Long-term behavior of monopile supported offshore wind turbines in silty sand

Sangeet Kumar Patra[1] and S. Haldar[2]

[1, 2] School of Infrastructure, Indian Institute of Technology Bhubaneswar, Odisha 752050, India.

ABSTRACT

Offshore wind turbine (OWT) has the potential to produce sustainable energy, if the structures are built economically considering the safety criteria. Monopiles are the common choice as an offshore foundation. The dynamic behavior of offshore wind turbine is extremely challenging due to complex nature of dynamic loads. The soil stiffness changes due to application of cyclic loading, which leads to change in stiffness of the overall system. Design of monopile supported offshore wind turbine primarily requires estimation of natural frequency of tower-monopile-soil system which has to be kept away from the wind, wave and rotor excitation frequencies to avoid resonance. Previous research studies on monopile foundation have been carried out under short term loading conditions and mostly on clay and pure sand. At various offshore sites silty-sand deposit is present at various depth. The effect of confining pressure, relative density, and strain rate on long term behavior of silty sand is reported in present study. Finally, the outcome is implemented in a finite element model to assess the long-term behavior.

Keywords: Offshore Wind Turbine; Monopile; Soil-Structure-Interaction; Cyclic Triaxial Test

1 INTRODUCTION

Wind energy has shown unprecedented growth to the production of renewable energy. Offshore wind turbines provide an increasing proportion of wind energy generation capacity because offshore sites are characterized by stronger and more stable wind conditions (Lombardi et al. 2013). Monopile is a common choice as foundation for OWT due to its simpler shape, easy to construct and economical (Cui and Bhattacharya 2016). OWT foundations are subjected to long-term cyclic loading arising from wind and wave and are designed for 25-30 years. During the design life it is subjected to 10^7 to 10^8 cycles of loading (Schaumann et al. 2011). The stiffness of the soil-foundation changes over the design life time of OWT due to which the natural frequency of the wind turbine-monopile-soil system also changes (Ma et al. 2017). Hence, understanding of the behavior of the wind turbine-monopile-soil system under long-term loading condition is essential. Offshore wind turbines are generally designed as soft-stiff approach, where the fundamental frequency of soil-monopile-tower system is placed between the rotor frequency (denoted as 1P) and blade passing frequency (denoted as 3P for 3 bladed turbines). Lombardi (2010) showed that the fundamental frequency of a wind turbine system changes with cycles of loading. Abhinav and Saha (2017) reported that change in the fundamental frequency of OWT structure is strongly dependent on the shear strain level in the soil surrounding the pile. API (2011) and DNV (2016) suggested the degradation of foundation stiffness under cyclic loading in sandy soil. However, Bhattacharya and Adhikari (2011), LeBlanc (2009) stated that the foundation stiffness for a monopile in sandy soil increases due to densification of the soil next to the pile. The primary reason for the change in foundation stiffness is due to strain-hardening (in sands) or strain-softening (in clays) behaviour of the soil supporting the pile (Bhattacharya et al. 2013).

The past studies examined the behavior of foundations on pure sand and pure clay. Various offshore sites have different sub soil profiles, such as silty sand, soft clay and dense sand at various depth (Gulathi 1989). Hence, the long term dynamic behavior of monopile supported offshore wind turbine founded in different types of soil need to be examined. This study examines the long dynamic behavior of silty sand under long-term cyclic loading using element tests. The formulation of a finite element (FE) model to predict the long term response of soil-monopile-tower system is also presented.

2 METHODOLOGY

2.1 Experimental program

To study the long term cyclic behavior of silty sand, strain controlled drained cyclic triaxial tests were carried out on dry samples. Dry specimens of silty sand with relative densities 30%, 50%, and 70% were prepared by pouring the pre weighted dry sample through a funnel whose spout was placed at the bottom of the membrane lined split mould. The funnel was slowly raised along the axis of symmetry and the mould was filled with soil in five layers and each layer is compacted with a tamping rod to achieve the desired density. The sample contains 86% sand, mostly fine graded with 10% silt and 4% clay. The soil is classified as silty sand (SM) as per unified soil classification system. The maximum and minimum void ratios of silty sand was observed to be 0.85 and 0.56 respectively.

