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Using NMR geophysics to obtain hydraulic conductivity data and mitigate ground risk for offshore wind substation installation in the Baltic Sea

Balázs Béla Rigler, Dénes Gaertner, Waqas Farrakh Latif, Süleyman Bilge Parlak
Fugro, Wallingford, United Kingdom b.rigler@fugro.com denes.gartner@gmail.com w.latif@fugro.com sb.parlak@fugro.com

ABSTRACT: Joint Venture HSI 50Hz (the Client) undertakes the installation of two offshore substations (OSS) in the Baltic Sea. The need for an accurate coefficient of permeability for soil conditions was critical for the project's success. In 2024, the Client contracted Fugro to conduct a nearshore site investigation to obtain essential geo-data, aiding in the design of suction caisson foundations for the proposed OSS. The dissipation test conducted in granular material, particularly highly permeable sand, did not generate sufficient excess pore pressure around the cone for dissipation measurements. Other in situ permeability tests were considered, but packer testing and other methods were considered unsuitable for the local unconsolidated, highly permeable strata horizons. Consequently, the Nuclear Magnetic Resonance (NMR) wireline geophysical logging method was a viable option for providing the required data in a timely and cost-effective manner. Though well-established in the oil and gas, water, and health sectors, NMR remains innovative in geotechnical site investigations. Temporary plastic liners were used in the boreholes to ensure successful data acquisition due to the soft and collapsible nature of the shallow offshore sediments. Hydraulic conductivity, porosity and formation density data were finally delivered in high (25cm) vertical resolution to the Client by the unique NMR method to support their offshore based foundation design. The paper outlines the scope and methodology of the geotechnical investigation campaign, and the results including dissipation testing, and evaluation of hydraulic conductivity using laboratory testing and wireline (downhole) geophysical methods.

KEYWORDS: Nuclear Magnetic Resonance, Permeability, Porosity, Density, Geophysics, Geotechnical, Offshore, Site Investigation.

1 INTRODUCTION

The Client contracted Fugro to undertake a nearshore geotechnical site investigation to obtain detailed ground information which would assist with the design of suction caisson foundations for two proposed offshore substations in the German Baltic. A detailed geotechnical site investigation was executed to validate the structural integrity and assess the installation feasibility of offshore substation (OSS) jacket foundations under anticipated loading and seabed conditions. The campaign focused on characterizing soil strength, stiffness, and hydraulic parameters through a combination of in situ testing and laboratory verification. Obtaining the required hydraulic parameters from the site appeared to be more difficult due to local hydrogeological conditions. To overcome this situation, an approach was utilized comprising a unique borehole geophysical method the nuclear magnetic resonance.

1.1 *Site location*

The study area is located approximately 20 km (10.8 nautical miles) north off Zingst at the Baltic coast of Germany. This area is situated in the western Baltic Proper, between the Danish islands in the west and the Swedish coast in the north-east (Figure 1).

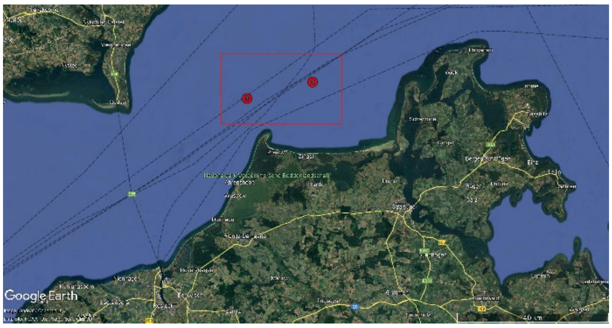

Figure 1. General location plan.

2 THE SITE INVESTIGATION

2.1 *Subsurface hazard mitigation for coastal power transmission*

The development of offshore wind as a successful renewable energy source means not only building wind farms but also being able to transport that power to land and connect to the grid. This often poses a challenge as coastal landfall environments can present complex geology and a range of potential sub-surface hazards. Fugro worked with the Client to ensure that their planned installation of two substation locations would be viable and safe. The site investigation included geophysical and geotechnical methods to ensure there were no obstacles or geo-hazards present that could potentially interfere with the installation of the OSS.

