INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 10th International Conference on Physical Modelling in Geotechnics and was edited by Moonkyung Chung, Sung-Ryul Kim, Nam-Ryong Kim, Tae-Hyuk Kwon, Heon-Joon Park, Seong-Bae Jo and Jae-Hyun Kim. The conference was held in Daejeon, South Korea from September 19th to September 23rd 2022.

Physical Modelling in Geotechnics
© 2022 KOREAN GEOTECHNICAL SOCIETY (KGS), Seoul, Korea, ISBN 978-89-952197-7-5

Monopile and hybrid foundation system comparisons under monotonic lateral loading

Y.A. Alsharedah, T. Newson & M.H.E. Naggar
Civil and Environmental Engineering Department, Western University, Canada
Affiliated with Civil Engineering Department, Qassim University, Saudi Arabia

J.A. Black
Department of Civil Engineering, University of Sheffield, United Kingdom

ABSTRACT: The move to ever deeper water for hydrocarbon recovery or for renewable energy sources, such as offshore wind farms, creates specific challenges for foundation designers. Large fixed vertical wind turbine tower structures are typically used to transfer complex loads to the foundations due the to combined effects of wind, wave and self-weight loading. All of these must be accommodated within very small displacement envelopes and natural frequency bands to allow the turbines to operate effectively. A series of centrifuge tests were conducted to investigate the benefits of adding a circular plate at the mudline to monopiles to form a “hybrid foundation system”. This type of foundation can benefit these structures since the turbines have low vertical to horizontal load ratio and are subjected to high overturning moments. Scaled physical modelling has been used to investigate the lateral capacity and stiffness under monotonic loading. Two models were tested: a monopile (MP) and a hybrid foundation (HF). Lateral loads were applied at similar eccentricity for both models to replicate prototype (field) conditions. Models were tested at 50g in over-consolidated kaolin clay beds prepared by inflight consolidation with a sand surcharge to increase the shear strength in the zone of influence of the model foundations. S_u and OCR varied from 12-27 kPa and 22-0.4 at the surface to the base of the centrifuge boxes, respectively. Results indicated that the HF had higher lateral capacity and comparable stiffness to the MP, whilst enabling a reduction of the monopile penetration depth and diameter.

Keywords: offshore wind turbines, monopile, hybrid foundation, centrifuge, green energy.

1 INTRODUCTION

Wind generated electricity production is on the rise, with the UK and Germany leading in Europe with output generating more than 20% of their electricity needs. Other countries are also resorting to green energy sources including Canada, US, China and few other countries. Offshore Wind Farms (OWF) have larger areas and uninterrupted wind providing higher power production (Lombardi et al., 2013). However, this comes at a penalty of higher grid cost, difficulty in maintenance and, from a civil engineering perspective, complicated loading leading to expensive foundation options. Typically, OWF support structures are predominately of a fixed nature with floating systems still in the research realm. The majority of fixed structures, about 80%, are founded on monopiles (MP) with routinely used diameters of 5-8m. Other types of fixed supports including gravity base foundations (GBF), jackets steel structure and suction caissons (Byrne and Houlsby, 2003). The turbine is carried on a tapered tower (superstructure) which is 3-6m in diameter that is supported on a transition piece which mounts on the foundation system (substructure). The tower diameter must be designed to withstand vertical loads and have sufficient capacity against buckling whilst being small enough to prevent increased wave and wind loadings. A variety of loads act upon the turbine components from waves, wind, 1P and 3P loadings. These loads, which are predominantly cyclic in nature, are transferred from the foundations to the ground leading to displacement and rotation, scouring, resonance and fatigue to the supporting foundation.

