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Predicting long term performance of Offshore Wind Turbines using Cyclic Simple Shear apparatus

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Abstract:
Offshore wind turbine (OWT) foundations are subjected to a combination of cyclic and dynamic loading arising from wind, wave, 1P (rotor frequency) and 2P/3P (blade passing frequency) loads. Under cyclic/dynamic loading, most soils change their characteristics. Cyclic behaviour (in terms of change of shear modulus change and accumulation of strain) of a typical silica sand (RedHill 110) was investigated by a series of cyclic simple shear tests. The effects of application of 50,000 cycles of shear loading having different shear strain amplitude, cyclic stress ratio (ratio of shear to vertical stress), and vertical stress were investigated. Test results were reported in terms of change in shear modulus against the number of loading cycles. The results correlated quite well with the observations from scaled model tests of different types of offshore wind turbine foundations and limited field observations. Specifically, the test results showed that; (a) Vertical and permanent strain (accumulated strain) is proportional to shear strain amplitude but inversely proportional to the vertical stress and relative density; (b) Shear modulus increases rapidly in the initial cycles of loading and then the rate of increase diminishes and the shear modulus remains below an asymptote. Discussion is carried out on the use of these results for long term performance prediction of OWT foundations.

Keywords: Cyclic Simple Shear, Offshore Wind Turbines**,** Stiffness,

1.0 Introduction and load complexity

Designing foundations for OWTs are challenging as these are dynamically sensitive structures in the sense that natural frequencies of these structures are very close to the forcing frequencies [1 2]. A designer apart from predicting the global natural frequency of the structure, must also ensure that the overall natural frequency due to dynamic-soil-structure-interaction does not shift towards the forcing frequencies. Further details can be found in references [2 3 4 5 6]. Figure 1 shows a schematic diagram of a monopile supported wind turbines with the main loads acting on them. The figure also shows the characteristics of the mudline bending moment acting on the pile head.

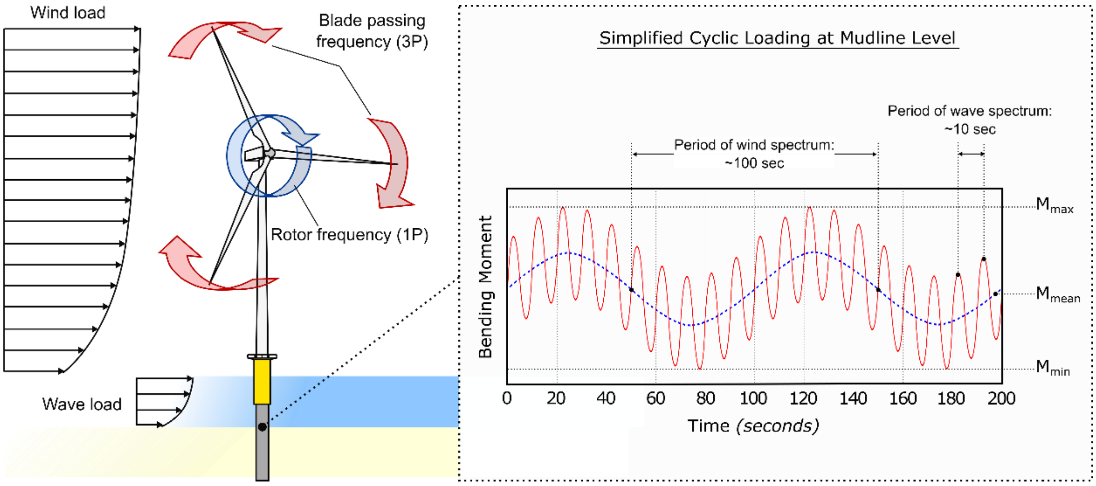

Figure 1: Loads acting on a typical offshore wind turbine foundation and typical mudline moment

