Increasing the Lateral Resistance of Offshore Monopile Foundations: Hybrid Monopile-Footing Foundation System

Harry S Arshi[1] and Kevin J L Stone[2]

Abstract

Due to the limitations of locations some of the recently found offshore oil and gas reservoirs, or the proposed locations for some of the offshore wind farms, there is clearly scope for developing foundations that are more efficient. One approach in increasing the lateral load bearing capacity of monopile foundations is the 'hybrid' monopile-footing foundation system with a proven record of improving the ultimate lateral resistance, particularly in cohesionless soils. This work builds on to the previous studies by investigating the behaviour of the hybrid system further. The effect of footing size, the magnitude of pre-loading and its significance in developing sufficient contact pressure beneath the footing, and the importance of the degree of rigidity is reported in this paper.

Introduction

Due to the needs of on-going developments in the oil and energy sector, the design of offshore foundations is constantly evolving. In the hydrocarbon extraction sector, exploration and development is moving in to ever deeper water resulting in ever more challenging geotechnical conditions. The development of sites for offshore wind farms (such as round 2 and 3 in the UK) is also extending into deeper water. The capacity of wind turbine generators is also increasing requiring significant development in foundation design to generate economic and practical solutions to the installation of these deep water wind farms.

The main challenge for deep-water foundations is the loading conditions. Offshore foundations are generally subject to combined loading conditions consisting of self-weight of the structure (V), relatively high horizontal loads (H) and large bending moments (M). The preferred foundation system to date has been the monopile that has been successfully employed for the majority of the offshore wind turbines installed. The advantage of the monopile is that it can be employed in a variety of different soil conditions even when loading conditions are very high. For instance in many of the proposed offshore wind farm locations it is often the case that the surficial seabed deposits are underlain by rock, generally weak rocks such as mudstones and chalk. Consequently it becomes necessary to install the monopiles, generally by driving, through the soil and into the rock, in order to achieve adequate lateral stiffness and moment resistance in order to carry the applied loads.

1 PhD Research Student, Division of Built Environment & Civil Engineering, University of Brighton, Brighton, UK, Tel: +44-1273-642268, Email: H.Arshi@brighton.ac.uk.

2 Principle Lecturer, Division of Built Environment & Civil Engineering, University of Brighton, Brighton, UK, Tel: +44-1273-642283, Email: Kevin.Stone@brighton.ac.uk.

One of the recently developed solutions for increasing the lateral resistance of deep-water monopiles is the hybrid monopile-footing system. The role of the footing is to provide a degree of rotational restraint at the pile head, leading to an improvement in the lateral resistance of the pile. It has also been shown that the use of a relatively thick pile cap leads to an increase in the lateral resistance through the development of passive soil wedges (Mokwa, 1999), in a similar way to the behaviour of skirted foundations (Bransby and Randolph, 1998).

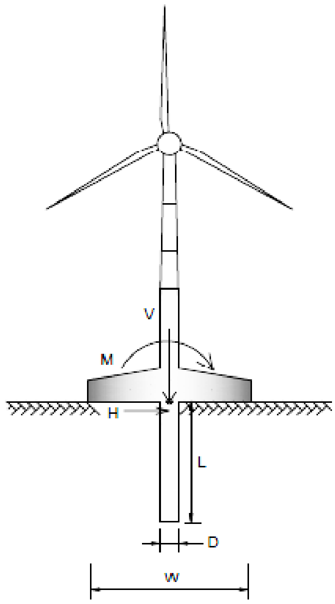

Figure 1. Schematic illustration of the prototype hybrid system

As schematically represented in Figure 1, this foundation system comprises of a circular footing is attached to the monopile at mudline. The 2D analogy of this system is that of a retaining wall with a stabilising base (Powrie and Daly, 2007). Where the plate diameter is relatively small, the system is similar to a single capped pile, for which methods have been developed for analysing the influence of the pile and pile cap under axial loading (Poulos and Randolph, 2008), and the effect of the pile cap on the lateral performance of single piles has also been investigated by others (Kim *et al* 1979), (Mokwa and Duncan, 2001; 2003), (Maharaj, 2003).

The lateral response of piles is well reported in the literature and various methods of analysis have been proposed by numerous researchers, such as Matlock and Reese (1960), Broms (1954), Poulos (1974), Reese *et al* (1974), Randolph (1981), Duncan *et al* (1994) and Zhang *et al* (2005). The bearing capacity problem has also been investigated under different loading conditions relevant to offshore foundations, see for example references Houlsby and Puzrin (1999), and Gourvenec and Randolph (2003).

