Practical Considerations for Advanced Laboratory Tests to Assist Pile Design for Offshore Wind Projects in Vietnam

Minh Nguyen[1](✉) and Man Bui[2]

[1] ODE Ltd., London, UK
minh.nguyen@ode-ltd.co.uk
[2] Soil Analysis Services, Dubai, UAE

Abstract. Recently, a significant number of new offshore wind projects has been proposed and some are under development in Vietnam and in Asia Pacific. For Vietnam, such move is logical as the country has abundant potential in offshore wind energy, as well as being very experience in the O&G developments since 1970s and particularly keen on promoting renewable energy. In fact, it is generally expected that although offshore wind is a relatively new in Vietnam, its development may be faster, lower in cost and less troublesome in comparison with other nearby Asian countries.

This paper gives an overview of the differences in obtaining the soil mechanical (stress-strength-stiffness) parameters in the foundation design between an Oil and Gas (O&G) platform jacket and an Offshore Wind Turbine (OWT) piled foundation (jacket pile or monopile) in accordance with accepted offshore standards (e.g. DNVGL-ST-0126 and DNVGL-ST-0437). It then describes the practical considerations which should be given to Advanced Laboratory Tests (ALT), especially cyclic testing strategy to reflect the extra demands given in the cyclic and fatigue behavior of the WTG piled foundation. The scope and content of the ALT strategy should be tailored to each OWT project, including the need for site-specific data, project budget and schedule.

The practical considerations for ALTs are well acknowledged by WTG design engineers but will need to be adapt into Vietnam condition. In addition, the existing capability and capacity constraints of accredited labs are known as other challenges, and these are opportunities for future study and co-operation.

Keywords: Laboratory testing · Site investigation · Offshore wind project · Cyclic tests · Site characterisation

1 Introduction

It has been estimated that Vietnam has a significant capacity of more than 100 GW in offshore wind energy resource, placing the country in the top-ranking potential areas for Offshore Wind Turbine (OWT) projects. The Vietnamese government is currently promoting and supporting renewable energy developments, especially offshore wind. It

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is expected that its offshore wind industry may develop quickly due to the success and extensive experience gained from the offshore Oil & Gas industry since 1970s.

In Vietnam, offshore projects are regulated at the national level with references to international offshore codes. It is anticipated that international standards and best practices, such as [1] and [2], will be of popular usage. To obtain a project certification at any stage (e.g. concept, feasibility, FEED, detailed design), the OWTs need to be evaluated for compliance with site-specific conditions. Consequently, the laboratory (lab) testing data, consisting of both standard and advanced lab tests (ALTs), becomes one of the critical inputs within the site dataset throughout the project's design life cycles. The ALT strategy is often a challenging issue for the engineer due to varying technical requirements from different required limit states. Moreover, its scope is subjected to both schedule and cost constraints. Furthermore, each project has many Wind Turbine Generators (WTGs) spreading over a very wide area and potentially employing several types of supporting foundation, introducing additional level of complexity. With these unique characteristics, the ALT strategy for any OWT project differ distinctly with the ones applied for a typical O&G platform.

Due to paper length limitation, the discussions and recommendations in this paper are purposely concentrated on the development of an ALT strategy applicable for WTG piled foundations (including monopile). The ALTs identified herein are specifically limited to the tests for determination of the stress-strength-stiffness characteristics from boring samples. These ALTs shall be carried out by accredited geotechnical lab, requiring full integration and supervision from the design and lab testing teams.