Typically, in shallow to medium deep waters, the wind thrust loading at the hub will produce the highest cyclic overturning moment at the mudline. However, the frequency of this loading is extremely low and is in the order of magnitude of 100s (see Figure 1). Typical period of wind turbine structures being in the range of about 3 seconds [22] no resonance of structure due to wind turbulence is expected resulting in *cyclic* soil-structure interaction. On the other hand, the wave loading will also apply overturning moment at the mudline and the magnitude depends on water depth, significant wave height and peak wave period. Typical wave period will be in the order of 10sec (for North Sea) and will therefore have *dynamic* soil-structure interaction. A calculation procedure is developed in Arany et al [6] and the output of such a calculation will be relative wind and the wave loads and an example is shown in Figure 1. It is assumed in the analysis that the wind and wave are perfectly aligned which is a fair assumption for deeper water further offshore projects (i.e. fetch distance is high). Analysis carried out by Arany et al [6] showed that the loads from 1P and 3P are orders of magnitude lower than wind and wave but they will have highest dynamic amplifications. The effect of dynamic amplifications due to 1P and 3P will be small amplitude vibrations. Resonance has been reported in operational wind farms in German North Sea, see Hu et al [7]. Furthermore, there are added soil-structure interactions due to many cycles of loading and the wind-wave misalignments. Typical estimates will suggest that offshore wind turbine foundations are subjected to 10 to 100 million load cycles of varying amplitudes over their lifetime (25 to 30 years). The load cycle amplitudes will be random/irregular and have broadband frequencies ranging several orders of magnitudes from about 0.001 Hz to 1 Hz.

1.1 Dynamic and Cyclic Soil-Structure Interaction in offshore wind turbines

Based on the discussion above, the soil-structure interaction can be simplified into two superimposed cases, see [19] and is discussed below:

(a) Cyclic overturning moments (typical frequency of 0.01Hz) due to lateral loads of the wind acting at the hub. This will be similar to a "*fatigue type*" problem for the soil and may lead to strain accumulation in the soil giving rise to progressive tilting. Due to wind and wave load misalignment, the problem can be bi-axial. For example, under operating condition, for deeper water and further offshore sites, wind–wave misalignment will be limited for most practical scenarios. Wave loading, on the other hand, will be moderately dynamic as the frequency of these loads are close to natural frequency of the whole wind turbine system (typical wind turbine frequency is about 0.3Hz).

(b) Due to the proximity of the frequencies of 1P, 3P, wind, and wave loading to the natural frequency of the structure, resonance in the wind turbine system is expected and has been reported in German Wind farm projects [7]. This resonant dynamic bending moment will cause strain in the pile wall in the fore-aft direction which will be eventually be transferred to the soil next to it. This resonant type mechanism may lead to compaction of the soil in front and behind the pile (in the fore-aft direction).

Deformation of the pile under the action of the loading described in Figure 1 will lead to 3 dimensional soil-pile interaction as shown schematically in Figure 2. Simplistically, there would be two main interactions: (a) due to pile bending (which is cyclic in nature) and the bending strain in the pile will transfer (through contact friction) strain in the soil which will be cyclic in nature; (b) due to lateral deflection of the pile there will be strain developed in the soil around the pile. Figure 2 shows a simple methodology to estimate the levels of strains in a soil for the two types of interactions and is given by Equations 1 and 2. The average strain in the soil at any section in a pile due to deflection can be estimated using Bouzid et al (2013) as follows:

$$\gamma = 2.6\frac{\delta}{D_P} \tag{1}$$

Where δ is the pile deflection at that section (for example A-A in Figure 2) and D_P is the pile diameter.
On the other hand, the shear strain in the soil next to the pile due to pile bending, can be estimated using equation 2.

$$\gamma_1 = \frac{M \times D_P}{2 \times I \times E_P} \tag{2}$$

Where M is the bending moment in the pile, I is the second moment of area of pile and E_P is the Young' Modulus of the pile material. It must be mentioned that equation 2 assumes that 100% of the strain is transmitted to the soil which is a conservative assumption and calls for further study. In practice, this will be limited to the friction between the pile and the soil.

