The role of the geotechnical consultant in derisking offshore wind projects

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Net zero is currently one of the most discussed topics around the world, and renewable energy, and in particular offshore wind farms, are seen as a key part of achieving the net zero target. While offshore windfarms are not new to the renewable industry, the scale and complexity of offshore seabed conditions in which windfarms are being developed, have changed drastically over the last couple of decades.

Vindeby Offshore Wind Farm, the first offshore wind farm in the world, erected in 1991 off the coast on the Danish island of Lolland, had 11 wind turbine generators (WTGs) with a total capacity of only 5 MW, in water depths ranging from 3m to 6m. Hornsea One, which is currently the world's largest windfarm, commissioned in 2020 and located off the Yorkshire coast in the southern North Sea, has 174 WTGs with a total capacity of 1281 MW in water depths ranging from 24m to 37m. These facts highlight how far offshore windfarms have come in terms of capacity and complexity.

In an associated trend, the risk elements associated with wind farms have also increased severalfold. While the first foundations were simple gravity foundations, newer fixed windfarm foundations are typically monopiles, jackets, suction buckets or drilled & grouted piles. The seabed sites for early windfarms were less complex in terms of geological and geotechnical conditions, typically sands or clays, but sites for recent and future windfarms are complex and have high variability e.g. varying layers of sand and clays, silty soils, rock etc. These factors always increase risks inherent with offshore windfarms' development and are linked to foundations and cables which need to be designed to perform within the soil and rock conditions on site.

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Geotechnical consultants provide key services at all stages of offshore windfarm development: conceptual design, FEED, details design and installation. These services include concept and desk top studies, site selection assessments, planning and implementation of geophysical & geotechnical surveys and associated laboratory test specifications.

Further services can also be included, such as the interpretation of resulting data to characterise the seabed soil and rock conditions, identifying geohazards in the seabed and implementing risk mitigation, as well as designing the foundations for WTGs, the design of cable routes/protection and help in planning and installing foundations and cables. All of these activities have considerable risk associated with the project, therefore geotechnical consultants can play a key role in risk identification and mitigation in offshore wind projects.

Geotechnics in offshore windfarm projects

Geotechnical consultants play a vital role in six key stages in offshore windfarm projects, as shown in Figure 1. In each of these stages, input from a geotechnical consultant is critical in identifying and managing ground risks to offshore wind projects. The following sections highlight some technical insight into how each stage needs in-depth geotechnical knowledge for risk managing offshore wind projects effectively.

Stage 1,2&3. Desktop study, surveys & geotechnical testing

Stages 1, 2 and 3 are associated with desk top studies, geotechnical and geophysical survey implementation, and geotechnical testing. Desk top studies provide an early indication as to the likely seabed conditions to be expected at the project site. During site surveys, seabed soils would be subjected to in in-situ testing and seabed soil samples would be further characterised by laboratory testing.

The number of intrusive geotechnical tests required to characterise the offshore windfarm site would depend on several factors such as geology, accuracy and resolution of the available geophysical survey data, geohazards etc., and hence it cannot be generalised. In general, soil conditions cannot be assumed to be uniform across a site unless proven with geotechnical and geophysical data.

Therefore, knowing the seabed soil stratigraphy at two locations does not necessarily enable one to interpret the soil stratigraphy between those two locations. Since intrusive geotechnical testing has a high impact on project schedule and cost, it is often the case that the number of test locations is optimised to save cost and time. A geotechnical consultant is best placed to advise on this optimisation as - if not undertaken properly - this can lead to increased project risk.

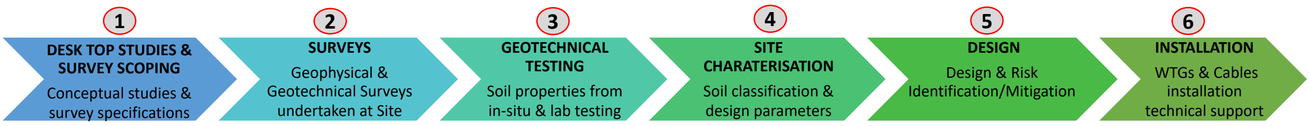
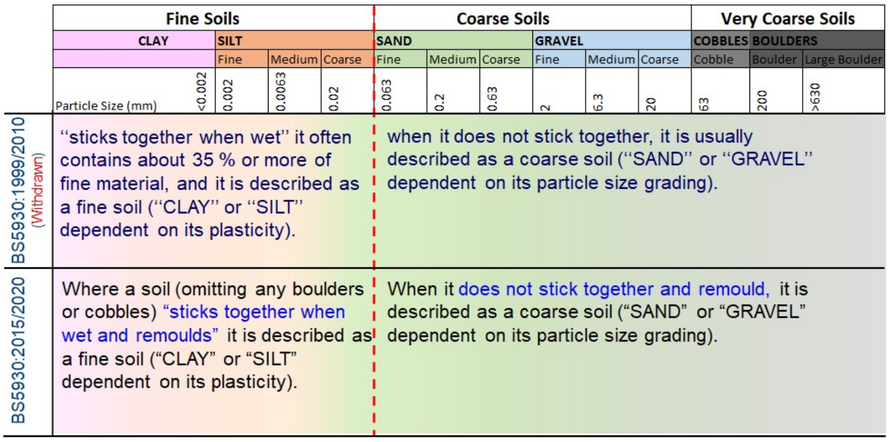


