Centrifuge testing of offshore wind turbine foundations

Madhuri Murali[1], Francisco Grajales[1], *Giovanna Biscontin[2]*, Charles Aubeny[1]

[1] Texas A&M University, [2] University of Cambridge,

It is widely recognised that a mix of renewables will be required to meet mainstream energy needs and to bring about the benefits of a diversified energy portfolio. Offshore wind farms are becoming increasingly popular in the quest for renewable sources of energy. Many of the areas with the greatest potential for offshore wind energy development are in coastal waters where shallow depths extend relatively far offshore (DOE, 2008). Traditional offshore structures have very large vertical gravity loads and smaller horizontal loads. Wind towers, on the other hand, will have moderate vertical gravity loads with large horizontal loads and moments in proportion to vertical loads. Design paradigms which evolved in the offshore oil and gas industry are not readily applicable to the design of wind tower foundations offshore. Design codes for offshore wind towers are still very much in their infancy and do not provide sufficient guidance for designers.

The cost of the support structures accounts for about 24% of the total cost of building and operating an offshore wind plant. Decreasing the cost of the foundation system can be an important part of making wind a viable source of energy. However, it will require better understanding of the soil-foundation system response and better tools to model realistically, accurately, and effectively the influence of the soil and foundation on the whole system (Byrne et al., 2003). Currently, plans for offshore wind farms across Europe and North America are in various stages of development, with most of the projects being limited to less than 30-m deep waters in the North and Baltic Seas, primarily in the 5 to 12-m water depth range (Musial et al., 2006). Various structural configurations have been developed with monopiles or gravity based structures being the most common solutions for water depths shallower than 30 m (Byrne et al., 2003).

Although piled foundations under offshore loading conditions have been studied in detail over the years, the response of short aspect ratio piles (<L/D = 8) is not well understood. A principal aspect of pile response that requires assessment is the ultimate pile capacity to ensure that the foundation has sufficient strength in an extreme loading condition (Andersen, 2004).

A series of centrifuge model tests were carried out to investigate the response of short aspect ratio monopiles (L/D = 2) with both fixed and rotating head subjected to lateral loads in soft, normally consolidated clay.

The centrifuge experimental testing consisted of the following components:

1. Design and construction of the testing tools and model foundations.
2. Centrifuge testing of model caissons in soft clay (kaolin) at 70 g over a range of eccentricities, loading sequences and displacement amplitudes.

The centrifuge testing was carried out at the Network of Earthquake Engineering Simulations (NEES) facility at Rensselaer Polytechnic Institute. Loads were applied on the model foundations using the 4-degree of freedom in-flight robot with a customized tool, consisting of an adaptor designed and fabricated to latch onto the in-flight robot. This adaptor is used with 2 different types of pile caps to achieve both pinned and rigid connectors (Figure 1). The connectors to transfer the load onto the short monopile were designed and fabricated to allow both rotation and translation.

1. A ball and socket joint was developed with a spherical ball on the top of the pile cap and a cylindrical socket on the adaptor allowing the pile to rotate freely for a pinned joint (Figure 1a). The pinned connection was designed to apply moment with four different eccentricities; 1.2D, 1.5D, 2.5D and 3.5D

2. A rigid locking connection was designed with a flat plate to fit into a groove in the adapter providing a rigid connection (Figure 1b).

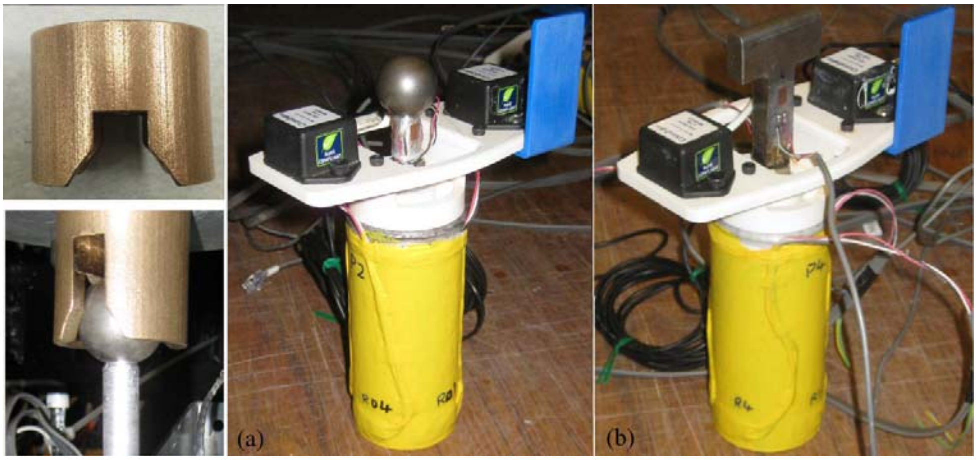

Figure 1: Adapter and pile cap connectors for rotation and translation.

Single dimensional Memsic 10 g accelerometers based on Micro-Electro-Mechanical Systems (MEMS) were used to measure the tilt by mounting them to the model foundations, Linear Variable Displacement Transducer's used to measure displacement. The model piles were also strain gauged to measure the applied lateral and vertical force.

The shear strength of the clay bed was characterized in flight by using a T-bar penetrometer developed at the University of Western Australia available at RPI (Randolph, 2006). The tests were carried out using a T-bar that was 5 mm in diameter and 20 mm in length, at a penetration rate of 2 mm/s. Water content profiles were also measured along the length of the test bed to compute shear strength.