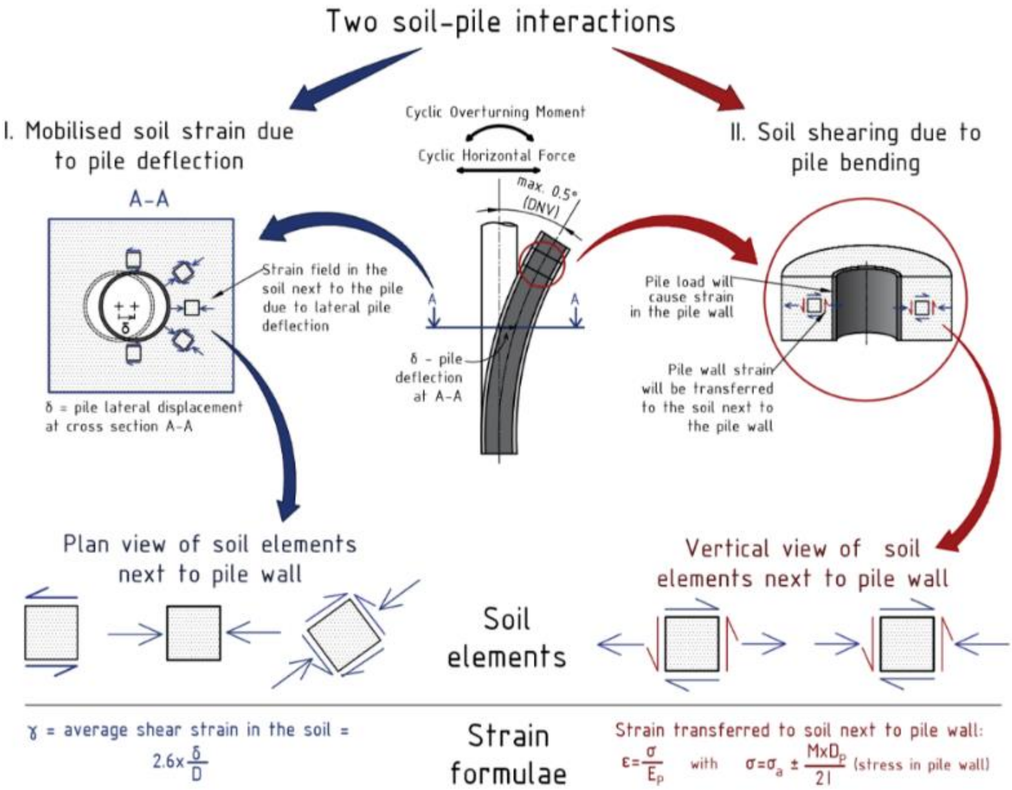

Figure 2: Two types of soil-pile interaction on a monopile supported wind turbine

1.2 Aim and scope of the paper

The aim of this paper is to study the cyclic soil-structure interaction through Cyclic Simple Shear apparatus where many testing parameters were changed. Tests have been carried out on a silica sand on three different relative densities (25%, 50% and 75%) where 50,000 or more cycles of uniform cyclic strain of different amplitudes were applied and also under three different vertical stresses. The intention is to develop a framework of understanding which can be used to develop a methodology for prediction of long term performance.

2.0 Cyclic Simple Shear Apparatus, materials and method of testing:

Cyclic simple shear apparatus, as shown in Figure 3 is used for testing cylindrical samples of 50mm in diameter and 20mm in height. The apparatus is capable of applying vertical and horizontal loads using two electro-mechanical dynamic actuators. External LVDTs were also used to record displacements and to verify the effectiveness of feedback control. Loads up to +/-5kN can be applied in two directions with horizontal travel up to 25mm and vertical travel of 15mm. These are sufficient to study the effects of large strain levels applied to the soil. This therefore allows to study effects of cyclic shear stress under drained and undrained conditions. The loads can be applied at frequencies of up to 5Hz. RedHill 110 Sand (poorly graded fine grained silica sand) was tested in this research as this soil has been used to carry out scaled model tests on different types of foundations. The sand has a specific gravity, G_s of 2.65 and minimum and maximum void ratio of 0.608 and 1.035 respectively. Further details of the properties can be found in [4].