Figure 1. Key stages in an offshore windfarm project where geotechnical consultant's input is critical

Stage 4. Site characterisation: insight into soil classification and its impact in design

There are three classifications systems that are in practice today. These are ASTM D2487, BS 5930 and ISO 14688. BS5930 and ASTM D2487 are the most commonly used standards in the industry. BS 5930 and ASTM D2487 follow different methodologies when they classify the soils.

BS 5930 (2020) states that, where a soil, omitting any boulders or cobbles, 'sticks together when wet and remoulds' it is described as a fine soil: 'clay' or 'silt' dependent on its plasticity and when soil does not stick together and remould, it is described as a coarse soil: 'sand' or 'gravel' dependent on its particle size grading. BS 5930 (2010) stated that fine soil often contains about 35 % or more of fine material, however this statement was removed in the 2015 and 2020 version of BS5930 Figure 2, because soils with even less than 35% fine material can stick together when wet and remould.



	Fine Soils				Coarse Soils						Very Coarse Soils		
	CLAY	SILT			SAND			GRAVEL			COBBLES	BOULDERS	
		Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	Cobble	Boulder	Large Boulder
	Particle Size (mm) <0.002	0.002	0.0063	0.02	0.063	0.2	0.63	2	6.3	20	63	200	>630
BS5930:1999/2010 (Withdrawn)	"sticks together when wet" it often contains about 35 % or more of fine material, and it is described as a fine soil ("CLAY" or "SILT" dependent on its plasticity).				when it does not stick together, it is usually described as a coarse soil ("SAND" or "GRAVEL" dependent on its particle size grading).								
BS5930:2015/2020	Where a soil (omitting any boulders or cobbles) "sticks together when wet and remoulds" it is described as a fine soil ("CLAY" or "SILT" dependent on its plasticity).				When it does not stick together and remould, it is described as a coarse soil ("SAND" or "GRAVEL" dependent on its particle size grading).								

Figure 2. BS 5930 definition of coarse and fine soils

As per ASTM D2487, if more than 50% of the soil is retained on No. 200 sieve, 0.075mm, the soil is classed as a coarse-grained soil, and if 50% or more passes the No. 200 sieve, the soil is classed as a fine-grained soil. Note that the particle size boundary between fine soils and coarse soils is different in these standards, in BS 5930 it is 0.063mm whereas in ASTM D2487 it is 0.075mm.

It is evident that BS 5930 and ASTM D2487 do not define the classification of fine soils (clay or silt) and coarse soils (sand or gravel) in the same way. This leads to potential uncertainty in that the same material can be classified as coarse or fine soils depending on the standard followed. This in turn can lead to engineers mispredicting soil behaviour in design. The issue is highlighted in Figure 3 with an example of soil particle size distribution which would be classed as coarse soils, sand as per ASTM D2487, but it would be classified as fine soils, clay or silt as per BS 5930. The same issue would exist for soils whose particle size distribution is within the 'zone of contradiction'. Soils in these regions are predominantly silts which can have clay or sand type behaviour. Design engineers are often unaware that the classification standards followed in the project can have a major impact on the resulting soil classification. It is always advisable that design evaluations and soil behaviour is based on properties measured and not solely based on soil classification.