Pervious investigations carried out at one gravity in ‘sand box’ tests (Stone *et al*, 2007; 2010), (Arshi 2011; 2012), (Arshi and Stone, 2011) together with 2D numerical modelling (El-Marassi, *et al* 2008), (Arshi *et al*, 2011) have shown that the lateral stiffness and ultimate capacity of the monopile is enhanced by the addition of the footing. Preliminary centrifuge model tests have also indicated that for cohesionless soils the ultimate lateral capacity of a monopile is enhanced by the presence of a footing (Stone *et al*, 2011). However, centrifuge tests performed on clay samples did not indicate much improvement in the lateral performance of the monopile (Lehane *et al*, 2010). It should be noted that these centrifuge tests are not directly comparable since the relative geometries of the pile and bearing plates were significantly different in both studies.

Figure 2. Model foundation system

This paper focuses on analysing the load transfer mechanism within the system. It is the subject of this study to investigate how loads are transferred through different elements within the foundation system. The influence of the degree of rigidity at pile head (boundary condition in the connection between pile and footing) on the lateral resistance is also looked at. Moreover the relationship the ratio between the diameter of footing to pile and its effect on the lateral resistance of the pile is reported. This ground model is felt to be of particular relevance for offshore wind farm development duo to the potential economical benefits.

Experimental Procedure

Materials and model prepration

Medium dense sand models were prepreated by pulvation sand into a box measuring 310 mm x 210 mm x 240 mm. Rounded to sub-rounded, uniformly graded quartez sand with an average particle size of 0.25 mm (Fraction D from David Ball Ltd) was used for the experiments. The maximum and minimum void ratios were 1.04 and 0.59 respectively with a correnpondant dry unit weights of 12.6 and 16.1 kN/m^3. The ciritical state angle of friction was meassured using direct shear box test and was found to be 32 degrees.

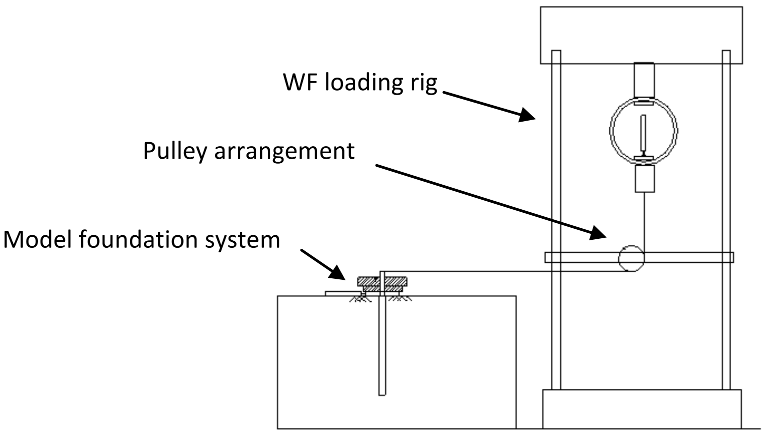

Figure 3. Test arranment for the model foundation system under lateral loading

The model foundation system comprised of a 10 mm thick 150 mm long steel rod together with 5mm thick steel plates with three different diameters of 40 mm, 60 mm and 80 mm, corresponding to pile to footing ratios of 0.4, 0.6 and 0.8 (Shown in Figure 2). The footings were fabricated in such a manner to give the option of having one directional vertical translations of the pile about the footing (i.e. translations along the y axis).

The installation of the model piles consisted of pushing the pile to about 70 % of the desired depth by hand followed by driving the rest of the pile via light tapping using a hammer until the required penetration depth was achived.

Test procedure

All experiments took place in a single gravity Wykeham-Farrance loading rig at the University of Brighton, designed to load piles both horizontally and vertically. For tests involving only vertical loading, the load was applied directly to the top of the footings and/or piles, whereas for the tests involving lateral loading a wire and pulley arrangment was utlised (Illustrated in Figure 3).