2.2 *The walking jack-up barge solution*

Fugro's four-legged liveaboard WaveWalker1 jack-up barge is a unique 'walking' jack-up, allowing precise manoeuvring around the site. With its technology-enhanced efficiency it avoids disturbance to foundation locations and cable routes with no need to be towed to each drilling location. This capability reduced disruption to sample capture, minimised environmental impact and maximised efficiency.

2.3 *Borehole locations*

Planned boreholes and CPT locations are illustrated on Figure 2. Detailed investigation layouts are provided for Leg No. 1 and Leg No. 2. Legs No. 3 and No. 4 are indicated by black dashed lines through their centre points, as those legs have the same investigation plan as Leg No. 2. The exact location of completed borehole and CPT positions are slightly different. Additional boreholes were drilled specifically for wireline geophysical logging with NMR. All borehole and CPT locations were positioned within a few meters apart.

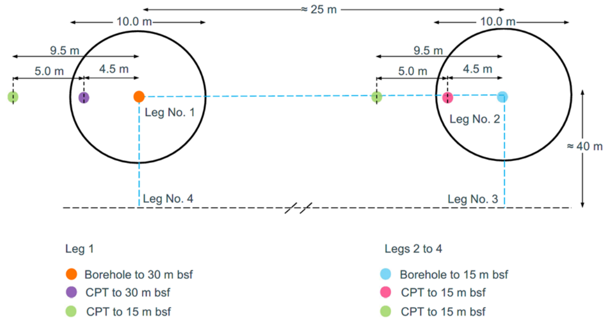

Figure 2. Illustration of planned borehole and CPT positions at the two OSS locations (image not to scale).

2.4 *Local geology*

The subsoil at the OSS locations in the investigation area consists of the following main soil types:

- Marine Sand with gravel.
- Holocene Clay/Silt.
- Glacial Till Sand.
- Glacial Till Clay/Silt.
- Structureless Chalk.
- Structured Chalk Grade B/C.
- Structured Chalk Grade A.

2.5 *Scope of work*

A total of eight cone penetration tests with pore pressure measurement (CPTU) were performed at each OSS platform. This included one CPTU targeted to reach 30 m below seafloor (mbsf), and seven CPTUs targeted to reach 15 mbsf. Each CPTU was advanced using a seabed deployment system until refusal or maximum penetration depth, followed by a downhole CPTU.

Of the eight CPTUs for each OSS platform:

- Four on the first OSS platform and eight on the second OSS platform location included dissipation tests to evaluate in situ permeability.
- Three on the first OSS platform and two on the second OSS platform incorporated cyclic testing to assess soil degradation under repeated loading conditions.

Additionally, four boreholes were drilled at each OSS platform location, where one borehole was targeted to reach 30 mbsf and three boreholes to reach 15 mbsf.

2.6 *Dissipation testing*

Pore pressure dissipation tests were conducted to monitor the decay of excess pore water pressure generated during cone penetration. The rate of dissipation is influenced by several factors, including the geometry of the probe, the compressibility of the soil, and its permeability. The time required to reach 50% dissipation (t_{50}) is typically recorded, as it enables estimations on soil compressibility and supports the classification of soil behaviour (Lunne et al. 1997).

2.6.1 *Evaluation of permeability testing strategies*

Following initial testing, the client requested an evaluation of the feasibility, time, and cost implications of conducting dissipation tests at all CPT locations. It was noted that:

- In granular soils, dissipation occurs rapidly, offering limited insight and adding ~1.5 hours to total testing time.
- In cohesive soils, dissipation may be prolonged, potentially impacting operational efficiency.

This was highlighted in the first exploration location, CPT1, where pore pressure dissipation tests (PPDTs) conducted in sand layers clearly indicated almost full drainage (Figure 3). Dissipation tests were attempted in these sand layers because an earlier site investigation had identified a certain amount of fine material in these layers. The objective was to assess how this fine content in the sands might influence permeability.