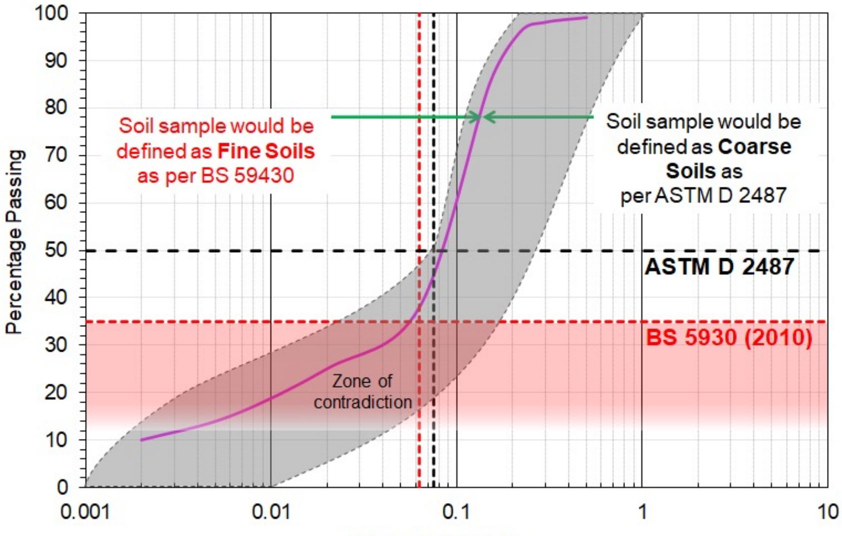


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Figure 3. Particle size distribution of a soil sample and how one soil sample could be classed differently by different standards

Stage 5a. Ground risks: geohazards

Windfarms can cover hundreds of square kilometres of seabed, hence ensuring that WTGs and cables are not exposed to geohazards both during their installation and operational lifetime is vital. Below are the most common geohazards that need to be considered during design and installation;

- Seafloor slope
- Landslides and earthquakes
- Faults
- Pockmarks
- Presence of boulders
- Shallow gas
- Channel system: palaeochannels
- Environmentally sensitive areas
- Manmade Hazards e.g. Unexploded Ordnance (UXO))

These geohazards need to be identified early in the project timeline and all identified risks need to be managed using appropriate risk mitigation mechanisms. This may include a modified or more stringent design, micrositing WTGs locations or re-routing the cable routes, change of installation procedure etc. It is acknowledged that some risks can never be fully eliminated, and residual risks may need to be managed through design or mitigated by some commercial mechanisms, such as insurance etc.

Stage 5b. Design: foundation design in rock

As windfarm sites move towards rocky seabeds, drilled and grouted piles in rock are becoming a common type of foundation. Therefore, insight into the skin friction of drilled and grouted piles in rock is critical for optimised design. While there are numerous empirical correlations that provide shaft friction in rock as a function of Unconfined Compressive Strength (UCS) of rock, they are mainly based on back-calculation for a given set of data from a particular rock type or a selected range of rock types. The shaft friction in rock is mainly dependent on rock mass modulus (E_m), roughness height (Δr) of rock socket and diameter of the rock socket.

Figure 6 presents a new framework that demonstrates the effect of E_m and socket diameter on the shaft resistance (Thusyanthan et al.2021). Unlike piles in sands and clays where larger socket diameters always provide larger pile axial capacities, larger piles in rock do not follow the same trend. If one assumes that the shaft friction of pile B is S, the shaft friction of pile

> ‘Unmanaged ground risks can have escalated impact on project cost and programme. Geotechnical consultant’s role in ground risk identification and mitigation is paramount for successful offshore wind projects’

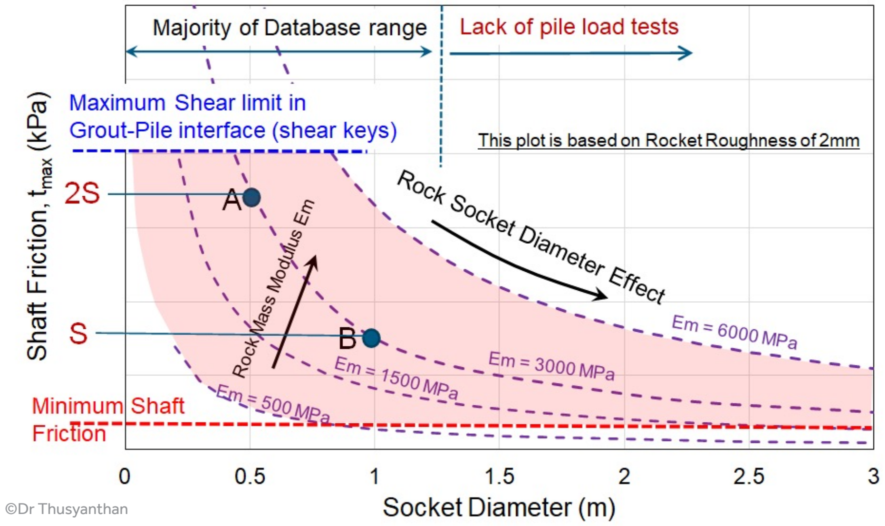

Figure 4. A framework for skin friction of drilled and grouted piles in rock after Thusyanthan et al.2021(Shaft friction of grouted piles in rock from new database of Pile load tests, ISOPE 2021)

