Centrifuge testing of a hybrid foundation for offshore wind turbines: experimental technique and preliminary results

M. Loli
National Technical University of Athens, Greece

K. Kassas
University of Dundee, UK

I. Anastasopoulos
University of Dundee, UK

ABSTRACT: A hybrid foundation for offshore wind turbines has recently been proposed, combining a monopile with a light-weight circular footing. The latter is composed of steel plates and stiffeners forming compartments, backfilled to increase the vertical load. A key aspect is a special pile–footing connection, which allows transfer of lateral loads and moments, but not vertical loads. The paper presents a preliminary experimental study, which was conducted at the University of Dundee, in order to investigate the performance of the hybrid foundation. Centrifuge model tests were conducted, comparing the response of the hybrid foundation to that of a traditional monopile. A novel modelling technique was developed in order to apply monotonic loading due to wind and cyclic loading due to waves, using a single screw-jack actuator. It is shown that the stiffness of the hybrid foundation is equal to that of a double length monopile, confirming its efficiency.

1 INTRODUCTION

Installation of offshore wind-farms equipped with larger, "new generation", wind turbines is planned with increasing frequency worldwide as a result of the consistently high winds in such environments, which guarantees reliable high power output. Especially in Europe, this is also motivated by the newly set EU target for 20% of the energy product to be produced via renewable sources.

The operation of a wind turbine generates substantial horizontal loading (wind and waves) which may be of the order of 65% of the vertical load in relatively lightweight systems (Houlsby & Byrne, 2000). Thus, their design is governed by the challenging combination of large, multi-cycle, overturning moments with low vertical loading as well as extremely strict deformation limitations. As a result, there is an urgent need for development of economically efficient foundation schemes. Currently, several types of foundations are implemented for offshore wind turbines, depending on the site conditions and water depth. In waters of medium depth, the monopile option dominates the industry, with the alternative being a recently introduced scheme. The latter was originally proposed for the foundation of offshore oil platforms and is generally known as 'suction caisson'.

Despite the advantages suction caissons, which are easier to install and can safely carry significant overturning moments (Byrne, 2000; Houlsby et al., 2005), the industry persists in the use of monopiles being reluctant to try out "untested" solutions. On the other hand, with the foundation and installation cost being of the order of 25% of the total cost, there is a very strong incentive to develop novel cost-efficient foundation schemes.

2 THE HYBRID FOUNDATION CONCEPT

The relatively new concept of hybrid subsea foundations has recently gained substantial ground due to particularly encouraging experimental and numerical research findings (Gaudin et al. 2011; Dimock et al., 2013; Fu et al., 2014). Such foundation systems typically consist of a combination of different, usually two, foundation types designed appropriately so as all the different parts to contribute to the total capacity in a targeted manner.

A hybrid foundation which combines a monopile with a surface footing has recently been proposed (Anastasopoulos & Theofilou, 2016), as schematically illustrated in Figure 1. This novel hybrid foundation system proposes the addition of a shallow foundation to the traditional solution of the monopile, aiming to increase the total moment capacity of the system and also provide a lateral restraint to the monopile. As a result, the length of the monopile may be substantially reduced, in comparison to the traditional solution, achieving significant cost savings. The footing is a specially-designed lightweight steel structure. It is proposed to use stiffeners forming compartments, as shown in Figure 1c, in order to minimize material cost. After installation on the seabed, the compartments are filled with soil (ballast) to increase the vertical load acting on the footing.

This invention also relies on a novel installation process: after installing the footing and the monopile, the wind turbine tower is connected to the footing, but not to the monopile. Due to this fact, the vertical loads of the tower and the wind turbine rotor (i.e., the dead loads of the structure) are transmitted only to the footing, increasing the vertical loads acting on it, and therefore enhancing its lateral resistance. Thanks to such decoupling of the two foundation systems involved, the entire vertical load of the structure is undertaken by the footing, while the monopile is engaged for lateral loads only. This is expected to significantly restrain the accumulation rotation during multi-cycle wave loading.