The soil specimen having size 50 mm diameter and 100 mm height with relative densities 30%, 50% and 70% were prepared in the laboratory. The cyclic axial strain having ±0.2% and ±0.3% were applied at 0.5 Hz frequency for 10,000 cycles. Each sample were tested at 50 kPa, 100 kPa and 150 kPa confining pressures. The hysteresis loop in different cycles of loading is obtained and variation of secant shear modulus and damping ratio of soil is derived. The effect of relative density, confining pressure, and strain rate on the secant shear modulus and damping is studied. Amplitude of shear strain is computed from the axial strain using the following equation: $\gamma = (1+\mu)\varepsilon$, where μ is the Poisson's ratio of soil and taken as 0.3, ε is the axial strain, and γ is the shear strain applied to the soil specimen.

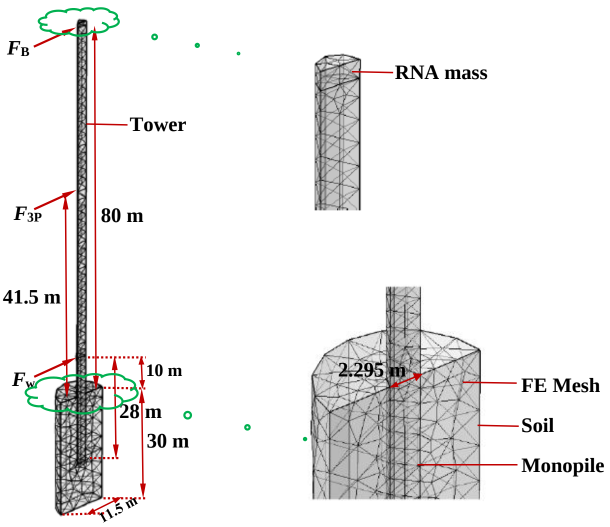

Fig. 1 Finite element model of monopile supported offshore wind turbine in silty sand.

2.2 Numerical model

A three-dimensional (3D) finite element (FE) model was carried out in COMSOL (2013) shown in Fig. 1. The properties of Vestas V90 3 MW OWT are considered (Table 2). An equivalent solid cylindrical section for the monopile and tower is considered to reduce the computational time. An equivalent diameter = 2.295 m for monopile is computed by preserving the flexural rigidity of actual and equivalent sections. In order to preserve the mass of the actual section, an equivalent density of the transformed section is estimated to preserve the mass of the system. The length and elastic modulus are kept same as that of original OWT. The mass of the rotor nacelle assembly (RNA) at the top is taken as a point mass. An elasto-plastic material with Mohr–Coulomb failure criterion is used to simulate the behavior of soil. Tetrahedral element is used for this analysis. A stiffness improvement model is incorporated for sand as (LeBlanc 2015),

$$E = 24\times10^{6} + 8.02\ln(N) \tag{1}$$

where E is initial young's modulus of elasticity of soil and N is number of load cycles.

Various loads, namely wind load (F_B), wave load (F_W) and blade passing (3P loads, F_{3P}) load were estimated using DNV-OS-J101 (2010). Wind load having magnitude 282 kN and frequency 0.0017 Hz is applied at the hub height as horizontal point load. Wave load having magnitude and frequency 716 kN and 0.125 Hz respectively is applied at the mean sea level. The blade passing load having magnitude and frequency 1 kN and 0.605 Hz respectively is applied at a height 41.51 from tower base.