Table 1. Summary of single gravity model tests

ID	Type	Connection	Vetr. Load* (N)
F40	Footing	-	-
F60	Footing	-	-
F80	Footing	-	-
PW1	Pile	-	1000
PW2	Pile	-	5000
H40W2A1	Hybrid	Rigid	5000
H40W2A2	Hybrid	Free	5000
H60W2A1	Hybrid	Rigid	5000
H80W1A1	Hybrid	Rigid	1000
H80W2A1	Hybrid	Rigid	5000

* self weigh of foundation neglected

A summary of the programme is presented in Table 1. The footing only tests were carried out to determine the bearing capacity of footings with three different diameters and free from dead loads. This involoved loading the footings vertically at the middle and measuring the relative vertical deflections. The defelctions were measured using two LDVTs, attached to the far corners of the footings. For the pile only as well as hybrid system tests, dead loads were inserted on top of the pile, the piles were then pulled laterally and relative lateral deflections were measured using the LVDTs.

Results and Analysis

In order to be able to differentiate the contribution of different elements comprising the hybrid system, the indivial performance of each element was investigated seperately. Figure 4 show the plot of applied moment against relative rotation for individual footing tests. This plot shows the behaviour of footings with three diamaters of 40 mm, 60 mm and 80 mm corresponding to ultimate bearing capacities of 65 Nmm, 240 Nmm and 490 Nmm respectively. The performance of the pile-only tests, represented in terms of moment and pile head rotation, have been shown in three differents graphs shown in Fugure 5, 6 and 7. The performance of the pil-only tests have been used as a benchmark for analysing the behaviour of the hybrid foundation system.

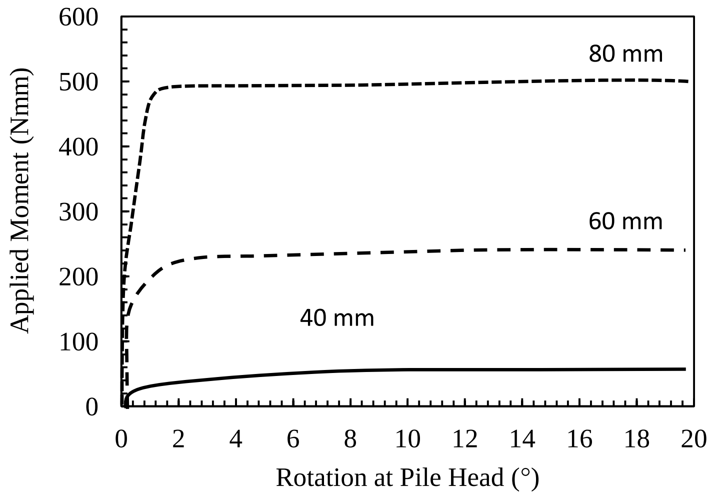

Figure 4. Moment-rotaion plot for vertical footing-only tests

A total number of 5 tests were carried out on the hybrid system and the results have been presented in Figures 5, 6 and 7. All tets had a dead load of 5000 N (with the exception of PF3W1A1) and the degree of rigidity between at the pile-footing connection was set at fully fixed for all tests expect for PF1W2A2. All tests follow the same moment-rotation pattern with differences in the values of initial stiffness as well as the ultimate lateral resistance.

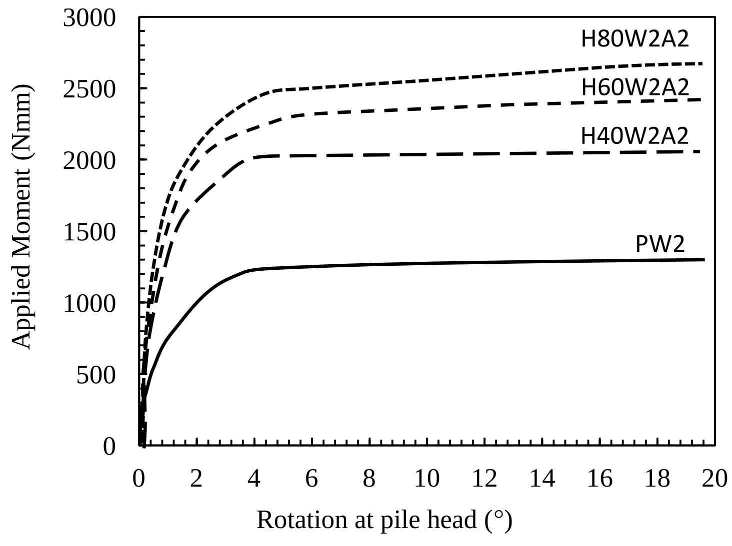

Figure 5. Moment-rotation plot for hybrid foundation system with varying footing size

Looking at the plot presented in Figure 4, it is apaprent that the bearing capacity of circular footings increase with an incease in the diamater. The contribution from the addition of the footings to the pile is illustrated in Figure 5, where the initial stiffness and the ultimate lateral resistance are significantly higher for the hybrid system. The hybrid system with the smallest footing had a 67% increase in value of the ultimate lateral resistance where the aditional 50% and 100% increase in the diameter of the footings only boosted the ultimate resistance by an additional 20% and 50%.