2 ALT Strategy for WTG Piled/Monopile Foundations

2.1 Main Considerations for the Design of Piled/Monopile Foundation

Offshore O&G platforms and WTGs are both subjected to challenging and varying wind and wave loading conditions during their installation and operational life. The offshore wind industry standards have been developed using earlier experience gained from the offshore O&G industry, such as the American Petroleum Industry (API) codes. There are, however, several distinct differences in the design for piles or monopile to support the WTG foundations as follow:

- Unlike an O&G platform, WTG structure is often considered as non-habitable and with shorter design life, and to be of lower Offshore Safety Class
- There are many more WTGs to be considered (via means of grouping/clustering)
- WTG loading is characterised by lower vertical load and higher horizontal and moment load compared to O&G platform, and this trend accelerates with increasing turbine size
- During its operation, the WTG rotates at different speeds/frequencies and therefore there are specific requirements to the system eigen-frequency range
- The jacket (four-leg) or tripod (three-leg) of WTG foundation is generally designed with less piles and offer limited means of loading redistribution. In contrast, O&G platform jacket provides more flexibility on load redistribution

- The monopile supporting the WTG is generally stiff and short, and its working behaviour is widely known to be significantly different from the long slender pile sizes normally employed under the offshore platform (see also [3–6])
- Lateral loading capacity of monopile at Ultimate Limit State (ULS) is often a controlling factor in pile size and pile length.
- Fatigue and cyclic degradation of pile capacity are more critical in WTG foundation
- It is important to establish/estimate the initial soil stiffness and subsequent changes for system frequency check and for the Fatigue Limit State (FLS).
- The WTG supporting structure must satisfy tighter limits for allowable deformations and permanent rotations in Serviceability Limit State (SLS).

2.2 ALTs for the Design of WTG Piled/Monopile Foundation

The discussions are specifically for the group of ALTs described in Table 1, with the details about test procedures and technical specifications can be found in [2] and the international codes for marine offshore site investigation [7].

Table 1. Identifications of the advanced lab tests (ALTs) required for WTG piled foundation

ALT group	Descriptions and objectives	Required testing equipment
ALT-1a	Compressibility/stiffness and consolidation characteristics, including intrinsic parameters	Incremental Oedometer & CRS Oedometer
ALT-1b	Static shear strength, stress-strain-response backbone curve and failure envelope	Triaxial (TX) & Direct Simple Shear (DSS)
ALT-1c	Static strength tests with small strain measurements (initial pseudo-elastic stiffness moduli)	TX with local strain sensors Bender Elements (BEs)
ALT-1d	Interface (soil-pile and soil-soil) strength tests	Torsional Ring Shear Bishop Ring Shear
ALT-2	Dynamic tests for small strain shear modulus, damping ratio, stiffness degradation	Resonant Column (RC) & BEs
ALT-3	Cyclic tests, strength and stiffness dependency w.r.t number of cyclic load and strain levels	Cyclic Triaxial (CTX) & Cyclic Simple Shear (CDSS)

2.3 ALT Strategy for WTG Piled/Monopile Foundation

The ALTs are often employed in conjunction with and as supporting evidence for in-situ tests. For example, tests in group ALT-1b are used to calibrate N_{kt} factor for PCPTs (piezocones). Another example is using ALT-1c & ALT-2 for checking the V_S profile obtained from using P-S suspension logging or seismic CPT. The tests in groups ALT-1c & ALT-2 are essential to define the damping ratio, small strain stiffness, and stiffness degradation. For all the required design limits (ULS, FLS, SLS) a combination of ALT-1a, ALT-1b, ALT-1c & ALT-3 help to create the static responses and the cyclic-dependent characteristics of the soils.

One important aspect of the ALT strategy is to identify a site-specific and design-phase dependent scope of ALTs to enable the derivations of realistic and well-defined soil parameters with reasonable degrees of confidence. The strategy should consider the previously described design characteristics of the WTG piled/monopile foundation and make use of the ground model interpreted. This requires closely collaboration between the design engineer and the site investigation lead engineer. Nowadays, more OWT projects are planned at sites that are outside the known database and experience of the Vietnam O&G industry. For example, silty soils with high mica content and prone to breakage are abundant in many parts of Asia Pacific. Another consideration is natural hazard such as typhoon, high sea current or geohazard like mega mobilized sand-waves. Due to paper's length constraint, such additional site-specific considerations for the ALT strategy are outside the scope of this paper.

