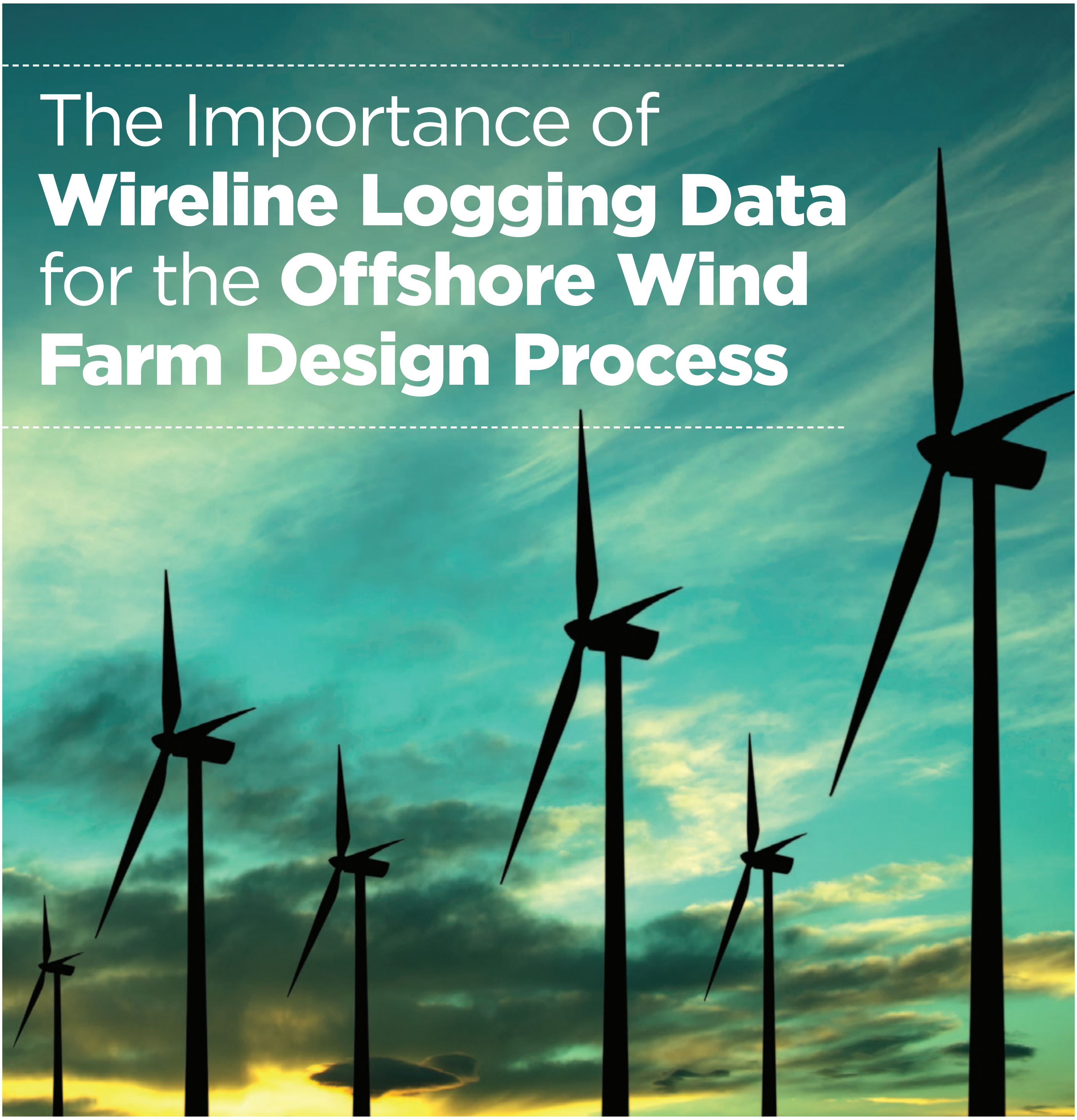
The Importance of **Wireline Logging Data** for the **Offshore Wind Farm Design Process**