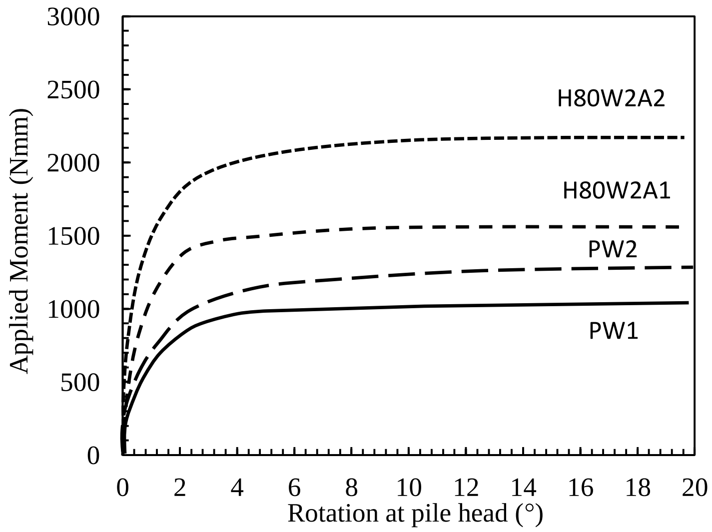

Figure 6. Moment-rotation plot for pile and hybrid foundation system test with varying dead loads

Dead loads play a major role in advancing the lateral resistance of the hybrid system. This is best illustrated in Figure 6 where pile-only as well as the hybrid system have to sustain dead loads of 1000 N and 5000 N. Clearly, the increase in the performance is signifitably higher for the hybrid (27% increase) compared to the pile-only (12%).

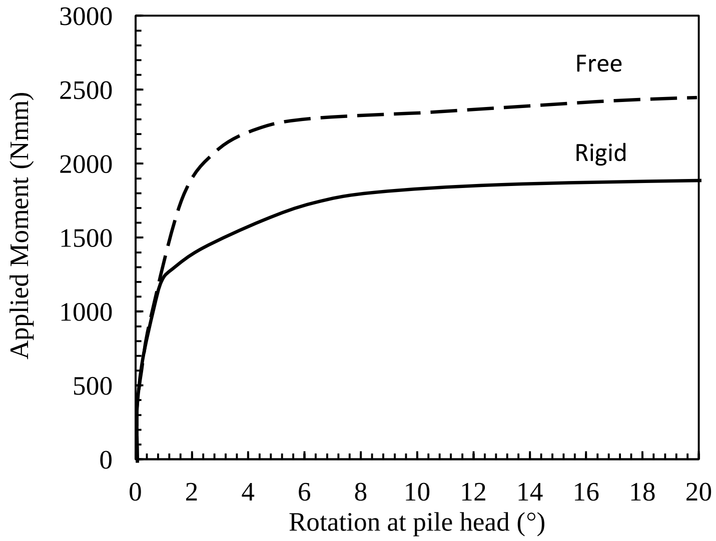

Figure 7. Moment-rotation plot for hybrid foundation system test with different degrees of rigidity at pile head

Futhermore, Figure 7 show two tests carried out in the same hybrid system but with different degrees of rigidity. For the systems under experiment, it was observed that having the pile free (in translation along the y axis) from the footing seem to have an advantage in improving the performance of the system, where the ultimate lateral reistance was about 40% higher when the pile was free. In a free system, dead loads are carried fully but the footings where magnitude of dead load is directly proportional to the bearing capacity of the footings.