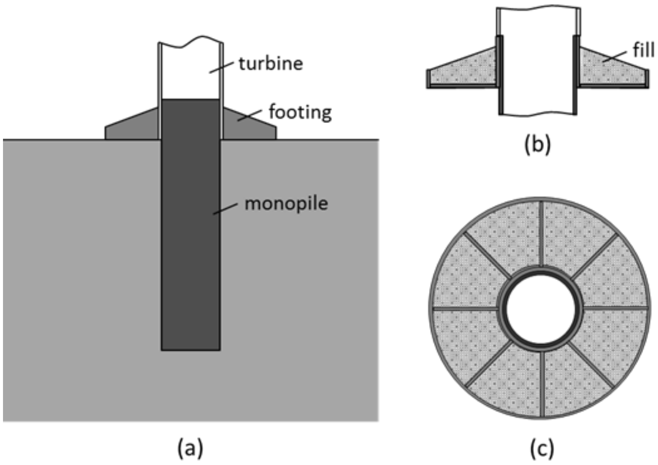

Figure 1. Schematic illustration of the proposed hybrid foundation: (a) the three main components of the system; (b) cross section of the footing and its connection to the tower and the monopile; (c) plan view of the footing.

Moreover, long-term consolidation settlements can be accommodated for, as in the vertical sense the monopile is not connected to the footing. This allows the footing to maintain contact with the soil, something that would not be feasible otherwise. The effectiveness of the proposed solution largely relies on the contact between the soil and the footing, and therefore such connectivity is of the utmost importance. Through special design of the connection, lateral shear forces and bending moments can be effectively transmitted onto the monopile, which can fully mobilize its stiffness and bearing capacity, working together with the footing. According to preliminary numerical analyses (Anastasopoulos & Theofilou, 2016), the invention may lead to a reduction of the order of 30% in foundation/installation cost, which corresponds to roughly 25% of the total cost. It may therefore have a very direct and measurable impact, leading to a reduction of the total cost of the order of 7%. Besides the obvious direct economic gains, such cost reduction can be instrumental in making the desired shift towards renewable energy as according to economic analyses, such investments are currently not viable, and means to reduce the cost are urgently needed.

Although the numerical analysis results are encouraging, experimental proof of the efficiency of the hybrid foundation was considered necessary. A series of centrifuge model tests were conducted to this end at the University of Dundee Soil Mechanics Laboratory and the results are presented in the following sections.

3 DEFINITION OF THE STUDIED PROBLEM

Figure 2 defines the main geometric properties of the specific problem investigated. The performance of the proposed hybrid foundation is assessed in comparison to the traditional monopile solution. Loading (N, Q_{wave}, Q_{wind}) for the case of a typical 3.5 MW wind turbine was considered. The total vertical load, N, is the result of the weight of the turbine and the tower (450 tons in total). Typical design values were adopted for the lateral, "working", loads: monotonic wind loading Q_{wind} = 1000 kN at 80 m height, cyclic wave loading $Q_{wave} \approx \pm$ 2000 kN.

Two alternative foundation solutions were compared, both installed in dense silica sand: (i) a conventional monopile of diameter d = 3.8 m and length L = 24 m (Figure 2a), and a hybrid foundation, consisting of a d = 3.8 m monopile of half the length, L = 12 m, and a footing of diameter D = 16 m (Figure 2b).