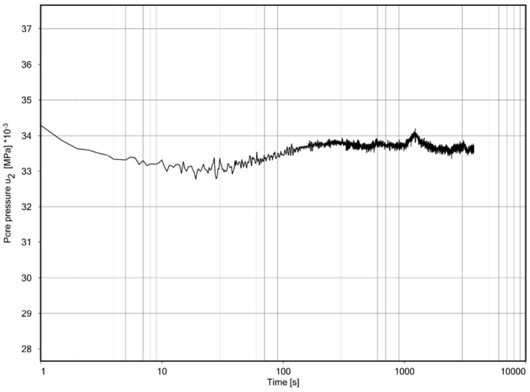

Figure 3. Pore pressure dissipation curve in sand layer.

In sands, full drainage is typically expected, so the pore pressure at the end of the test (u_2) should closely match the initial hydrostatic pressure (u_0). While a slight difference was observed in some tests—likely due to tidal variations—all PPDTs in sand consistently showed rapid dissipation, typically within a few seconds of starting the test, confirming drained behaviour. Additionally, a minor increase in u_2 (around 1–3 kPa) was noted toward the end of several tests, which is likely attributable to dynamic effects and does not compromise the reliability of the results. Similarly, if dissipation testing were in clays with certain properties, the tests could be much longer.

Alternative methods, such as falling head tests, were considered. However, the ISO (17892-11:2019) standard recommend this method for soils with permeability in the range of 10^{-6} to 10^{-9} m/s. Given that the Baltic Sea sands typically exhibit higher coefficient of permeability (10^{-4} to 10^{-5} m/s), falling head tests were deemed unsuitable. Packer permeability testing was also considered but also had limitations in soil due to the following issues:

- Risk of borehole collapse
- Challenges in achieving effective packer sealing.
- Difficulty in maintaining gauge pressure and obtaining reliable flow data

The use of slotted pipes was proposed as a mitigation strategy, though limitations remained.

3 NUCLEAR MAGNETIC RESONANCE (NMR)

3.1 *Introduction of the method*

Downhole or Borehole Magnetic Resonance (DMR or BMR) is the borehole application of the NMR method. NMR physics involves aligning hydrogen nuclei in pore fluids using a static magnetic field and perturbing them with radiofrequency pulses to measure their relaxation behaviours. The resulting relaxation times reveal fluid content and in fully saturated rocks the pore size distribution, also enabling direct estimation of hydraulic conductivity and formation fluid typing in subsurface formations (Coates et al. 1999).

Experiments with wireline NMR logging tools began in the 1960s, followed by the unique and already successful applications in the oil and gas exploration sector using larger diameter wireline logging tools. However, technical difficulties delayed further development of the commercially viable wireline logging tools until the 1990s (Coates et al. 1999). Use of the NMR method for formation evaluation in the oil and gas sector has been very popular since then, but due to limiting factors (tool size and cost implications) it has been scarcely used in near surface borehole geophysical applications. The first slim hole NMR logging tools, which are designed for near surface investigations, only appeared on the market in the early 2010s (Walsh et al. 2013). Unless it is specific to environmental or underground contamination applications, further discussions do not consider the possible presence of hydrocarbons as it is uncommon in near surface applications.

3.2 *NMR physics*

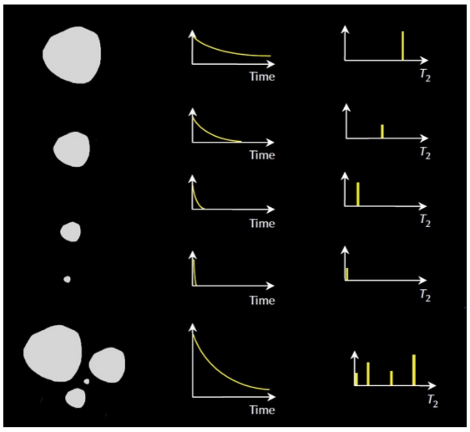

Figure 4. Relation between the exponential signal, NMR T2 relaxation time and pore size (Coates et al. 1999).