With increased capacity and strict rotation requirements coupled with more development in deep water to harness increased wind speed, it is anticipated that the monopile diameters will continue to increase posing problems of drivability and cost for development of new OWT. Since monopiles are free headed, i.e. having no pile cap to constrict rotations, they may undergo significant tilting and mudline displacement when laterally loaded. Because of strict regulations on tolerable tilting and to preserve the integrity of the offshore wind turbine generator (OWG), the maximum allowable rotation is set at 0.5 degrees (Malhotra, 2009). To limit tilting of OWT, either monopile thickness or diameters are increased to improve the foundation overall stiffness. However, increasing monopile diameter can lead to increased wave loading especially in deep water as wave loading is proportional to embedded structure diameter. Alternatively, improving the soil or adding a plate can increase the lateral stiffness and reduce the mudline rotation. To reduce the diameter of monopiles, several researchers attempted to use a hybrid foundation system which is a plate fitted with a short monopile in its centerline (Stone et al., 2007; Elmarassi et al. 2008). The physical mechanism by which improvement of the response of monopiles with plate added at mudline can be attributed to 4 aspects: it contributes to the restoring moment due to its weight, absorbs shear stresses through contact with soil, increases passive pressure underneath the plate thereby increasing resistance of lateral loads from the pile, and adds restoring moment from soil contact pressure (Lehane, 2014). For instance, Powrie and Daly (2007) studied an embedded retaining wall with a stabilising base in kaolin clay utilizing centrifuge modelling. Their results indicated beneficial effects from the stabilizing base to the retaining wall system. Wang et al. (2018) conducted a centrifuge study to investigate different OWT foundation systems, including a monopile, a GBF, gravel and steel wheeled foundations installed in a sand deposit and subjected to laterally applied monotonic and cyclic loading. They concluded hybrid foundation systems had higher stiffness compared to a monopile for resisting the lateral loads. Lehane et al. (2014) investigated the lateral and rocking responses of different hybrid foundations and suggested that the hybrid foundation plates improved the foundation performance compared to monopiles. Cherchia (2014) suggested that hybrid foundations can have a considerable cost advantage because the diameter and length of their pile is reduced compared to a monopile counterpart, and the material weight could be significantly lower than that of the monopile. Therefore, this study builds on the previous research indicating potential benefits of the hybrid foundation to the overall performance under lateral loads. This paper reports and discusses the results of monotonic lateral loading on model tests of a monopile and a hybrid foundation tested in Kaolin clay. The results from this study pave the way for future applications of this novel foundation.

2 CENTRIFUGE TEST PROGRAMME

The centrifuge testing program was carried at the Center of Energy and Infrastructure Ground Research (CEIGR) at the University of Sheffield. The 4m diameter beam centrifuge had a payload of 50g/t and is equipped with 32 channels data acquisition system. Two foundation options are investigated and compared to each other in an overconsolidated kaolin clay. Namely, a monopile (MP) of L/D ratio of 4.4 and D of 3.3 cm and a hybrid foundation (HF) with plate diameter (W) of 5cm and length of penetration (Lp) of 10cm. The models were all tested in an OC Kaolin clay made by Imerys, UK. A 4cm sand layer was placed at the bottom of the centrifuge tub and covered with a filter paper. The kaolin clay was mixed with water at 1:1 by mass and poured over the filter paper in the 0.5 m diameter centrifuge tub and left to settle. Afterwards the centrifuge tub was loaded to the beam centrifuge. Consolidation was done in stages moving from 10g to 50g over a period of 15 minutes to allow for equalisation of pore pressure. Models were tested in two different tubs (Tub1 and 2) under laterally applied monotonic and cyclic loading. This paper presents the results of the monotonic lateral loading. Table 1 shows tests information. Figure 1 shows an elevation view of the tested models, while table 2 presents model information. In both tubs, the clay bed was consolidated until 50g with 10cm sand surcharge giving 72 kPa at 50g. Subsequently, the sand was scrapped off and the models were installed at 1g (wished in place). This practice is reported in other studies (Lai et al., 2020; Hong et al., 2017). All instrumentation was calibrated to ensure their accuracy and functionality. Since wind turbines resist VHM loading, it was necessary to have vertical load applied, hence weights representing 20% of the vertical capacity were mounted on top of these models. Each model was pushed to failure under laterally applied load from a stress-controlled actuator. The clay profile was probed for shear strength, OCR and moisture content and unit weight determination. Figure 2 and 3 show the test setup and shear strength profile.