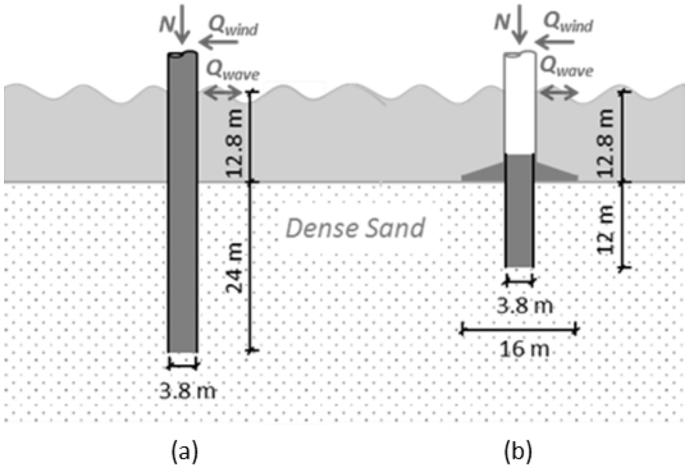

Figure 2. Definition of the two different foundation systems studied.

4 EXPERIMENTAL METHOD

Centrifuge modelling is an important tool in the armory of the geotechnical engineer, particularly for complex offshore engineering problems, because thanks to enhanced gravity it enables realistic simulation of stress fields in reduced scale models. Similitude is the main consideration in physical modelling using reduced scale models that are intended to capture the response of field-scale prototypes. A set of scaling laws have been developed to achieve similitude in centrifuge modelling, as detailed by Schofield (1980) and Kutter (1995), and were utilized herein to produce valid 1 : 80 (n = 80) models of the prototype foundation systems shown in Figure 2.

The physical models were constructed within a strongbox with dimensions 800 x 500 x 580 [mm], which provided enough space for both foundations to be tested during one spin. Figure 3 shows a cross-section of the physical model within the strongbox, containing both foundation alternatives, and indicates dimensions and instrumentation. Furthermore, Figure 4 illustrates photos taken at different stages of the model preparation.

The soil was prepared by air pluviation of dry fine Congleton silica sand (HST95, γ_{max} = 1758 kg/m^3, γ_{min} = 1459 kg/m^3, D_{60} = 0.14 mm, D_{10} = 0.10 mm) to achieve a uniform relative density $D_r \approx 80\%$. The sand was pluviated using a sand raining system (Figure 4a), capable of achieving controllable and repeatable relative density. The piles and the footing were modelled with aluminum and were put in place at 1 g during sand raining and model preparation. Emphasis was placed on the installation process and the connection of the footing with the monopile, allowing transmission of moment and shear forces, but not of axial loads.

The wave loading was imposed using a servo actuator, capable of imposing cyclic loading. Yet, lacking a second actuator to apply the constant wind load, the experimental set up was developed in such way that the constant moment acting on the pile or the footing due to the wind be applied indirectly through placing the mass of the turbine eccentrically. A cantilever beam was used to this end to support the (steel) mass at an appropriate distance so as the moment applied at the foundation midpoint (mass x g x cantilever length) to be equal to the moment load due to wind. This configuration has the important limitation of ignoring the simultaneous lateral load, yet it was the optimal viable option in view of the available resources and the project timescale.

A plate was attached upon the turbine to support the LVDTs measuring horizontal and vertical displacements as shown in Figure 3. It should be noted that the Figure shows the loading and instrumentation set up for testing the monopile, but exactly the same configuration was adopted while testing the hybrid foundation as well. In the conducted experiments, the monopile was tested first. Then, the centrifuge was forced to spin down and the loading and instrumentation set up was moved to the hybrid foundation model. Afterwards, the model was spun at the same g level and the loading protocol was repeated.

Before spinning the soil model was saturated with water. Yet, during the first test, a significant amount of water was lost due to leakage taking place during spinning. Therefore, a second test was conducted where fully saturated soil conditions were achieved. The following presentation of results focuses on the second, more realistic, test.