Table 2 Dimensions and technical data for Vestas V90 3MW (Lombardi 2010)

Characteristic	Value
Rotor radius	45 m
Tower length	80 m
Tower mass	145 t
Tower base diameter	4.20 m
Tower top diameter	2.31 m
Tower second moment of area	0.5702 m^4
Tower Young's modulus	210 GPa
Tower flexural rigidity	1.20×10^{11} Nm^2
Monopile length	28 m
Monopile diameter	4.3 m
Monopile wall thickness	45 mm
Monopile mass	132 t
Monopile Young's modulus	210 GPa
Monopile second moment of area	1.3615 m^4
Monopile flexural rigidity	2.86×10^{11} Nm^2
Rotor-nacelle mass	111 t
Rotor operational Interval	8.6-18.4 rpm

3 RESULTS AND DISCUSSION

3.1 Experimental result

The hysteresis loops were obtained from the experiment which are shown in Fig. 2 for relative density (D_R) 50% and at 50 kPa confining pressure. Figure shows the variation of shear modulus at different loading cycles (1000 - 10000 cycles). It is found that the hysteresis loop is shifting upward up to 5000 cycles and remains constant for the subsequent cycles. This means at a particular strain amplitude the resistance offered by the soil to the externally applied load increases till 5000 cycles and remains constant thereafter. It indicates the strength of the soil first increases and then remains constant. It shows damping ratio decreases with number of cycles. Its value at 50 kPa confining pressure is found to be more than 150 kPa confining pressure. During loosest state the behavior of sand is nonlinear and have high value of damping. When confining pressure increases the particles come closer, hence the variation of damping ratio is small at high confining pressure. More denseness refers to less value of damping ratio (Fig. 3). As number of loading cycles increases damping ratio decreases. It means soil particles come closer and become denser. As a result, non-dimensional shear modulus ratio (ratio between the secant shear modulus at N^{th} cycle, $G_{S,\,N}$ to secant shear modulus at first cycle, G_{ini}) increases with respect to number of cycles (up 5000) and almost remains constants afterwards.

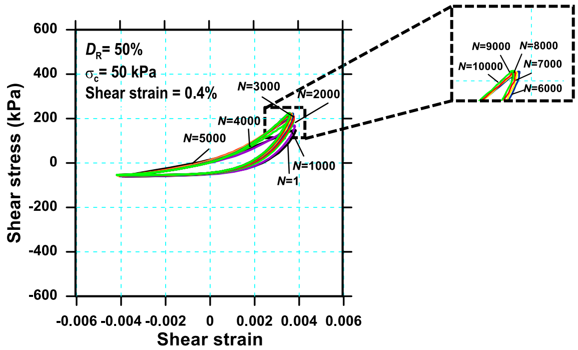

Fig. 2 Hysteresis loop at different cycle of loading at 0.4% shear strain for D_R = 50% and Confining pressure = 50 kPa.

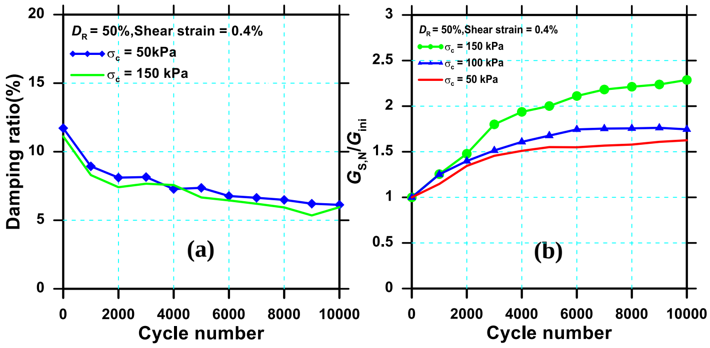

Fig. 3 (a) Damping ratio and **(b)** modulus ratio at different loading cycles at shear strain = 0.4% for D_R = 50% and confining pressures 50 kPa and 150 kPa.