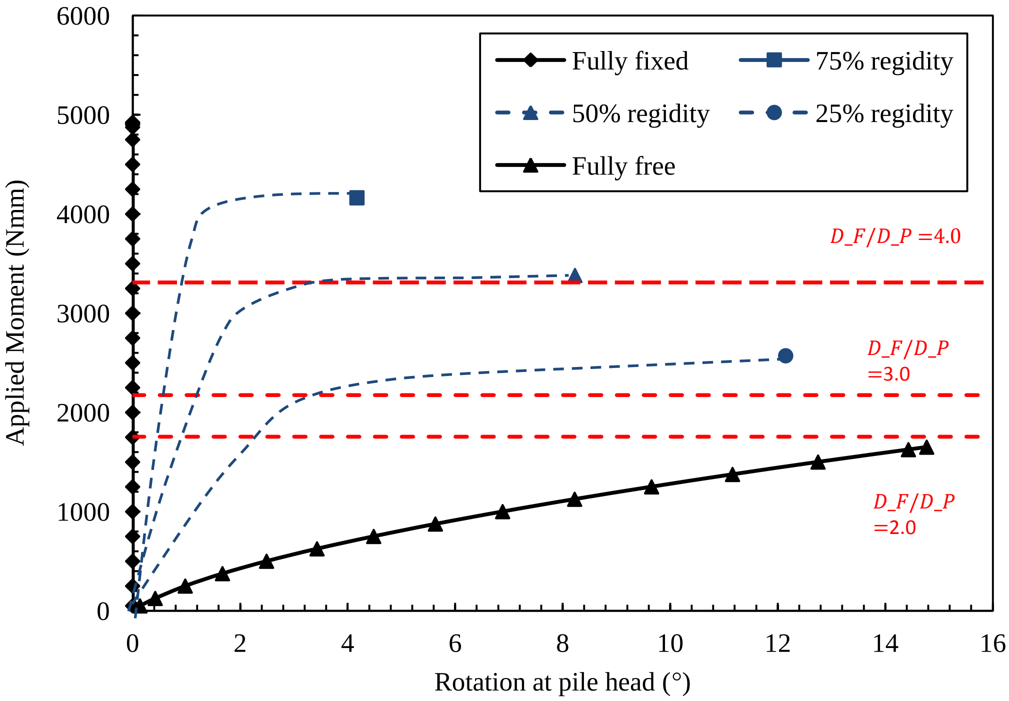

Figure 8. Moment-rotation plot for hybrid foundation system obtined using LPILE

The behaviour of the hybrid system was numerically analysed using the computer program LPILE and the results are illustrated in Figure 8. This program does not have an option for adding the footing to the pile and creating a hybrid system, however it does allow the user to introduce bending moments to the pile head in all directions. In order to illustrate the behaviour of the system, the resistance of the footings was calculated analytically and was added to the ultimate resistance of the fully free pile. This is shown as dashed red lines in Figure 8 for different pile to footing diameter ratios. Furthermore it is shown how the resistance of the hybrid system compares to piles with different degrees of rigidity.

Discussion and Conclusion

It was demostrated that the additon of the footing to the pile, which creates the 'hybrid' system, increases the initial stiffness as well as the ultimate lateral restsiance of individual monopiles. Individual tests were carried out to establish the ultimate bearing capacity that would be mobilised on the underside of the footings of the hybrid system. Clearly, the actual degree of rigidity provided at the pile head depends on several factors such as (i) size of the footing (ii) the initial contact ot bedding with soil surface (iii) the stiffness of the soil beneath the footing.

If the actual capacity of the pile is very high, it is difficualt to get a good positive contact between the footing and the soil until the system starts to rotate and that means that the stiffness does not increase significantly. It is apparent that a more efficient system would require a good contact between the footing and the soil and that the contact remains present during the loading cycle. In a fully rigid system, the drawback is that the pile needs to be rather short in order to let the working loads generate the contact pressure undernearh the footing. However, the results here show that it is possible to overcome this by designing the system with a sliding connection where vertical translations of the pile is permitted.

The resutls of this investigation is limited to 1g tests. A comprehensive sereis of centrifuge tests are currently undertaking. The results of the tests together with a series of 3D numerical model study will be reproted in the near future.

References

Arshi HS. (2011). Structural behavior and performance of skirted hybrid monopile-footing foundations for offshore oil and gas facilities. *Proceedings of the Institution of Structural Engineers: Young Researchers Conference '11*. London: IStructE Publications, 8.

Arshi HS, Stone KJL and Newson TA. (2011). Numerical modelling on the degree of rigidity at pile head for offshore monopile-footing foundation systems. *9th British Geotechnical Association Annual Conference, London*.