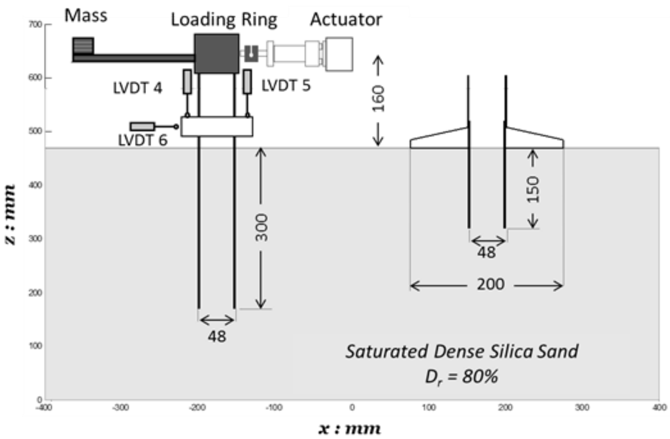

Figure 3. Cross-section of the physical model within the strongbox in model scale.

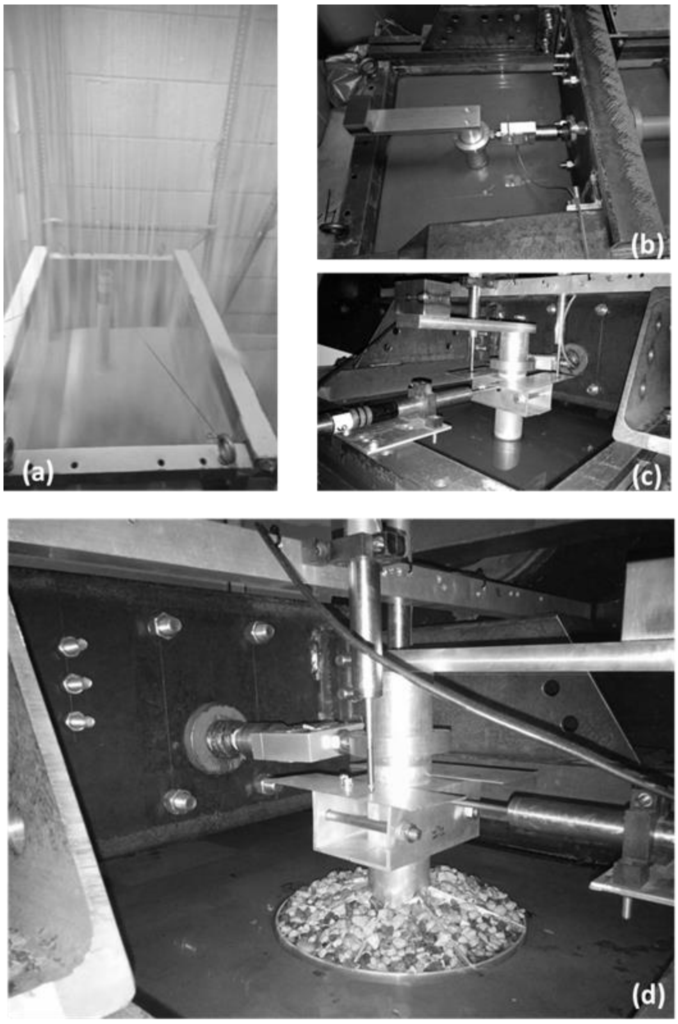

Figure 4. Photos of different model preparation stages: (a) pluviation using soil raining; (b) setting up the loading ring and

the actuator; (c) monopile model with instrumentation ready to be tested; and (d) hybrid foundation model with instrumentation ready to be tested.

5 PRELIMINARY RESULTS

The intention was to apply the same multi-cycle load protocol on both models. Yet, this was no easy task due to the significant noise associated with data acquisition. Figure 5 shows the time history of the cyclic (wave) load imposed on each of the two studied models. 10 cycles of lateral load with an amplitude of about 2000 kN were imposed in each case, yet, unluckily, only half of the response history was recorded during testing of the monopile (Figure 5a) due to instrumentation failure. It should be noted that the loading cycles where applied very slowly, practically statically.