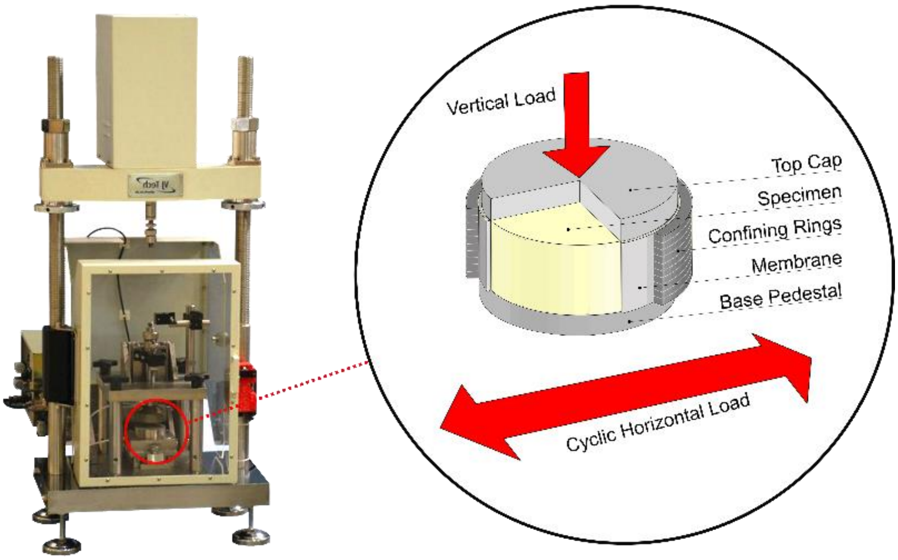

Figure 3: Dynamic/Cyclic Simple Shear Apparatus with details of the sample

Strain controlled tests were carried out on a loose to medium dense sand (Dr=50%) whereby the shear strain amplitudes were ranging from 0.02% to 10% and 50 000 cycles were applied. Table 1 shows the testing programme followed. The following types of tests were carried out:

Series A: Cyclic shearing at seven different shear strain amplitudes (γ_c) with constant vertical stress of 100kPa.

Series B: Cyclic shearing at three different vertical stresses (σ_v) with shear strain amplitude of 0.2%.

Series C: Cyclic shearing at two relative densities with shear strain amplitude of 0.2% and a constant vertical stress of 100kPa.

Table 1: Testing programme

Series	Test	Relative density, D_r	Frequency (Hz)	Vertical Stress, σ_v'(kPa)	Shear strain Amplitude (%)	Estimated* Cyclic Stress Ratio (CSR), τ_{max}/σ_v'	Cycles
A	T1	50 %	0.5	100	0.02	0.05	50,000
	T2	50 %	0.5	100	0.1	0.13	50,000
	T3	50 %	0.5	100	0.2	0.17	50,000
	T4	50 %	0.5	100	0.3	0.18	50,000
	T5	50 %	0.5	100	0.4	0.20	50,000
	T6	50 %	0.5	100	0.5	0.26	50,000
	T7	50%	0.5	100	10.0	0.95	50,000
B	T3_1	50 %	0.5	25	0.2	0.84	50,000
	T3_2	50 %	0.5	50	0.2	0.2	50,000
	T3_3	50 %	0.5	200	0.2	0.22	50,000
C	T3_a	25 %	0.5	100	0.2	0.15	50,000
	T3_b	75 %	0.5	100	0.2	0.14	50,000

* *Tests were strain-controlled and therefore shear stress is the response and CSR is based on the maximum shear stress recorded during the test.*

3.0 Test Results and Discussion:

3.1 Effect of shear strain amplitude on accumulated strain and shear modulus

Figure 4(a) shows the average vertical strain accumulation with number of cycles for seven shear strain amplitude tests for a vertical consolidation stress of 100 kPa plotted in a log scale. The rate of vertical strain accumulation reduces with number of cycles. Also, the accumulated vertical strain increases with increasing shear strain amplitude. Table 1 shows the Cyclic Stress Ratio (CSR) i.e. (τ_{max}/σ_v') for each of the Series A tests. It may be observed that with increasing CSR, the rate of accumulation of vertical strain increases. This observation is similar to Silver and Seed [8] where cyclic simple shear experiments were carried out on crystal silica sand for approximately 300 cycles. Figure 4(b) shows the shear modulus of the soil plotted for seven different shear strains. As expected, the initial shear modulus (i.e. before the cyclic stresses are applied) is dependent on the shear strain amplitude and reduces with increasing strain. The tests showed that the shear modulus generally increases with cycles of load.