Raw or measured NMR data are oscillating, electromagnetic signals. The envelope of the spin echo maxima is a multi-exponential curve, a superposition of various exponential curves with different T2 time constants where T2 is a function of the distance of the water molecule from the pore wall, therefore the pore size. Laplace transformation is applied on the multi-exponential curve to extract the T2 distribution (Figure 4). Total area under T2 Distribution curve is proportional with total water content, which equals total porosity in fully water saturated soils. Shape of the curve reveals the distribution of the water amongst different pore sizes (Figure 5).

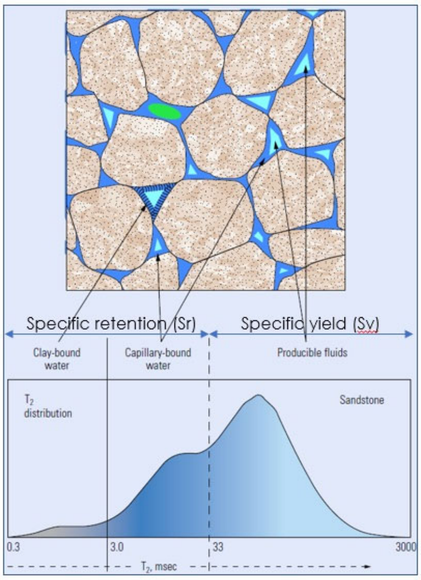

Figure 5. T2 distributions (bottom) to identify fluid components of clastic rocks (after Allen et al. 2000).

3.3 *NMR permeability estimation*

$$k_{TC} = c_{TC} \cdot \phi^{N_{TC}} \cdot \left(\frac{FFV}{BFV}\right)^2 \qquad (1)$$

Empirical equations are used as a common practice to estimate permeability from NMR data.

$$k_{SDR} = c_{SDR} \cdot \phi^{N_{SDR}} \cdot T2_{LM}{}^2 \qquad (2)$$

Most commonly used methods in near surface applications (Ellis & Singer, 2007) are the Timur-Coates (TC) equation (Equation (1)) and the Schlumberger-Doll Research (SDR) equation (Equation (2)), where

- k_{TC} and k_{SDR}: permeability in mDarcy.
- c_{TC} and c_{SDR}: empirical constant (premultiplier).
- N_{TC} and N_{SDR}: empirical constant (porosity exponent).
- FFV: Free/Moveable Fluid Volume in V/V ratio (Sy on Figure 5.
- BFV: Bound Fluid Volume in V/V ratio (Sr on Figure 5).
- $T2_{LM}$: Logarithmic Mean of T2 Distribution (Figure 5).
- Φ: Porosity in V/V ratio.

Timur-Coates equation has proven to perform poorly on some NMR datasets (Kendrick et al. 2023) and is rather sensitive to BFV. SDR equation has by far the largest publication record out of all empirical equations and performs well in most formation environments. As the main lithology of the study area is sand or silty sand, TC equation was excluded and only SDR method (Equation (2) was used for permeability evaluation.

Empirical constants used for k_{SDR} estimations are the global constants for clastic rocks determined by Kenyon et al. (1988):

- c_{SDR}=4.
- N_{SDR}=4.

3.4 *Hydraulic conductivity estimation*

A general preference in water industry and geotechnical site investigations is to use “the term” hydraulic conductivity (also referred as coefficient of permeability) instead of intrinsic permeability. To compare NMR derived data with other methods, estimated permeabilities were converted to hydraulic conductivity values according to Equation (3):

$$K_{SDR} = 9.869233E - 16 \cdot k_{SDR} \cdot \rho_W \cdot \frac{g}{\mu_W} \qquad (3)$$

- K_{SDR}: hydraulic conductivity in m/s.
- k_{SDR}: hydraulic permeability in mDarcy.
- ρ_W: water mass density, ρ_W=1000 kg/m^3 was used.
- g: gravitational acceleration, g=9.81 m/s^2 was used.
- μ_W: dynamic viscosity of water, 0.001 Pa·s was used.