ALT strategy becomes even more critical in special conditions, such as highly complex and irregular cyclic loadings, or dealing with intermediate soils (partial drainage), or where the design is pushed to the limit of existing technology. Suitable ratio of tests for ALT-1b (reference static strength tests) versus ALT-3 (cyclic tests) are essential. ALT is also important where previous database or soil type is not available, and to increase to confidence of the correlations to similar soil units/lithologies.

All in all, ALTs are expected as compulsory requirements by certifiers. An early and suitable (often small in relative cost) investment will return cost-efficient foundation solutions, bringing significant savings in overall foundation installation cost, helping to reduce project insurance premium, and limiting potential delays.

3 Establishing Backbone Stiffness Curve from a Combination of Various ALT Techniques

It is well established that geomaterials exhibit non-linear stress strain behaviour (Fig. 1, Fig. 2, and Fig. 3). In principle, The design of WTG piles requires stiffness degradation curves (G/G_{max} or G/G_0 versus shear strain, see Fig. 3) and damping curves.

The establishment of the backbone curve of soils to use with cyclic tests is achieved via using groups ALT-1b, ALT-1c, ALT-2 and ALT-3. Further detailed recommendations can be found in [8, 12]. Figure 3 shown in example of a backbone stiffness curve, drawn using a combination of various techniques: i.e. resonant column test (ALT-2) for strain level between 10-4% and 0.05%, triaxial test with local strain measurement (ALT-1c) for strain from 10-3% to 1–2% and conventional triaxial test (ALT-1b) for strains larger than 0.1%.

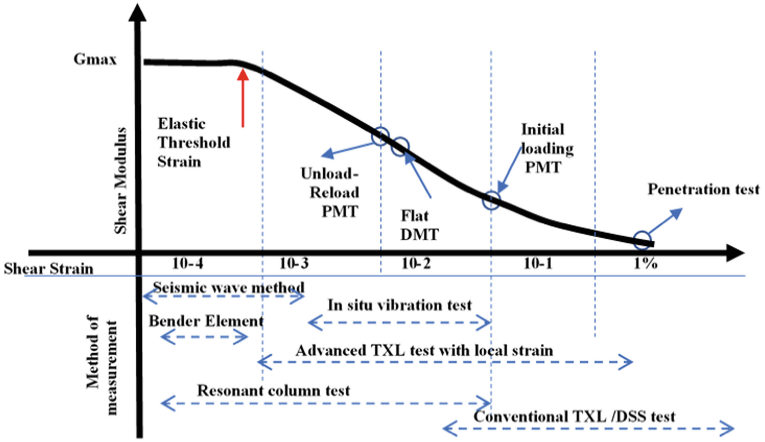

Fig. 1. None-linear stress-strain behavior of soil and testing techniques applied.

Figure 2 shows an example that due to system compliance, the conventional test with external strain measurement (ALT-1b group) yield significantly lower values of Young' modulus in comparison with test in which small strain sensors are employed (ALT-1c). In Fig. 2, the increase in stiffness at 0.05% local axial strain could be attributed to the closing of rock fissures/factures, which can be observed using local strain gauges but not external LVDTs.

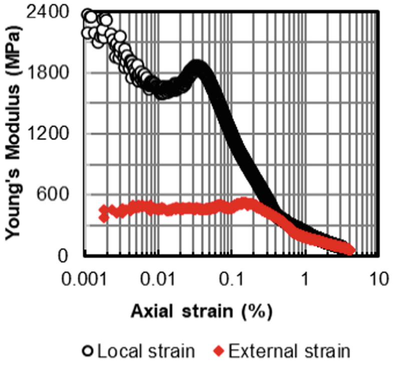

Fig. 2. Young's modulus for marine conglomerate (from ALT-1b/1c tests).