Introduction

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

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

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

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

Histories

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

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

OWF Site Investigation Techniques

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

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

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

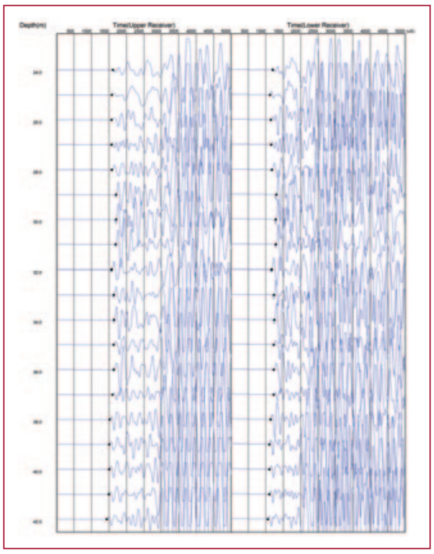
Geotechnical surveys employ invasive techniques and are usually conducted following the geophysical investigations. For shallow near-shore pilot or small-scale sites this was often carried out on small jack-up platforms where the crews were changed each shift. These arrangements also required a variety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

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

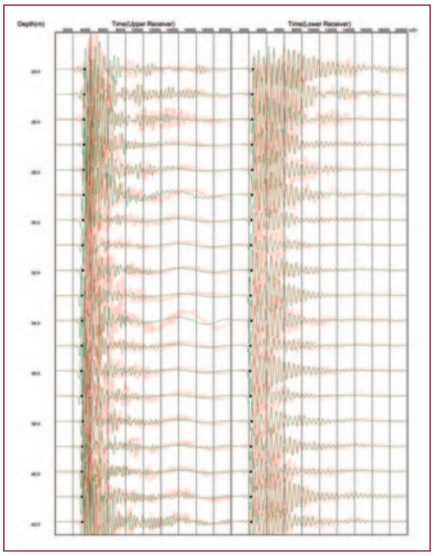
Once the borehole has reached target depth wireline logging is performed on the completed borehole, usually in stages to ensure maximum coverage. The PS Logger®, now a standard requirement for European and USA OWF, is run to provide P wave and S wave velocity profiles, often in conjunction with a caliper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

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

Figure 1: Example OWF Site Investigation Programme



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



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

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

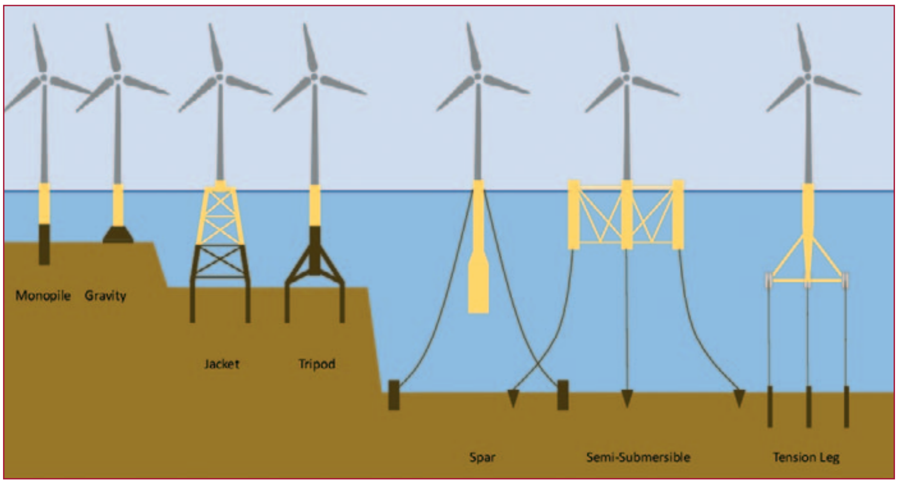
As drilling is often only conducted at a percentage of turbine locations it is vital that as much data as possible is extracted by wireline means from each borehole.

Foundation Designs

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

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.