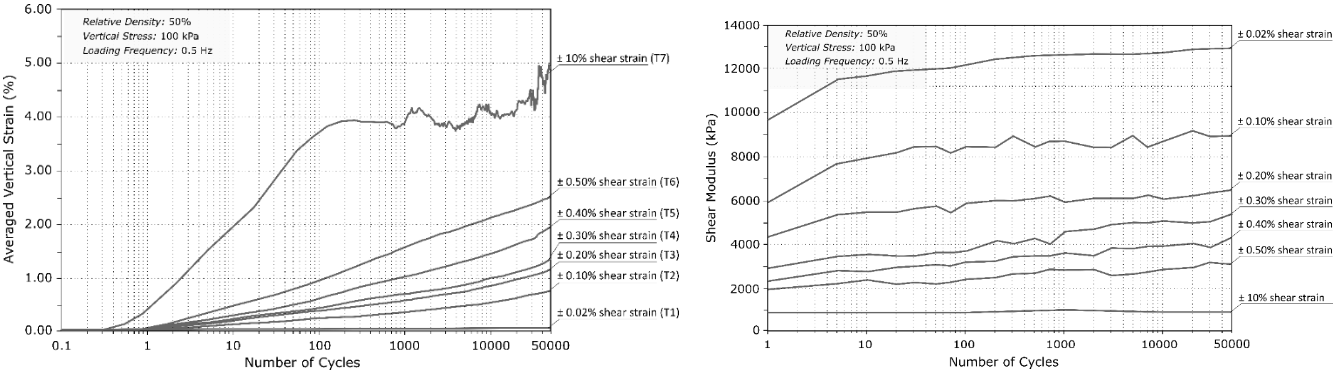

Figure **4**: **(a)** Vertical strain accumulation at vertical consolidation stress of 100 kPa**; (b)** Variation of Shear Modulus for different cyclic shear strain plotted against the number of cycles

In the context of Offshore Wind Turbine, the Soil-structure Interaction will differ at different depths and can be described by CSR (Cyclic Stress Ratio) which is essentially the ratio of shear stress to the vertical stress. Scaling laws deduced by Bhattacharya et al (2011), Lombardi et al (2013) showed CSR is proportional to the average shear strain around the pile. It is also quite clear that the soil at shallower depths are subjected to higher shear stress and low vertical stress giving a higher value of CSR. In this context, it must be mentioned that Abdel-Rahman et al (2014) used cyclic simple shear test to predict cyclic capacity degradation of axially loaded piles which are applicable for small diameter pile supporting a jacket structure.

3.2 Effect of vertical consolidation stress

The effect of vertical stress on the settlement of sand was studied by varying the vertical stress for constant shear strain amplitude of 0.2 %. Figure 5(a) shows that the vertical strain accumulation decreases with higher vertical stress. Figure 5(b) on the other hand plots the change in shear modulus with cycles of loading for increasing vertical consolidation stress suggesting shear modulus increase with increasing depth which is consistent with the expectations and observations of Series A tests.

3.3 Effect of density

The effect of density on behaviour of sand during cyclic loading was investigated for 3 relative densities [25%, 50%, and 75%] for a constant shear strain amplitude of 0.2 % and constant vertical stress of 100 kPa. Vertical strain reduce with increasing relative density as shown in Figure 6(a). In other words, sands with lower relative density will have a higher strain accumulation. Similar observations were also reported by Seed and Silver [9] but for much lower number of cycles. Shear modulus also increases with cycles of loading, see Figure 11.

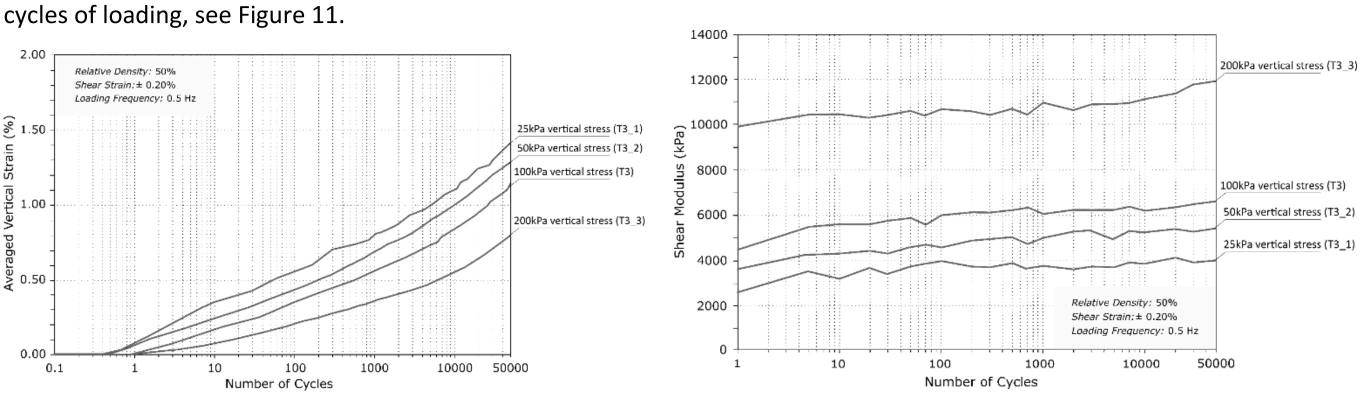

Figure **5**: **(a)** Vertical strain accumulation for different vertical consolidation stress applied at constant shear strain amplitude of 0.2%.**; (b)** Shear modulus with number of cycles at vertical consolidation stress of 100 kPa.

