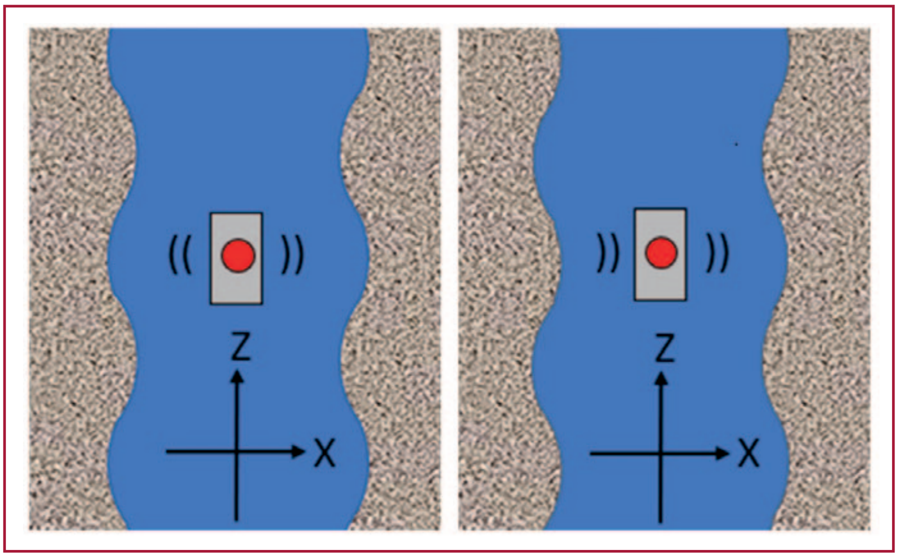
Theory

The PS Logger® is a dipole tool which excites a flexural or bending mode in the borehole wall, using a solenoid operated shuttle striking the inside of a steel cylinder alternately in opposite directions, *as shown in Figure 2*. The flexural wave at the borehole wall travels to the receivers at the formation shear wave velocity if the source frequency is sufficiently low. Monopole tools, such as conventional sonic probes, are limited as they excite only the Stoneley mode which relies on refraction of shear waves along the borehole wall, which is not possible in slow formations where the shear velocity of the formation is less than the fluid velocity. *Figure 3* shows a comparison between the particle motions at the borehole wall for Stoneley and flexural modes.

The PS Logger® was initially developed for use in boreholes up to 150mm diameter where the affect of the borehole diameter itself caused minimal disruption to the signal. The underlying assumptions however can be seen to be still valid if the frequencies involved are low enough, with the PS Logger® source centre frequency of around 1.5kHz or less being considered low enough not to introduce borehole effects in even large diameter boreholes.

The data examples across a range of borehole diameters *as shown in Figure 1*. clearly show the presence of the flexural mode, characterised by the 180° reversal of the signals between left and right shots. Frequency analysis of the signals also confirms that the frequency of the flexural mode waves is sufficiently low as to be largely unaffected by increasing diameter.