The pneumatic actuator can provide cyclic and monotonic loading. It has a capacity of 375N generated at 7Bars of input air pressure (Bayton et al., 2018). The eccentricity of loading was 115 mm for both models to produce an equivalent eccentricity for both tests. A rigid frame system was fabricated to carry the load actuator and laser sensors. Two laser sensors (Baumer OADM 12) were placed halfway from the box center to record consolidation data while other two further laser sensors were mounted on the rigid frame system and held opposite to tower face at 100mm vertical distance to record lateral displacement and rotation. Both models were instrumented with half bridge strain gauges (at 2cm/1.5cm intervals for MP and HF, respectively) to monitor bending moment evolution with lateral loading while offering compensation for heat generated strains. Epoxy coating was used to protect the strain gauges from water damage. The water table was maintained at or slightly above the clay surface to avoid desiccation.

Table 1 Tests matrix

Test ID	Foundation	Description	e, mm
T1	Monopile	Mono. Lateral load	115
T2	Monopile	Mono. Lateral load	115
T3	Hybrid foundation	Mono. Lateral load	120
T4	Hybrid foundation	Mono. Lateral load	120

Table 2 Model foundation details

	Properties	Model MP (N=50g)	Model HF (N=50g)
Tower	**L [m]**	0.1	0.1
	D_t [m]	0.033	0.028
	t_t [m]	0.003	Solid
	Material	Acrylic	Acrylic
	Added weight, grams	87	150
Monopile	**L_p[m]**	0.143	0.1
	D [m]	0.033	0.022
	t_p [m]	0	0
	Material	Acrylic	Acrylic
Plate	**W [m]**	N/A	0.05 0.0145 Acrylic

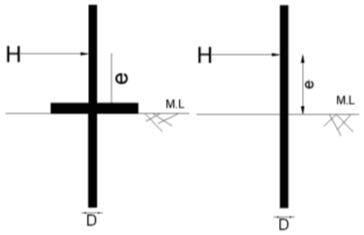

Fig.1. sectional view of the tested MP and HF models

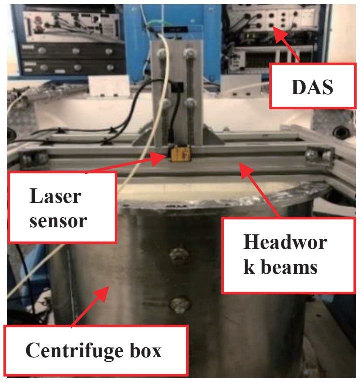

Fig.2. Centrifuge box and headwork before consolidation

3 RESULTS

3.1 Consolidation and shear strength profile

Inflight consolidation indicated a soft soil with average compression index of 0.49 and rebound index of 0.07. The C_v of the clay was estimated to be 8E-7 m^2/s while S_u (theoretical) and OCR varied from 12-22 to 27-0.4 at the surface to the base of the tub, respectively (Figure 3).