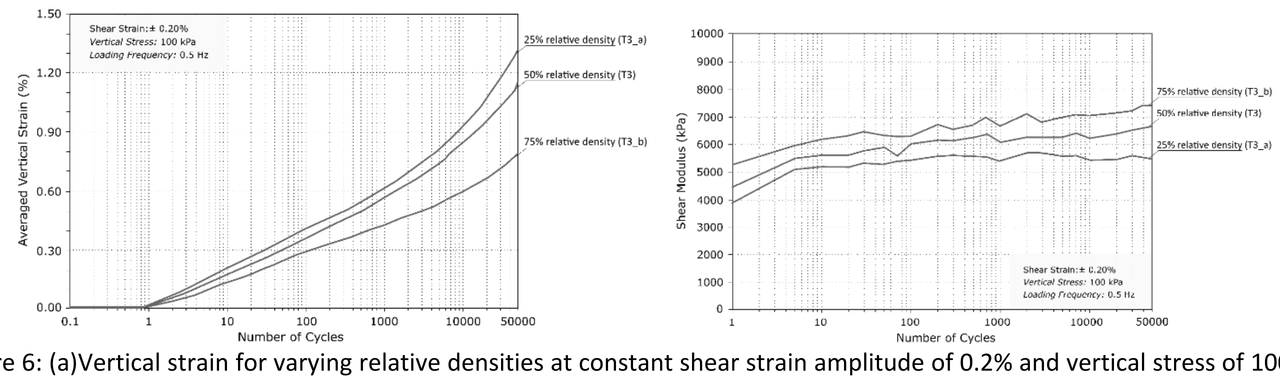

Figure 6: (a)Vertical strain for varying relative densities at constant shear strain amplitude of 0.2% and vertical stress of 100 kPa; (b) Shear modulus for varying relative densities at constant shear strain amplitude of 0.2% and vertical stress of 100 kPa.

4.0 DISCUSSION AND CONCLUSIONS

The reported cyclic simple shear test under different stress conditions (different strain amplitudes, vertical stress or density) showed that shear modulus increases with cycles of loading under drained condition. The increase of shear modulus is pronounced in the first few hundred cycles and then it stabilises. This result is consistent with the scaled model tests carried out on wind turbine foundations either in centrifuge [10] or 1-g [2 3 4 5 6 16] and Discrete Element Method (DEM) study [10]. While offshore wind turbine structures are designed for an intended life of 25 to 30 years, little is known about their long term dynamic behaviour under millions of cycles of loading. While monitoring of existing offshore wind turbine installations is a possibility and can be achieved at a reasonable cost, full scale testing is very expensive. An alternative method is to carry out a carefully planned scaled dynamic testing to understand the scaling/similitude relationships which can be later used for interpretation of the experimental data and also for scaling up the results to real prototypes. Leblanc et al [13] and later Cox et al [10] proposed an expression for change in foundation stiffness with number of cycles as shown by Equation 3.

$$K_N = K_0 + A_k \ln(N) \qquad (3)$$

where K_0 is the initial foundation stiffness and N is the number of cycles, A_K is a constant depending on the problem (load directionality and magnitude). However, the change in monopile stiffness is closely (if not solely) linked to change in soil stiffness. Methods based on numerical analyses have been proposed by Achmus et al [14], Bisoi and Halder [17 18] to analyse the soil-structure interaction issues. Based on a number of experimental investigations on monopiles and caissons, Equation 4 has been proposed to predict the accumulation of rotation with number of cycles [10] based on the data collected and subsequently best fitted.

$$\frac{\Delta\theta(N)}{\theta_S} = T.N^{\alpha} \qquad (4)$$

where N is the number of cycles and T is function of two parameters:

(a) ξ_b which specifies ratio of the maximum moment (M_{max}) to the static moment capacity, and
(b) ξ_c which represents the relative directionality (where ξ_c = -1 represents a symmetrical two-way loading and ξ_c = 0 represents a purely one-way regime). For detailed discussion about the function T, see [10] where the function is not presented in closed form but rather in figures.