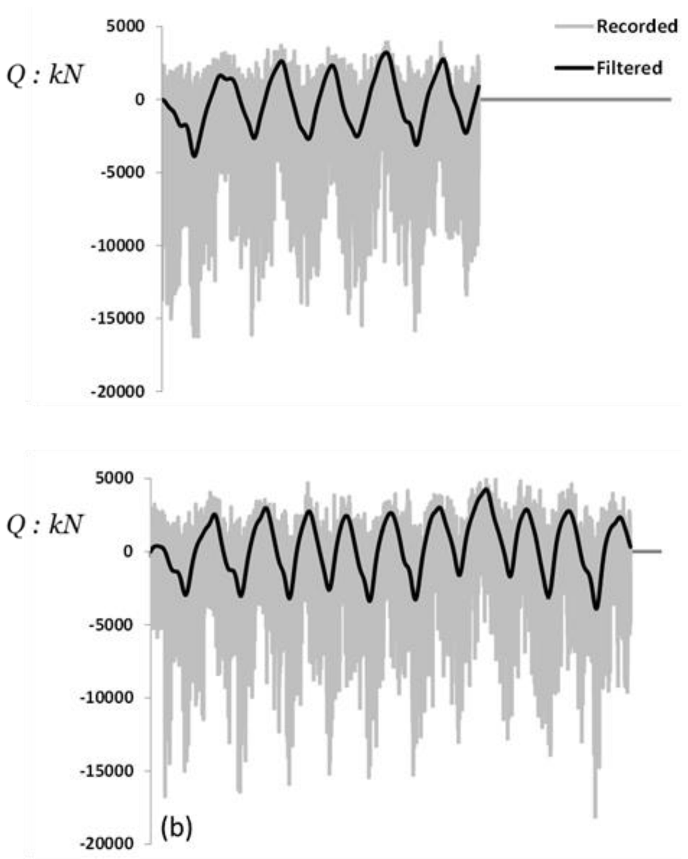

Figure 5. Cyclic loading protocol imposed on: (a) the monopile; (b) the hybrid foundation.

The hysteretic cyclic response of the two foundations is compared in Figure 6 in terms of lateral load − displacement ($Q - u$) and settlement − displacement ($w - u$). It is evident that, in both cases, the applied loads are significantly lower than the capacity of the foundations and both systems respond practically within the linear-elastic regime. Interestingly, and quite encouragingly, the hybrid foundation appears to have larger (although marginally) secant lateral stiffness than the monopile. Its performance is, however, less advantageous when settlements are considered. This came as no surprise as in the proposed hybrid foundation concept the vertical loads are carried by the shallow footing, which naturally has lower vertical stiffness in comparison to the pile.