All piles were tested at a centrifugal acceleration of 70 g by moving them laterally by a large displacement to obtain the ultimate lateral capacity under displacement control at a rate of 2mm/s. The effects of moment loading applied at different eccentricities and horizontal loading on piles was examined. T-bar penetrometer tests were carried out before and after each pile test to obtain the strength profile of the clay next to each pile. The self-weight of the pile and connectors simulated the constant vertical load of a light structure, while the lateral load was applied to reproduce the environmental loads. The ratio of vertical load to horizontal load (V/H) for these pile tests was computed to range between 2.1-3.2. Existing values for this ratio for offshore wind turbines in the literature are found to be ranging from 2.1 to 5.8.

The load-deflection curve for the pile tested in pure translation is presented in Figure 2a along with the calculated ultimate lateral capacity using methods proposed by Murff and Hamilton (1993), the API method (API, 2000) and finite element analysis for comparison. The lateral head load, H, is normalized by the product of the projected vertical area, LD, and a shear strength profile ($s_{u\ avg}$) based on the T-bar and water content strength profiles over the depth of pile embedment.

The monotonic response of the monopile subject to rotation was examined for four different eccentricities; 1.2D, 1.5D, 2.5D and 3.5D and is presented in Figure 2b. Similarly to the pile tested in translation, the lateral head load, H, at the top of the pile cap was computed and normalized by the product of the projected vertical area, LD, and an average shear strength profile over the depth of pile embedment, ($s_{u\ avg}$). The lateral displacement, y, was computed at the mudline using the tilt and displacement measurements and normalized by the pile diameter, D.

All the piles were pushed laterally at the top of the ball and socket connector to a displacement amplitude equal to 30% of the pile diameter. Thus the pile displacement amplitude at the mudline varied depending on the eccentricity. As expected the ultimate lateral capacity of the piles decreased with increasing eccentricity. Also observed is that the piles tested in rotation mobilize increasing strength with increasing displacements due to the rotational failure mechanism of short aspect ratio piles. Experimental data on model offshore foundations is particularly necessary to study combined loading and the influence of vertical loads on the lateral bearing capacity of these foundations.

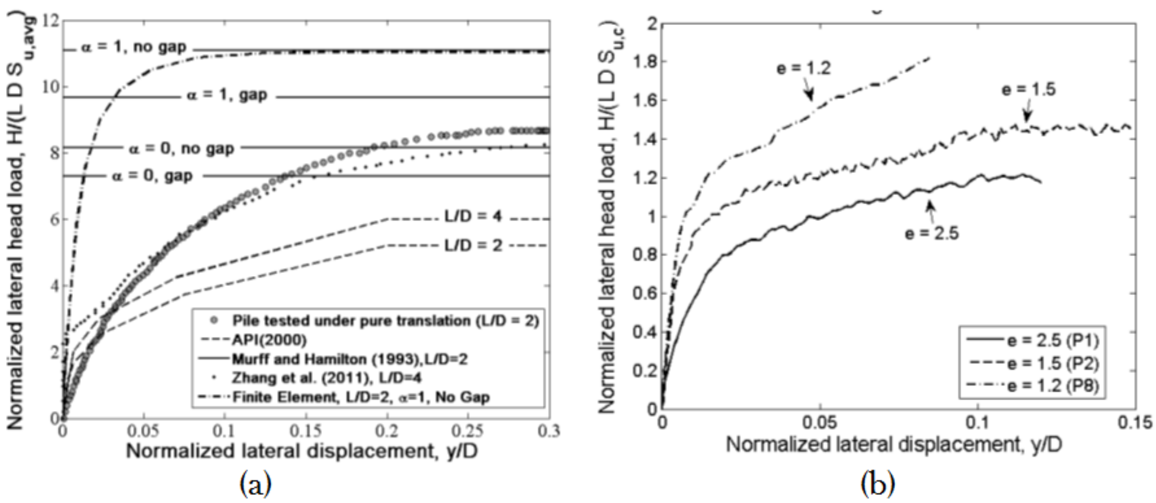

Figure 2: Force-displacement curves for pile tested in; a) translation; b) rotation.

Better tools are needed to model realistically, accurately and effectively the influence of the soil and foundation on the offshore wind turbine system. Good experimental data gives us a better understanding of the soil-foundation system response enabling the development of more efficient numerical models leading to more confidence in our designs.

Acknowledgements

The authors also acknowledge the National Science Foundation, NEES, and the project Capacity and Performance of Foundations for Offshore Wind Towers, Award Number: 1041604.

References

API, 2000. Recommended practice for planning, designing, and constructing fixed offshore platforms working stress design.

Andersen, K., 2004. Cyclic Behaviour of Soils and Liquefaction Phenomena. Taylor & Francis Group, London, Cyclic clay data for foundation design of structures subjected to wave loading.

Byrne, B., and Houlsby, G., 2003. “Foundations for offshore wind turbines”. Phil. Trans. R. Soc. Lond. A, 361, pp. 2909–2930.

DOE, 2008. 20% wind energy by 2030: Increasing wind energy contribution to u.s. electricity supply. Tech. Rep. DOE/GO-102008-2567, Department of Energy.

Murff, J., and Hamilton, J., 1993. “P-ultimate for undrained analysis of laterally loaded piles.” ASCE Journal of Geotechnical Engineering, 119 (1), pp. 91–107.