For each loading condition the accumulation or retention of rotation could be assessed. The resulting change in rotation $\Delta\theta(N)$ could then be normalised with respect to the static rotation of the foundation [θ_s]. The fitting parameter α ranges between 0.18 and 0.39 and is obtained through scaled model tests where standard laboratory tests were used.

The next section highlights the main limitations of the above method:

(a) Equation 4 predicts a continuous increase of tilting with cycles of loading which seems to be physically unrealistic and may lead to overestimation of the tilt and uneconomic foundation design.
(b) It is difficult, if not impossible, to reduce many millions of cycles of complex load patterns (wave, wind, 1P and 3P) into a single amplitude (T) and cycle count value (N) number. The method may work if it is calibrated which seems a formidable task.
(c) The load acting on the foundation is a combination of different amplitudes arising from four different loads and may act in two different planes. However, the above method cannot take into account wind and wave misalignment. Apart from the above, wind turbines may vibrate in more than one direction and these directions will be different even in a single day.
(d) The method is calibrated for laboratory sand and real soil will have a very different behaviour. Therefore using equation 4 for real problems needs further thoughts.

Possible use of element tests for long term prediction

The element tests presented in this paper shed light on the cyclic soil-structure interaction and can be used to predict the long term change in soil stiffness under different combination of loads. While there is continual increase in accumulated strain, there is a flattening of the shear modulus suggesting non-progressive (non-monotonous) tilting of the foundation. Considering Figure 4(a), strain level depicted in tests T_7 will have a very low probability of occurrence in the lifetime while strain levels in T_1 will have a high probability of occurrence in normal operating conditions. Again, based on the understanding developed on the particular soil from the site (say Figure 4(a)), one can find the damage equivalence (for example accumulation of strain) of N_1 cycles of a particular strain level to N_2 cycles of another strain level. For example, based on Figure 4(a), it is clear that 100 cycles of ±0.5% strain level will cause a similar amount of strain accumulation to about 19400 cycles of ±0.2% strain level (follow the vertical strain between 0.5% and 1%). The real challenge is how to understand whether or not a linear strain accumulation model (as in fatigue) is acceptable for soils. In other words, if it is acceptable to take the linear combination of cycles of different strain levels due to extreme events (breaking waves, swell etc.) throughout the lifetime of the wind turbine according to Equation 4. An alternative way to avoid these issues is to find out from element tests, a threshold strain where cycles of loading will not cause any strain accumulation. In analogy with Fatigue Limit, this is *Endurance limit* of the material. Zero strain accumulation will suggest no tilting and it may imply larger pile diameter. If zero accumulation is ensured, it will not matter if the loading is one way cyclic or two way cyclic.

Conclusions

A series of element tests using Cyclic Simple Shear (DSS) Apparatus has been carried out to find out the change in shear modulus of the soil under different conditions of cyclic loading. The loading pertained to the particular scenario of offshore wind turbines. The results obtained from the element tests reinforced the observations from the scaled model tests and DEM analysis thereby boosting our confidence in the understanding of the physical mechanism and processes controlling the long term behaviour of these new structures. While scaled model tests can be insightful to understand the physical mechanisms, the scalability of the results to real application is difficult if the same soil is not used for the model tests. In such cases, element tests provide a better alternative. This paper shows element tests that may be helpful to predict the long term performance.

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References:

[1] BHATTACHARYA, S. & ADHIKARI, S. (2011). Experimental validation of soil–structure interaction of offshore wind turbines. *Soil Dynamics and Earthquake Engineering,* 31 (5-6)**,** 805-816.

[2] Bhattacharya, S (2014) Challenges in design of foundations for offshore wind turbines, IET Journal, Engineering & Technology Reference, 9 pp. DOI: 10.1049/etr.2014.0041 , Online ISSN 2056-4007

[3] Bhattacharya, S, Lombardi, D. & Muir Wood, D (2011): Similitude relationships for physical modelling of monopile-supported offshore wind turbines, International Journal of Physical Modelling in Geotechnics. 11, No. 2., 28-68.