3.1.2 Effect of relative density on shear modulus and damping ratio

Fig. 4 shows the variation of shear modulus at 150 kPa confining pressure and 0.4% shear strain rate for different relative density. From the figure it is concluded that if relative density increases shear modulus also increases because soil particles are in denser state of packing at higher relative density. Fig. 5 shows the variation of damping ratio at 30% and 50% relative densities for 0.4% shear strain rate and 150 kPa confining pressure. Damping ratio at 30% relative density is found to be higher than 50% relative density due to more nonlinearity in former case.

3.1.3 Effect of shear strain rate on shear modulus

The variation of shear modulus with number of cycles at 30% and 50% relative densities, 100 kPa and 150 kPa effective confining pressures and 0.26% and 0.4% shear strain rate is plotted in Fig. 6 and Fig. 7. If strain rate increases at a particular relative density and confining pressure shear modulus decreases.

3.2 Numerical analysis

Based on the experimental observation, an increasing trend of soil stiffness was observed due to increase in load cycles. A numerical analysis was carried out by applying the wind load, wave load and blade passing load on the offshore wind turbine structure. These loads were dynamic in nature. The time dependent analysis was also carried out for 500 loading cycles. The stiffness improvement model for soil proposed by LeBlanc (2015) is used. From the analysis, the maximum rotation of monopile at mud line is obtained at different load cycles which is shown in Fig. 8. From the Figure it is seen that the rotation angle is decreasing with number of cycles. It is due to the soil surrounding the monopile densifies due to cyclic loading applied by wind and wave. The maximum rotation at the end of five hundred cycles is found to be 0.3 degree.

4 CONCLUSION

The following conclusions can be drawn from the study:

Increase of shear modulus pronounced for first 5000 cycles and then stabilizes. Damping ratio decreases with cycles and a total 5 to 10 percent change in value is recorded. From the numerical model it is concluded that the rotation of pile decreases with number of cycles of loading. A detailed study is required on the development of a numerical model by calibrating the experimental results.

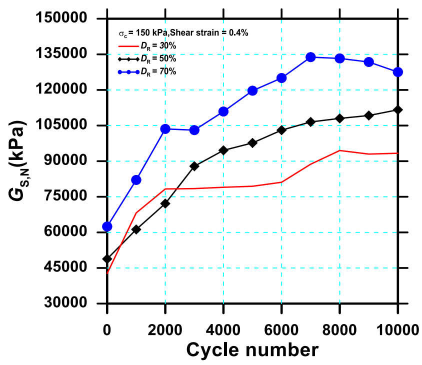

Fig. 4 Shear modulus at different cycle for confining pressure = 150 kPa, shear strain = 0.4% at different relative densities

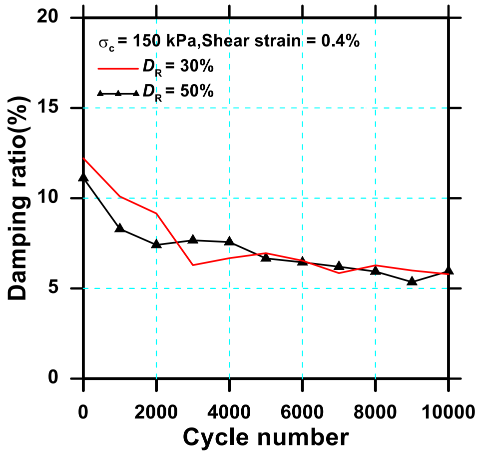

Fig. 5 Damping ratio at different cycles for Confining pressure = 150 kPa, shear strain = 0.4% at different relative densities.

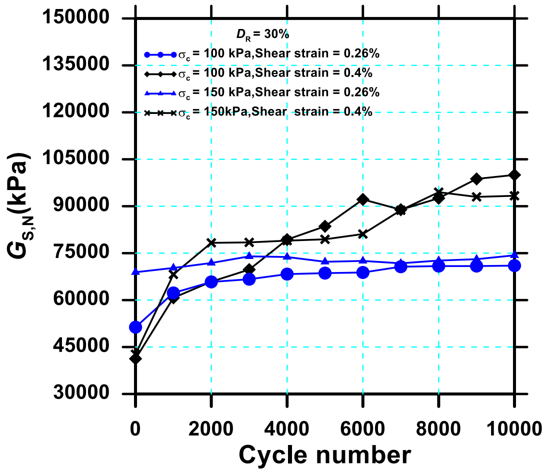

Fig. 6 Variation of shear modulus at different cycles for D_R = 30% at different confining pressures and shear strain rates.