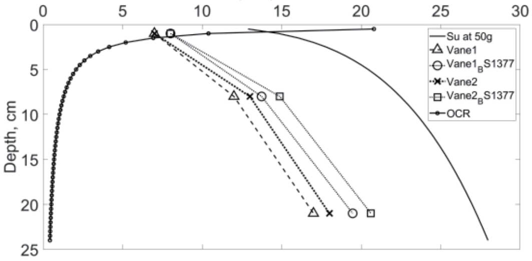

Fig.3. S_u and OCR profiles

3.2 Monotonic pushover

The capacity was taken as the highest reached value and was normalized by the foundation diameter and soil shear strength at 50g. Monopile and hybrid foundation had average normalized lateral ultimate capacity, $H_u/S_u{*}D^2$, values of 4 and 4.5 occurring at a deflection of 3.5 mm and 8mm, respectively, where H_u is highest reached load (Figure 4). This variation in capacity maybe attributed to load rate, installation disturbance, and consolidation effects. Test T2 was done after conducting T1 which could have resulted in a stiffer soil profile due to consolidation and reconsolidation happening between each test. Test 4, however, was conducted after T3 and showed smaller capacity. This may be a result of installation effects and contacts between plate and mudline. The initial stiffness values were 77.6 N/mm and 47 N/mm for MP and HF, respectively. Although the MP showed a stiffer response, the HF system, with smaller diameter and lesser embedment, continued to offer resistance at higher mobilized lateral loading. This improvement in lateral response with the hybrid foundation is believed to be from the positive soil structure interaction. It is believed that the positive interaction of the plate with the pile increased both the stiffness and the lateral capacity of the system providing comparable behavior with the MP. It is known that the soil shear strength is stress dependant, with lateral load being applied at eccentricity, part of the plate experience increased stresses leading to increased shear resistance not only at the plate soil level but also at the pile front. Stiffness increase, although not high as the H_u, can also be indicative of HF performance at serviceability loads.

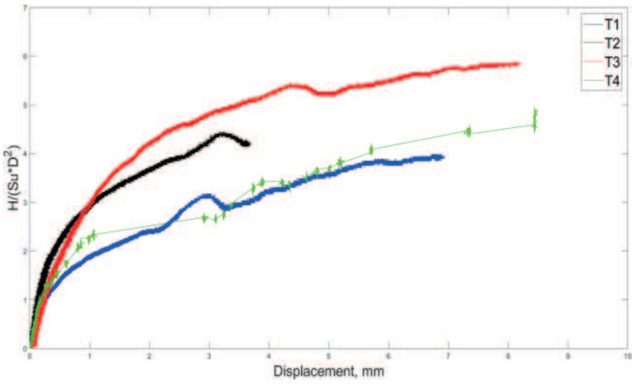

Fig.4. Load-displacement curves

3.3 Discussion of results

The monopile was loaded at 115 mm eccentricity above the mudline with the load-controlled actuator. The strain rate of loading for MP inferred from load displacement curve and the load time graph indicated the normalized speed, $\beta = (V{*}D)/C_h$, value is between 2.4 and 5.7 where C_h is the coefficient of consolidation, D is the diameter and V is the loading speed (Finnie and Randolph, 1994). These values fall within range of undrained loading. As the lateral loading proceeds, the pile face moves towards the soil and generates pressure on the soil both from pure shearing at pile edges and a combination of shear and compressive loading. This pressure is transferred to the soil pushing it outwards forming a gap with increased loading behind the pile. Under such high rate of loading, pore pressure is generated giving rise to undrained behaviour. This is believed to be a worst-case scenario as offshore wind turbines are typically exposed to low-speed wind loads for most of their lifetime with few major storm loads (Yu et al. 2019). These wave and wind loads can fall between drained and undrained loading therefore potentially increasing the soil strength and stiffness with time.

Having higher rigidity of the MP compared to the soil meant that its behavior can be classified as either flexible or rigid depending on the pile's relative rigidity compared to the soil. Poulos and Hull (1989) defined upper bound and lower bound values of E_pI_p/E_sL^4 for flexible and rigid pile as being 0.0025 and 0.208, respectively (Hong et al., 2017). Assuming the E_s value is $400S_u$, the pile has E_pI_p/E_sL^4 value of 0.109 which is within the above limits classifying the pile as semi-rigid. Figure 5 shows the B.M versus depth diagrams under different load levels from Test T1 (blue line in Figure 4). It can be observed the pile rotation and tilting is uniform across the height and the bending moment shows no sign of rotation and zero toe bending which is the typical behavior of rigid piles (Zhang et al. (2011), Wang et al. (2015), Byrne et al. (2015), Lau (2015), Lai et al. (2020)).