[4] BHATTACHARYA, S., COX, J. A., LOMBARDI, D. & MUIR WOOD, D. (2012): Dynamics of offshore wind turbines on two types of foundations. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering,* 166**,** 159 –169. doi:10.1680/geng.11.00015

[5] BHATTACHARYA, S., NIKITAS, N., GARNSEY, J., ALEXANDER, N. A., COX, J., LOMBARDI, D., MUIR WOOD, D. & NASH, D. F. T. (2013): Observed dynamic soil–structure interaction in scale testing of offshore wind turbine foundations. *Soil Dynamics and Earthquake Engineering,* 54**,** 47-60.

[6] Arany, L., Bhattacharya, S., Macdonald, J., Hogan,, S.J.(2014): Simplified critical bending moment spectra of offshore wind turbine support structures, Wind Energy http://dx.doi.org/10.1002/we.1812

[7] Wei-Hua Hu, Sebastian Thöns, Samir Said, Werner Rücker (2014) : Resonance phenomenon in a wind turbine system under operational conditions; Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014, Porto, Portugal, 30 June - 2 July 2014,A. Cunha, E. Caetano, P. Ribeiro, G. Müller (eds.); ISSN: 2311-9020; ISBN: 978-972-752-165-4

[8] SILVER, M. L. & SEED, H. B. (1971). Volume changes in sands during cyclic loading. *Journal of Soil Mechanics & Foundations Div*.

[9] JA Cox, CD O'Loughlin, M Cassidy, S Bhattacharya, C Gaudin, B Bienen (2014) Centrifuge study on the cyclic performance of caissons in sand; International Journal of Physical Modelling in Geotechnics 14 (4), 99-115(2014) http://dx.doi.org/10.1680/ijpmg.14.00016

[10] Cui, L. and Bhattacharya, S. (2014) Dynamic Soil-Structure Interaction around a monopile supporting a wind turbine; Micro to Macro IS-Cambridge.

[11] Lombardi, D., Bhattacharya, S. and Muir Wood, D (2013) Dynamic soil–structure interaction of monopile supported wind turbines in cohesive soil. Soil Dynamics and Earthquake Engineering 49, 165-180

[12] LEBLANC, C. (2009) Design of Offshore Wind Turbine Support Structures. Doctor of Philosophy, Technical University of Denmark.

[13] ACHMUS, M., KUO, Y.-S. & ABDEL-RAHMAN, K. 2009. Behavior of monopile foundations under cyclic lateral load. *Computers and Geotechnics,* 36 (5)**,** 725-735.

[15] Bouzid et al (2013) p-y curves from stress-strain of a soil: FE assessment, Geomechanics, Techno Press

[16] Cuéllar P, Georgi S, Baeßler M, Rücker W. (2012) On the quasi-static granular convective flow and sand densification around pile foundations under cyclic lateral loading. Granular Matter 2012; 14(1):11-25.

[17] Bisoi, S and Halder, S (2015) Design of monopile supported offshore wind turbine in clay considering dynamic soil–structure-interaction; Soil Dynamics and Earthquake Engineering 73, 103-117

[18] Bisoi, S and Halder, S (2014) Dynamic analysis of offshore wind turbine in clay considering soil–monopile–tower interaction; Soil Dynamics and Earthquake Engineering 63, 19-35

[19] Nikitas, G, Vimalan, N and Bhattacharya, S (2016) An innovative cyclic loading device to study long term performance of offshore wind turbines, Journal of Soil Dynamics and Earthquake Engineering, Volume 82, March 2016, Pages 154–160

[20] Abdel-Rahman, Achmus & Kuo 2014 “A numerical model for the simulation of pile capacity degradation under cyclic axial loading", 8th European Conference on Numerical Methods in Geotechnical Engineering (NUMGE 2014), Delft, 18-20 June

[21] Richter & Kirsch "Ein analytisch-empirischer Ansatz zur Bestimmung der Tragfähigkeit und der Verformungen von axial zyklisch belasteten Pfählen", Workshop Offshore-Gründungen von Windkraftanlagen, Karlsruhe (in German)

[22] Laszlo Arany, S. Bhattacharya, John H.G. Macdonald, S. John Hogan (2016): Closed form solution of Eigen frequency of monopile supported offshore wind turbines in deeper waters incorporating stiffness of substructure and SSI, Soil Dynamics and Earthquake Engineering, Volume 83, April 2016, Pages 18-32, ISSN 0267-7261, http://dx.doi.org/10.1016/j.soildyn.2015.12.011 **.**