4 HIGH RESOLUTION NMR LOGGING DATA

4.1 *Data acquisition*

NMR logging data were acquired in four purpose drilled boreholes (two boreholes at each OSS location), which were drilled with rotary coring (Geobor-S) method. The NMR boreholes were located within a few meters from the corresponding CPT and geotechnical borehole locations. Please refer to NMR borehole summary Table 1 for details of relevant borehole locations.

Table 1. NMR borehole summary

Borehole ID	Total Depth (mbsf)	Logged interval (NMR) (m)	Geology
BH1	18.0	3.0 – 6.0	Silty Sand
		6.0 – 10.2	Sand
		10.2 – 16.0	Gravelly Sand
BH2	17.0	2.5 –- 4.8	Silty Sand
		4.8 – 10.8	Sand
		10.8 – 14.8	Gravelly Sand
BH3	17.0	3.0 – 11.7	Silty Sand
		11.7 – 15.4	Sand
BH4	17.0	4.8 – 10.0	Silty Sand
		10.0 – 15.3	Sand

Due to the collapsable nature of shallow offshore sediments, selecting the NMR equipment with the right specification suitable for the work was a very important operational aspect to ensure provision of good quality data.

4.2 *Results*

A wireline geophysical composite log example of BH3 can be seen in Figure 6, which refers to Natural Gamma (Track 2), Total Porosity (Track 3), Hydraulic Conductivity - K-SDR (DMR) and K Lab (Rigid Wall Permeameter tests) (Track 3), Clay Bound, Capillary Bound and Mobile Water Volume (Track 4) logs.

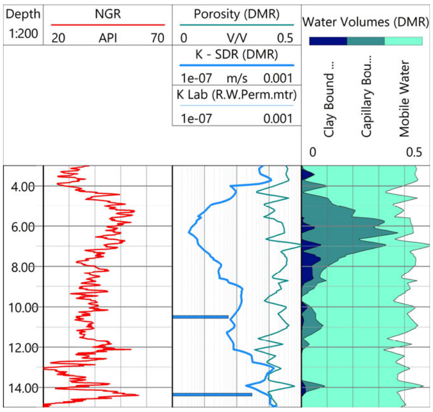

Figure 6. BH3 wireline composite log.

Rigid wall permeameter laboratory tests were also carried out in all geotechnical boreholes, with the test results compared with the NMR hydraulic conductivity (K- SDR DMR) data at corresponding depths (Figure 7).

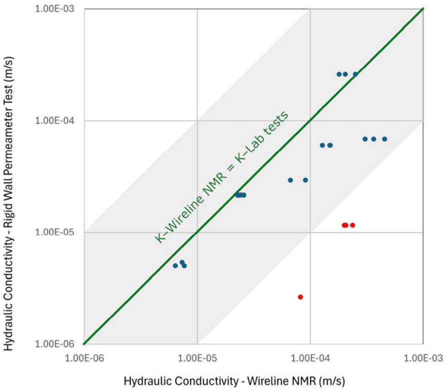

Figure 7. Correlation of NMR and laboratory derived hydraulic conductivity data.

General procedure is to first estimate NMR hydraulic conductivity according to the global sandstone constants by Kenyon et al. (1988) and later use laboratory data to fine tune the empirical constants. In this dataset, apart from a few outliers (red dots) the first hydraulic conductivity estimates according to Kenyon et al. (1988) proved to be within one order of magnitude (grey shaded area in Figure 7) to the laboratory derived values, therefore fine tuning the constants was not necessary.

5 CONCLUSIONS

The integrated testing approach provided a robust dataset for evaluating soil behaviour under static and cyclic loading. While dissipation and falling head tests presented operational challenges, the adoption of NMR logging offered a valuable alternative for hydraulic conductivity estimation along with the provision of additional valuable geo-data (e.g. porosity and density) to support the investigation. The findings will inform foundation design and installation strategies for OSS jacket structures in the Baltic Sea. The use of NMR geophysics in geotechnical site investigations has already been proven in other geotechnical site investigations in recent years (Maas et al. 2023, Rigler, 2018, Rigler, 2019).

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