The hybrid foundation was loaded at 120mm eccentricity above the mudline with the load-controlled actuator. The strain rate of loading for the HF inferred from load displacement curve and the load time graph indicated the normalized speed, $\beta = (V*D)/C_h$, value is between 6.8 and 8.7. These values fall within range of undrained loading. As the lateral loading proceeds, the plate rotates around its axis generating restoring moments from the soil pressure and increasing pressure in front of pile face, all contributing to resistance of the applied lateral loads. Under such high rate of loading, pore pressure is generated giving rise to undrained behaviour. Repeated applied loading may cause differential settlement underneath the plate. In order to avoid these conditions, it is important to have the plate penetrates through the mudline to prevent separation from taking place, although this is out of the scope of this work. Figure 5 shows the B.M diagram for HF (Test T3, red line in Figure 4) under different loads. The bending moment was obtained by multiplying output voltage at each strain gauge location with the corresponding equation from calibration process. It can be observed the pile is exhibiting similar bending moment profile as that of rigid pile as the bending moment diagram shows no sign of flexing happening and zero toe bending which is the typical behavior of rigid piles (Zhang et al. (2011), Wang et al. (2015), Lau (2015), Lai et al. (2020)). Figure 5 shows that at higher loading conditions, the HF showed smaller or similar bending moment to the MP on average, which can be viewed as a benefit of the system reducing the pile size and minimizing steel use; this resulted from positive interaction of the plate absorbing some of the shear transferred loads to the hybrid foundation's pile.

A key point for OWTs is serviceability and therefore we have compared the evolution of rotation with applied loading. Since the capacities of the systems are close to one another, they were normalized from $0\text{-}1H_u$. Figure 6 shows that as the load progressed the MP and HF rotations pick up at similar rates. However, at serviceability loading value of 0.2, both MP and HF show similar trend. Therefore, from this point of view the HF has the potential and effectiveness to replace MP although with a smaller pile and BM.

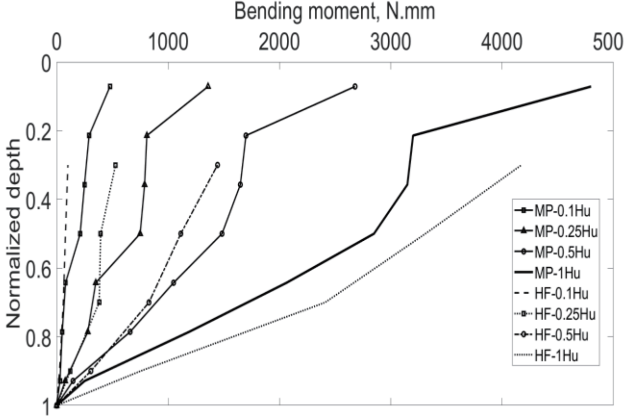

Fig.6. Bending moment profiles for HF and MP

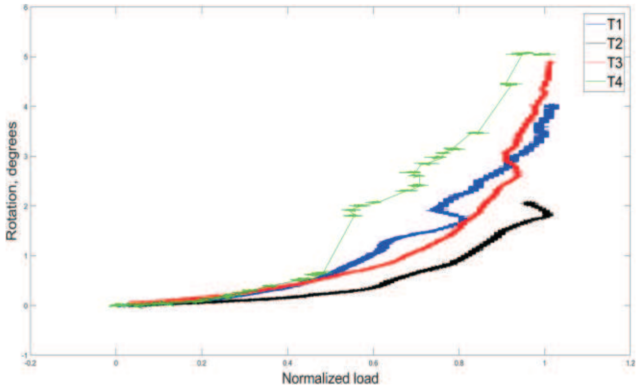

Fig.5. Rotation evolution with load

4 CONCLUSION

Models representing MP and HF systems have been scaled from prototype size to study their behaviour under monotonic lateral loading. The two models were pushed to failure laterally and their lateral ultimate capacity and response under working conditions were examined. The models were tested at 50g in an OC kaolin clay under undrained loading condition, a few conclusions were drawn:

1- At reduced length and pile diameter, the hybrid foundation offered similar capacity to monopile.