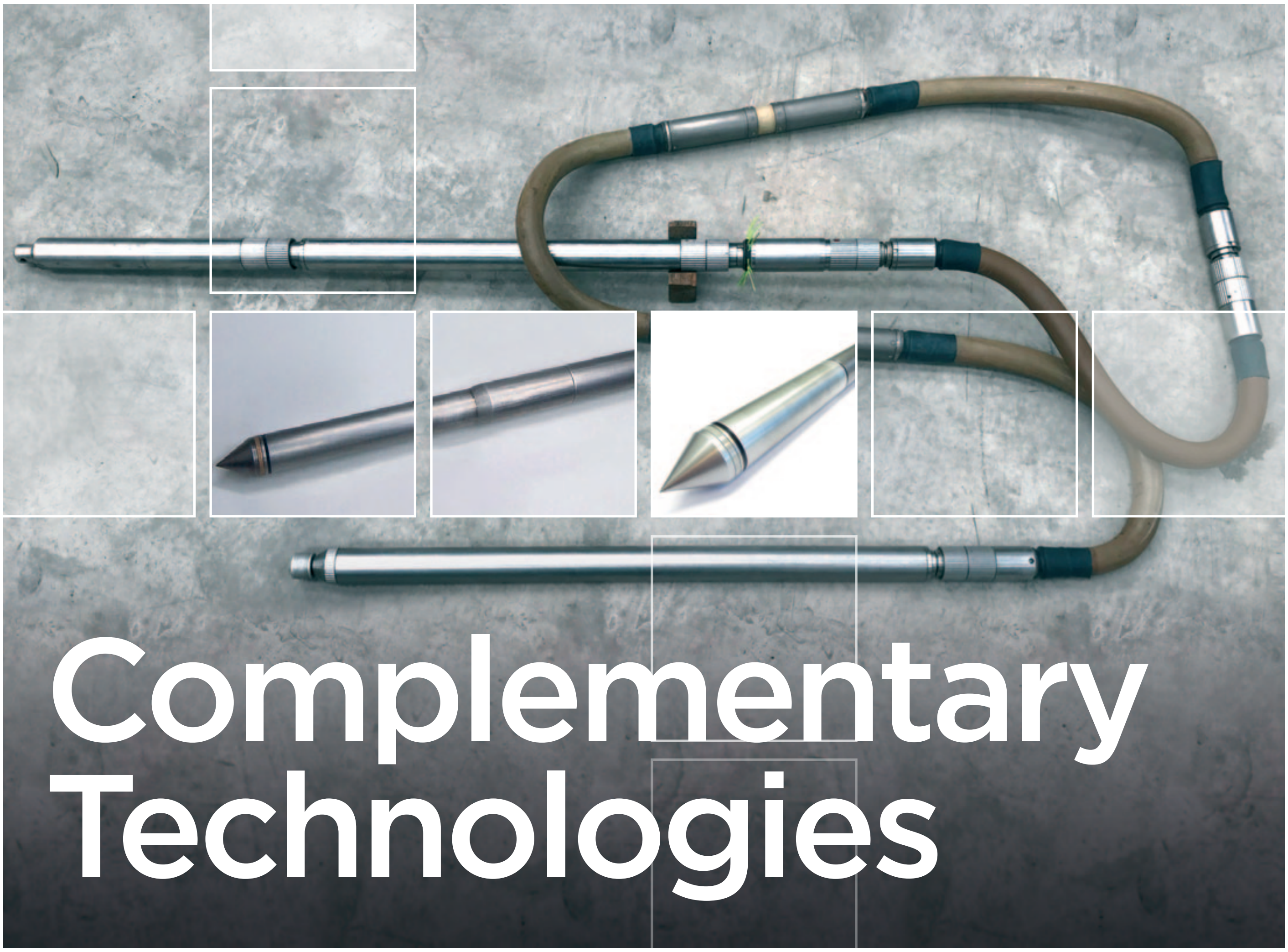
Figure 3: Stoneley Mode versus Flexural Mode.



Conclusion

The ability of the PS Logger® to extract accurate shear wave velocities (Vs) is determined not by the borehole diameter but by a range of other factors as discussed above. In boreholes with relatively smooth consistent borehole walls, with minimal interference from external noise, the PS Logger® has been shown to produce consistent results regardless of borehole diameter.

A paper entitled "Validation of the applicability of the PS logger borehole probe for diverse geotechnical scenarios" has recently been submitted by Robertson Geo to the XVIII ECSMGE 2024 conference, in which borehole diameter considerations are discussed in more detail.



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.

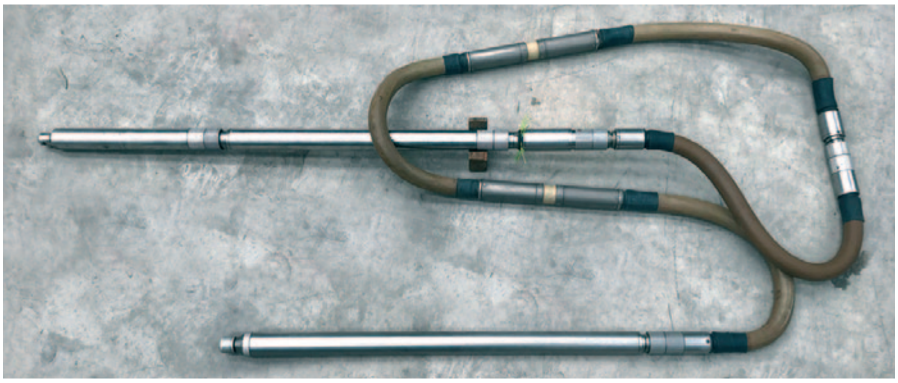
More accurate soil parameters for modelling loading response gives benefits in cost reduction due to better optimised foundation designs.