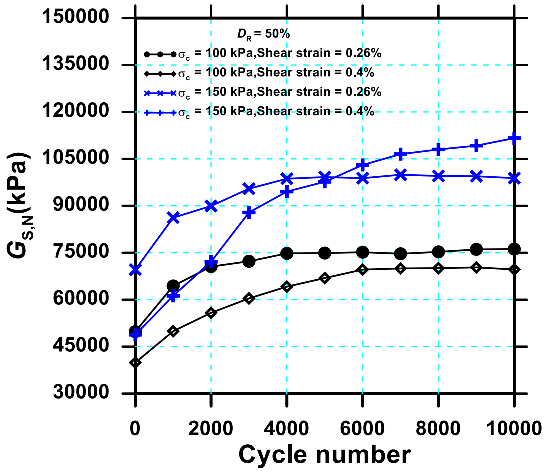

Fig. 7 Variation of shear modulus at different cycles for D_R = 50% at different confining pressures and shear strain rates.

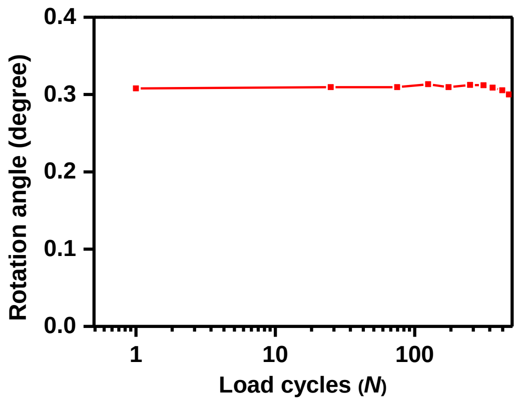

Fig. 8 Maximum rotation of monopile at mud line with number of load cycles

REFERENCES

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

Cui, L., and Bhattacharya, S. (2016). Soil–monopile interactions for offshore wind turbines. Proceedings of the Institution of Civil Engineers-Engineering and Computational Mechanics 169(4),171-182.

Schaumann, P., Lochte‐Holtgreven, S., and Steppeler, S. (2011). Special fatigue aspects in support structures of offshore wind turbines. Materialwissenschaft und Werkstofftechnik, 42(12), 1075-1081.

Ma, H., Yang, J., and Chen, L. (2017). Numerical analysis of the long-term performance of offshore wind turbines supported by monopiles. Ocean Engineering, 136, 94-105

Lombardi, D. (2010). Dynamics of offshore wind turbines. Doctoral dissertation, University of Bristol.

Abhinav, K. A., and Saha, N. (2017). Dynamic analysis of monopile supported offshore wind turbines. Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 170(5), 428-444.

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.

LeBlanc, C. (2009). Design of offshore wind turbine support structures. Doctor of Philosophy, Technical University of Denmark.

Gulhati, S. K. 1989. Geotechnical Aspects of the Indian Offshore Environment.

DNVGL-ST-0126 2016. Design of offshore wind turbine structures. DET NORSKE VERITAS.

API-RP-2GEO 2011. Geotechnical and foundation design considerations. American Petroleum Institute, Washington, DC, USA.

Bhattacharya, S., Nikitas, N., Garnsey, J., Alexander, N. A., Cox, J., Lombardi, D., Wood, D., M., and Nash, D. F. (2013). Observed dynamic soil–structure interaction in scale testing of offshore wind turbine foundations. Soil Dynamics and Earthquake Engineering, 54, 47-60.