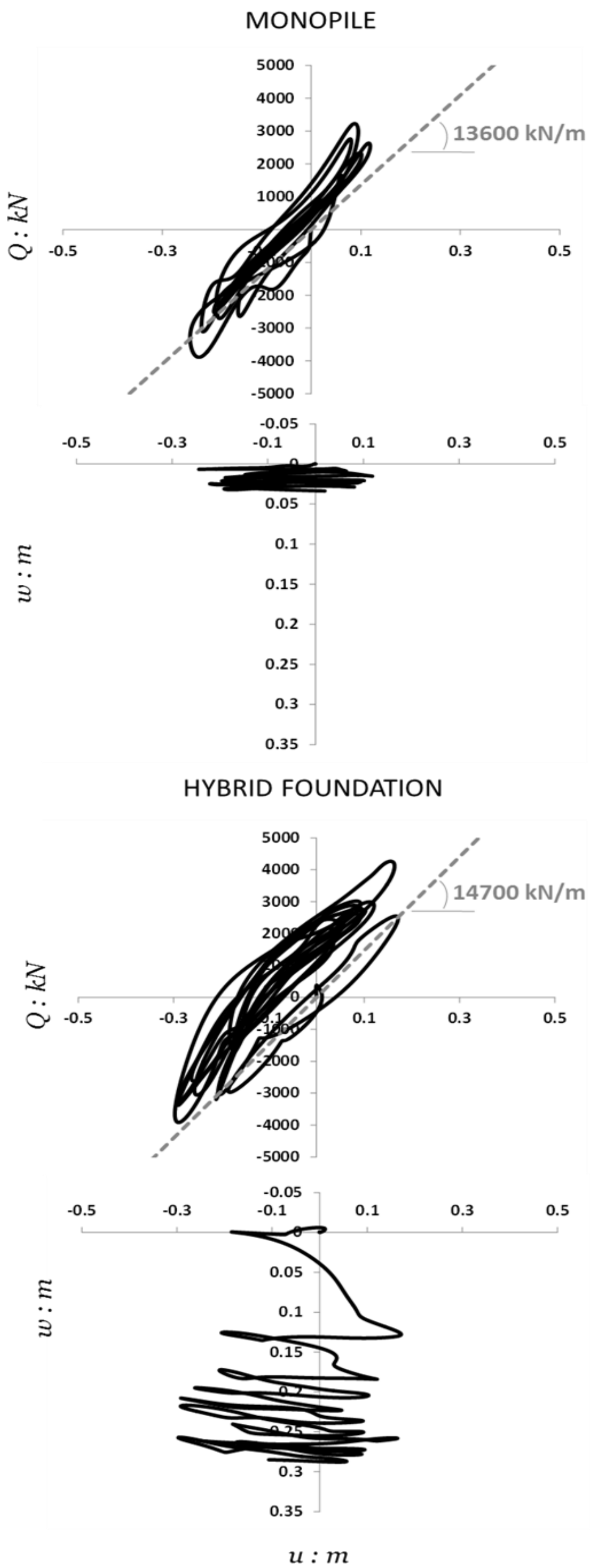

Figure 6. Comparison of the two alternative foundations performance in terms of: (a) lateral load Q − displacement u; and (b) settlement w − displacement u.

However, it is important to recognize that settlement rate drastically drops after a few cycles of loading. This observation, which becomes even more clear when settlement time histories are compared (Fig. 7), provides encouraging evidence that the proposed hybrid foundation will be able to safely accumulate settlements in real field loading conditions were thousands of loading cycles are involved.