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



The Robertson Geo PS Logger®.

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

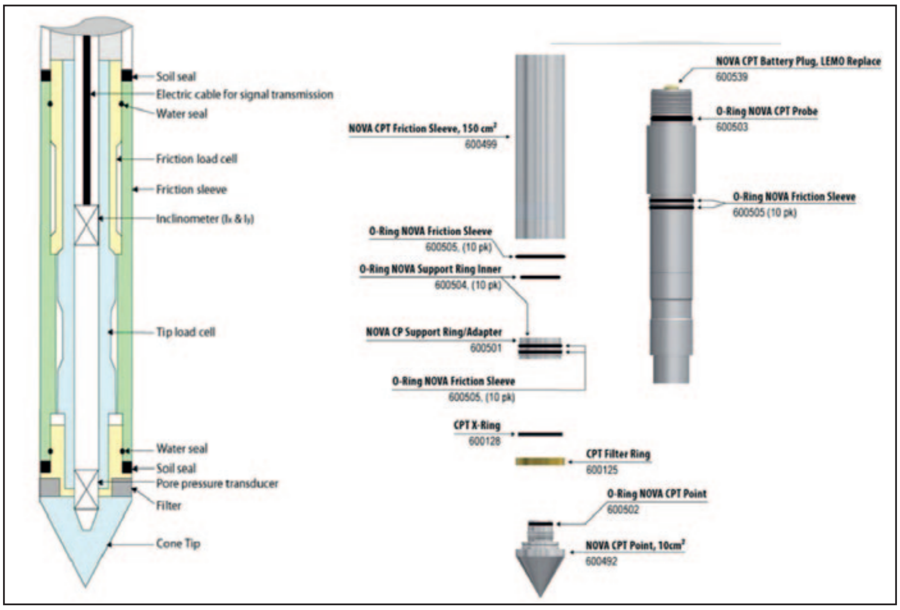
The PS Logger® (a registered Robertson Geo Trade Mark) was originally developed by the OYO Corporation in the 1970's to provide a full waveform tool that would produce reliable P and S wave velocity measurements in unconsolidated materials and rock formations, at depth, from a single borehole. The initial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

Deployment

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

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

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



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

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

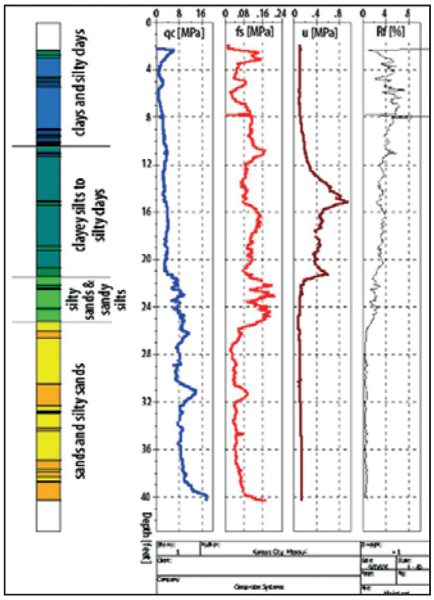
Comparison of PS Logger® versus SCPT for Offshore Ground Investigation

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

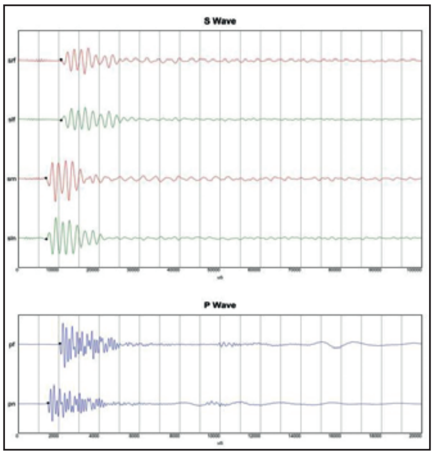
The CPT method uses a hydraulic rod fitted with a cone which is pushed vertically into the ground at a controlled speed. The sensors in the cone provide profiles, at centimetre resolution, throughout. As the cone penetrates it forces failure of the soil about 40cm ahead of the tip. The tip resistance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