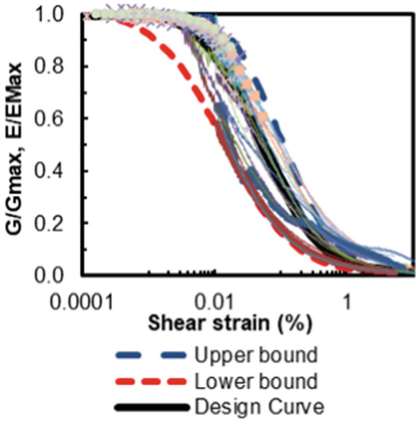

Fig. 3. G/Go curves established from ALT-2 (RC) and ALT-1b (TX) tests

4 Considerations to Cyclic Tests (ALT-3 Group)

Cyclic load causes pore water pressure built up, resulting in effective stress loss and soil strength and stiffness degradation, hence reduction in pile resistant capacity. Drained cyclic loading can also be important in the evaluation of soil stiffness changes. At relative (to vertical load) low loading levels, the WTG foundation is subjected to large number of cycles that create strain accumulation, which can affect the serviceability limit. Large number of loading cycles can also cause excessive permanent foundation settlement which affect the performance of the WTG as illustrated in Fig. 4.

Sample Preparation. Generally, sample preparation shall be carried out in accordance with testing standards (e.g. [7, 10, 11]). For sand it is important that the sand dry density should be the same of that in-situ, which can be estimated from CPT data [9].

Sample Saturation. It should be noted that 'saturation' process is not just simply adding water into the sample. Extra care should be made to avoid sample swelling (sample disturbance) during saturation, especially for overconsolidated clay. Therefore, dry dock method as per ASTM standard [10] or constant moisture content method [11] is recommended for saturation of cohesive soil. The maximum back pressure and minimum B-value should be identified depending on the actual soils.

Sample Consolidation. The consolidation stress path should take in to account the stress history, and/or pile driving effect such as densification and particle crushing for sand [12]. To minimize the effects of sample disturbance, recompression/reconsolidation methods [13] are recommended. For example, due to sample disturbance, undrained shear strength of a stiff clay sample with yielding stress ratio (YSR) of 3.0 could be significant underestimated up to 50%; this can be overcome by consolidating the sample to 2.5 times the overburden effective stress, $\sigma_{v0}^{'}$, then reduce the effective stress to $\sigma_{v0}^{'}$ prior to shearing. Ideally for overconsolidated clay, two phase K_0 consolidation stress path can also be employed, though the cost and testing time will significantly increase. It should be noted that some heavily consolidated clay soils with K_0 greater than one may lead to one-way cyclic loading mode instead of the two-way loading assumption. For sands, pre-drained shear stage may also be considered.

Cyclic Load Amplitude. Offshore WTGs are often subjected to a large number of repeated load cycles at extremely high amplitudes of wave, wind, and earthquake, etc. Cyclic stress amplitude shall be decided based on:

- The results of the structural analysis under the extreme wind/ wave load applied to the structures.
- The peak ground motion due to earthquake, if the windfarm is influenced by an active seismic zone in vicinity.
- The depth of the soil samples, e.g. the cyclic stress amplitude decreases with depth
- The design amplitude in relevant to the pile length for sense-check if the pile behaviour (in pile interaction diagram chart) are in stable zone or meta-stable zone.