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

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

Unique Characteristics of Fixed Bottom Wind Turbine Design

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

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

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

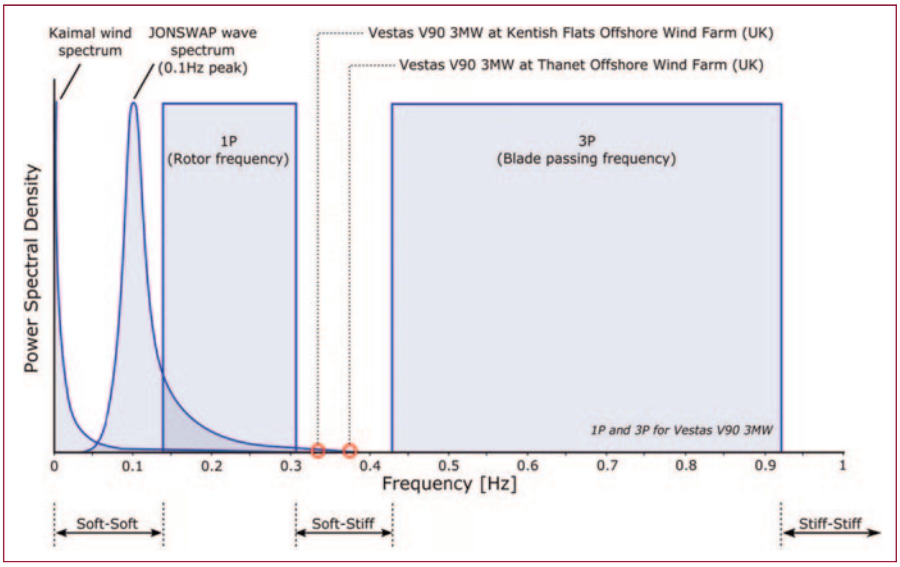
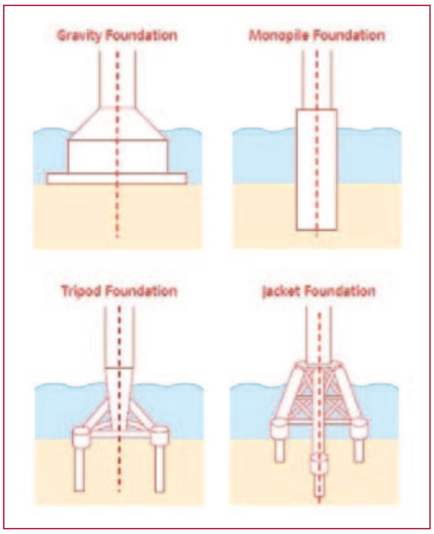


Figure 2: Example Power Spectra for OWT Design (Source: www.surrey.ac.uk).

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 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.

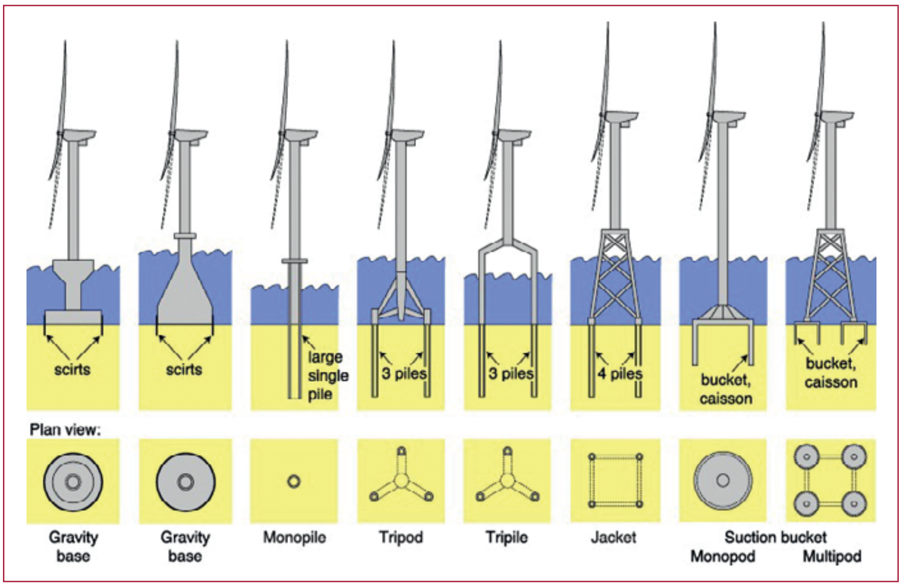
In addition to analysing stresses and determining natural frequencies there are many other factors that need to be considered for a successful design. These include turbine size, choice of foundation type, foundation installation methods, scour mitigation and supporting infrastructure, such as substations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

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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