Arshi HS and Stone KJL. (2011). An investigation of a rock socketed pile with an integral bearing plate founded over weak rock. *Proceedings of the 15th European Conference of Soil Mechanics and Geotechnical Engineering*. Amsterdam: Ios Pr Inc, 705 – 711.

Arshi HS. (2012). A new design solution for increasing the lateral resistance of offshore pile foundations for wind turbines located in deep-water. *Proceedings of the Institution of Structural Engineers: Young Researchers Conference '12*. London: IStructE Publications, 10.

Bransby MF and Randolph MF. (1998). Combined loading of skirted foundations. *Géotechnique*. 48(5), 637–655.

Broms BB. (1964). Lateral resistance of piles in cohesionless soils. *ASCE Journal of the Soil Mechanics and Foundation Division*. 90(SM3), 123-156.

Duncan JM, Evans LT and Ooi PS. (1994). Lateral load analysis of single piles and drilled shafts. *ASCE Journal of Geotechnical Engineering*. 120(6), 1018-1033.

El-Marassi M, Newson T, El-Naggar H and Stone KJL. (2008). Numerical modelling of the performance of a hybrid monopiled-footing foundation. *Proceedings of the 61st Canadian Geotechnical Conference, GeoEdmonton 2008*. Edmonton, (Paper No. 480), 97 – 104.

Gourvenec S and Randolph M. (2003). Effect of strength non-homogeneity on the shape of failure envelopes for combined loading of strip and circular foundations on clay. *Géotechnique*. 53(6), 575–586.

Houlsby GT and Puzrin AM. (1999). The bearing capacity of a strip footing on clay under combined loading. *Proc. R. Soc. London Ser. A*. 455, 893–916.

Kim JB, Singh LP and Brungraber RJ. (1979). Pile cap soil interaction from full scale lateral load tests. *ASCE Journal of Geotechnical Engineering*. 105(5), 643-653.

Lehane BM, Powrie W and Doherty LP. (2010). *Centrifuge model tests in piled footings in clay for offshore wind turbines*. Proceedings of *International Conference in Physical Modelling in Geotechnics, ICPMG2010*. Rotterdam: Balkema.

Maharaj DK. (2003). Load-deflection response of laterally loaded single pile by nonlinear finite element analysis. *EJEG*.

Matlock H and Reese LC. (1960). Generalized solutions for laterally loaded piles. *ASCE Journal of Soil Mechanics and Foundations Division*. 86(SM5), 63-91.

Mokwa RL. (1999). Investigation of the Resistance of Pile Caps to Lateral Loading. *Ph.D Thesis.* Virginia Polytechnic Institute, Blacksburg, Virginia.

Mokwa RL and Duncan JM. (2001). Experimental evaluation of lateral-load resistance of pile caps. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*. 127(2), 185 - 192.

Mokwa RL and Duncan JM. (2003). Rotational restraint of pile caps during lateral loading. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*. 129(9), 829 - 837.

Poulos HG. (1971). Behaviour of laterally loaded piles: Part I-single piles. *ASCE Journal of the Soil Mechanics and Foundations Division*. 97(SM5), 711-731.

Poulos HG and Randolph MF. (1983). Pile group analysis: a study of two methods. *ASCE Journal of Geotechnical Engineering*. 109(3), 355-372.
Powrie W, and Daly MP. (2007). Centrifuge modelling of embedded retaining wall with stabilising bases. *Geotechnique*. 57(6), 485-497.
Randolph MF. (1981). The response of flexible piles to lateral loading. *Géotechnique*. 31(2), 247-259.
Reese LC, Cox WR and Koop FD. (1974). Analysis of laterally loaded piles in sand. *Offshore Technology Conference*. Vol. II (Paper No. 2080), 473-484.
Stone KJL, Newson TA and Sandon J. (2007). An investigation of the performance of a 'hybrid' monopole-footing foundation for offshore structures. *Proceedings of 6th International on Offshore Site Investigation and Geotechnics*. London: SUT, 391-396.
Stone KJL, Newson T and El Marassi, M. (2010). An investigation of a monopiled-footing foundation. *International Conference on Physical Modelling in Geotechnics, ICPMG2010.* Rotterdam: Balkema, 829-833.
Zhang L, Silva F and Grismala R. (2995) Ultimate lateral resistance to piles in cohesionless soils. *Journal of Geotechnical and Geoenvironmental Engineering*. Vol. 131(1), 78–83.