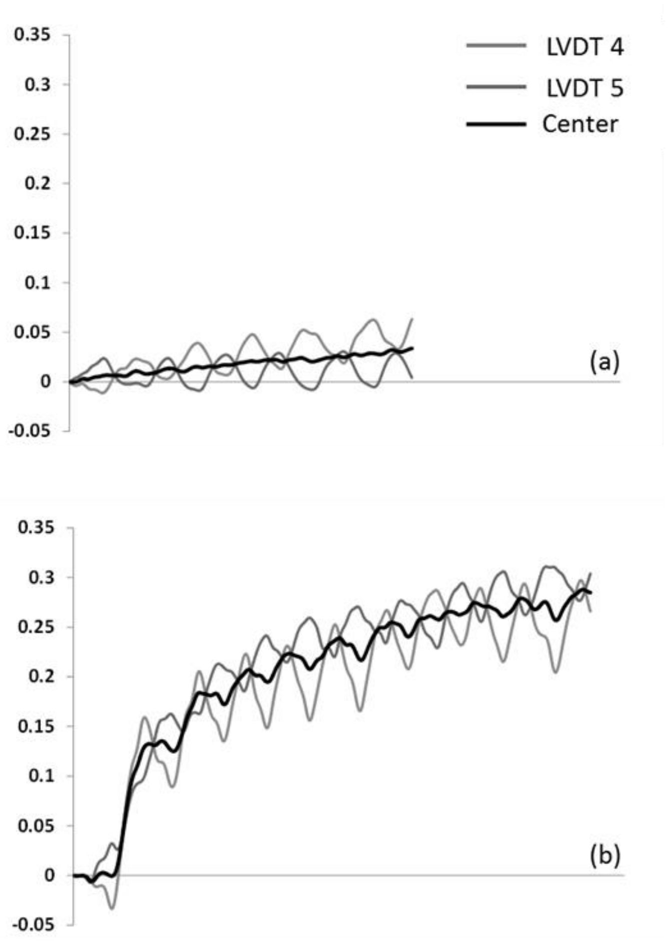

Figure 7. Comparison of recorded vertical displacements (LVDT 4, LVDT 5) and the thereby calculated settlement of the foundation center for each of the two studies systems: (a) the monopile, and (b) the hybrid foundation.

6 CONCLUSIONS AND LIMITATIONS

The main conclusions of the present experimental study may be summarized as follows:

(a) The developed experimental methodology may be used in the future to study similar problems and, despite its limitations/simplifications, may greatly facilitate physical modelers intending to incorporate both monotonic and cyclic lateral loading protocols in tests where only one actuator is available (due to limited resources or space);

(b) The reported results clearly indicate some significant potential in view of the lateral load − displacement performance accompanied by reassuring evidence regarding the magnitude of the unavoidably larger settlements; and

(c) It is important, and encouraging in terms of the repeatability and the credibility of the drawn conclusions, to note that the results of the test on partially saturated soil (recorded during the first test, where water leakage took place) show qualitatively the same comparative performance with the second test (Fig. 5).

(d) Additional experimental and numerical analysis of the response of the proposed hybrid foundation is necessary. More specifically, significant design considerations, such as (i) the vulnerability of the hybrid foundation system to scouring and the potential effectiveness of protective measures, and (ii) its performance in weaker and/or cohesive soils should be investigated before its use in practice can be supported with substantial confidence.

(e) The herein presented experiments were conducted using plain water and not a methylcellulose-water mixture. This was a deliberate decision in order to study the response of the two foundation systems in non-liquefiable soils and avoid the additional implications caused by excess pore water pressures. Hence, although the soil used in the experiments was fine sand, its draining behavior corresponds to a coarser material. However, it is essential to incorporate the effect of excess pore water pressure in future studies of the proposed hybrid foundation behavior.

7 REFERENCES

Anastasopoulos, I. & Theofilou, M. 2016. Hybrid foundation for offshore wind turbines: Environmental and seismic loading. In Soil Dynamics and Earthquake Engineering, Vol. 80, 192-209.

Dimmock, P.. 2013. Hybrid subsea foundations for subsea equipment. In Journal of Geotechnical and Geoenvironmental Engineering, 139(12), 2182-2192.

Dimmock, P., Clukey, E., Randolph, M., Murff, D., and Gaudin, C. (2013)

Fu, D. et al. 2014. Undrained capacity of a hybrid subsea skirted mat with caissons under combined loading. In Canadian Geotechnical Journal, 51(8), 934-949.

Gaudin, C. et al. 2011. Centrifuge experiments of a hybrid foundation under combined loading. In Proceedings of the 21st International Symposium on Offshore and Polar Engineering – ISOPE-2011, Maui, Hawaii. pp. 386–392.

Houlsby, G.T. & Byrne, B.W. 2000. Suction Caisson Foundations for Offshore Wind Turbines and Anemometer Masts. In Wind Engineering 24(4), 249-255.
Houlsby, G.T. et al. 2005. Suction caissons for wind turbines. In International Symposium on Frontiers in Offshore Geotechnics, Perth, Proceedings volume: 75-94.
Kutter, B. L. 1995. Recent advances in centrifuge modeling of seismic shaking. In Proceedings of 3rd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2- 7, St. Louis, Missouri.
Schofield, A.N. 1980. In Cambridge geotechnical centrifuge operations, Geotechnique: 30(3), 227 –268.