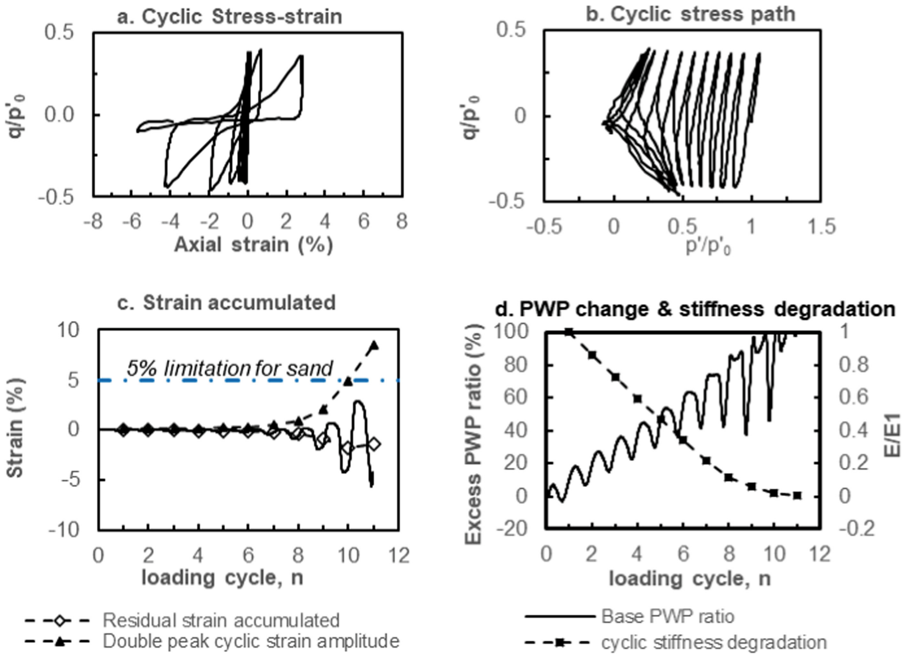

Fig. 4. Cyclic test and liquefaction of a calcareous sand at cyclic stress ratio of 0.20, $n_f = 10$

Loading Frequency. Equally important, the test rate effects shall be well considered. Rate of PWP built up depend on the loading frequency, which shall be specified as closest as possible to the actual frequency of the load actions. If the data are not available, the recommendations in Table 2 [after 7] can be used for guidance.

Table 2. Cyclic loading information in a CTXL test

Load type	Peak Earthquake	Extreme Hight Wave	Storm Gut (Extreme High Wind speed)
Minimum loading periods	10 s	3 h	10 min
commonly range of loading frequency (*)	1.0–2.0 Hz	0.08–0.18	0.20–0.50
Most common frequency specified	1.0	0.1	0.5
Minimum loading cycles	20	100–2000	100–300
Number of loading cycles specified	1500	2000	1500

Undrained vs Drained Cyclic Test. Cyclic tests can be conducted in either undrained or drained condition, depending on the testing purposes, soil types, and loading conditions, etc. For example, undrained test is likely the only option for liquefaction analysis or for assessment of soil stiffness degradation, while drained tests can be conducted for evaluation of long term foundation settlement under service loads [14] or time effects on pile shaft capacity due to increasing of soil stiffness.

Reference Monotonic Test (ALT-1b). It is also important to carry out the cyclic tests in ALT-3 group with identical procedures of sample preparation, saturation, and consolidation applied to the monotonic tests conducted at similar depths and soil units. A larger number of tests in ALT-1b group are commonly conducted in comparison with the cyclic tests in ALT-3 group to establish the reference shear strength envelopes.

5 Summary

This paper describes some main considerations for the ALT strategy to WTG piled foundation. One important aspect of the ALT strategy is to identify a site-specific and design-phase dependent scope of ALTs to enable the derivations of realistic and well-defined soil parameters with reasonable degrees of confidence. ALT strategy becomes even more critical in special conditions, where the design is pushed to the limit of existing technology. The strategy should consider the previously described design characteristics of the pile for WTG foundation and make use of the ground model/interpreted soil units. This requires due considerations to constraints on schedule, lab resource and technical capabilities. The points raised herein are brief due to paper length limitation, but it is expected to start the necessary interest and considerations of the practical geotechnical engineers and project managers.

The practical considerations are well acknowledged by WTG design engineers but will need to be adapt into Vietnam condition. Moreover, there are also known issues on existing capability and capacity constraints of many laboratories in the country. The Authors are looking forward seeing countermeasures to these challenges via co-operation and further studies.

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