A could be 2S considering an inverse diameter relationship. The shaft capacity of pile A is $2S \times (\pi \times 0.5) \times L$ and shaft capacity of pile B is $S \times (\pi \times 1) \times L$, where L is the pile length. Thus, both piles have the same axial capacity ($S\pi L$) even though pile B has twice the diameter. This demonstrates that careful assessment needs to be undertaken when deciding on socket diameter for pile design in rock. Increased pile diameter in rock will not lead to increased pile capacity.

Stage 6a. Installation: pile foundation

A foundation design that follows the optimum installation methodology leads to efficient foundation design and optimised installations costs. Pile installation methods in seabeds can be driven, drive-drill-drive or drilled & grouted. Seabed soil conditions determine which method is the most cost effective and has the lowest risk in a particular project as summarised in Figure 5. Selecting the appropriate installation method will lead to cost effective installation of the campaign.

Driven piles are common and cost effective in seabed conditions comprising sands and low to medium strength clays. In seabed conditions where driving refusal risk is high, for example in dense sands or high strength clays or soft rock, drive-drill-drive methodology is more suitable. In high strength clay and rocky conditions, driving could lead to pile fatigue damage and refusal. In this situation, a drilled & grouted pile installation would lead to an efficient solution.

Stage 6b. Installation: seabed ploughing and trenching for cable

All WTGs are connected via inter-array cables and linked to an offshore substation via terminal cables. The offshore substation is then connected to an onshore substation via export cables. All cables need to be installed at the correct burial depth to ensure they are protected from natural and man-made damage risks. Cable Burial Risk Assessment (CBRA) guidance offers a standardised and qualitative method to ensure that cable burial depths are determined consistently using a risk-based approach. It should be noted that CBRA only considers hazards anticipated during the operational lifespan of the cable and does not capture potential risks during installation.

Therefore, trenchability or ploughability assessment for cables needs to be undertaken to capture the installation feasibility and expected operation duration. There are several different methods for seabed intervention depending on the seabed conditions as shown in Figure 6.

Conclusion

If ground risks are not adequately mitigated in early stages of a project, their impact and consequences on project cost and programme can be very high at later stages. Thus, ground risks should be identified as soon as possible and mitigated early on through site investigation, ground modelling and design.

Geotechnical consultants play a key role in providing safe and efficient design solutions for foundations and cables in offshore wind projects. Ground risks in the project can be identified and mitigated by the early engagement of a specialist geotechnical consultant. In-depth knowledge of site surveys, geotechnical testing, seabed classification, foundation designs and seabed interventions are paramount for successfully derisking offshore wind projects.

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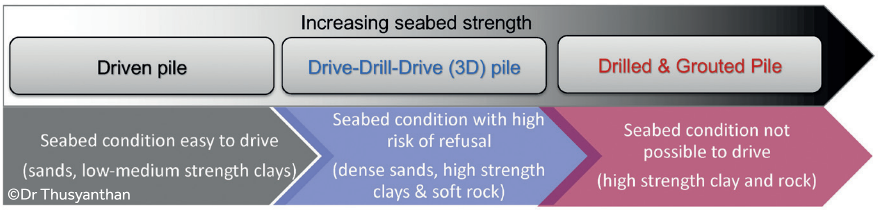

Figure 5. Recommended pile installation methods based on seabed condition

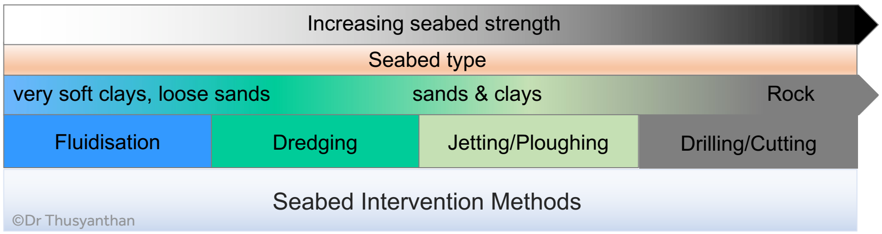

Figure 6. Recommended seabed intervention methods based on seabed condition