2- The observed bending moment (B.M) indicated rigid behavior for all models with no flexing due to the high E_pI_p/E_s values used.
3- At higher lateral loads, the HF pile experienced similar BM as the MP due to interaction of the plate with the soil and the pile. This indicates the HF can be advantageous in resisting lateral loads with improved distribution of stresses rendering efficient use of structural materials.
4- The soil structure interaction (SSI) improved the foundation response to lateral loading through distribution of loading into shear loads underneath plate, passive soil pressure in front of pile and through imparted resisting moment from plate.
5- On average, the MP offered increased stiffness response and less rotation at the mudline compared to HF. This is due to weak soil conditions underneath the plate, stiffer HF response is expected with stiff clay sites. This can be beneficial when pile driving is an issue and smaller piles are more practical.

REFERENCES

Bayton, S., Black, J., & Klinkvort, R. (2018). Centrifuge modelling of long term cyclic lateral loading on monopiles. In Physical Modelling in Geotechnics (1st ed., pp. 689–694). Routledge. https://doi.org/10.1201/9780429438660-103

Byrne, B.W. and Houlsby, G.T. (2003) “Foundations for Offshore Wind Turbines”, Philosophical Transactions of the Royal Society of London, Series A, Vol. 361, December, pp 2909-2930.

Cherchia, M. (2016). Centrifuge modeling of hybrid foundations for offshore wind turbines.

El-Marassi M., Elnaggar, M.H, Newson, T. and Stone, K. Numerical modelling of the performance of a hybrid monopiled-footing foundation. GeoEdmonton, 2008.

Finnie, I.M.S., and Randolph, M.F. 1994. Punch-through and liquefaction induced failure of shallow foundations on calcareous sediments. In Proceedings of the International Conference on Behavior of Offshore Structures, (BOSS), Boston, Mass. pp. 217–230

Lai, Y., Wang, L., Hong, Y., & He, B. (2020). Centrifuge modeling of the cyclic lateral behavior of large-diameter monopiles in soft clay: Effects of episodic cycling and reconsolidation. Ocean Engineering, 200, 107048– https://doi.org/10.1016/j.oceaneng.2020.107048

Lau, B. (2015). Cyclic behaviour of monopile foundations for offshore wind turbines in clay. ProQuest Dissertations Publishing.

Lehane, B. M., Pedram, B., Doherty, J. A., & Powrie, W. (2014). Improved Performance of Monopiles When Combined with Footings for Tower Foundations in Sand. Journal of Geotechnical and Geoenvironmental Engineering, 140(7), 4014027–.https://doi.org/10.1061/(ASCE)GT.1943-5606.0001109

Lombardi, D., Bhattacharya, S., & Muir Wood, D. (2013). Dynamic soil–structure interaction of monopile supported wind turbines in cohesive soil. Soil Dynamics and Earthquake Engineering (1984), 49, 165–180. https://doi.org/10.1016/j.soildyn.2013.01.015

Malhotra, S. “Design and Construction of Offshore Wind Turbine Foundations,” Wind Turbines, pp. 231-264.

Powrie, W., and Daly, M. P. (2007). “Centrifuge modeling of embedded retaining walls with stabilizing bases.” Geotechnique, 57(6), 485–497.

Stone K., Newson, T. and Sandon, J. (2007). An investigation of the performance of a ‘hybrid’ monopile-footing foundation for offshore structures. Proc. 6th Int. Conf. of theSociety of Underwater Technology, London, 391–396

Wang, X., Zeng, X., Yang, X., & Li, J. (2018). Feasibility study of offshore wind turbines with hybrid monopile foundation based on centrifuge modeling. Applied Energy, 209, 127-139. doi:10.1016/j.apenergy.2017.10.107

Y. Hong, B. He, L.Z. Wang, Z. Wang, C.W.W. Ng, and D. Mašín. Cyclic lateral response and failure mechanisms of semi-rigid pile in soft clay: centrifuge tests and numerical modelling. Canadian Geotechnical Journal (2017)