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Modelling of Monopile-Footing Foundation System for Offshore Structures in Cohesionless Soils

Modélisation du système de semelle de fondation monopile sur les structures extracôtières dans les sols pulvérulents

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ABSTRACT: While monopiles have proven to be an economically sound foundation solution for wind turbines, especially in relatively shallow water, their installation in deeper water and in hard ground may require a more complex foundation design in order to satisfy the loading conditions. One approach is that foundation systems are developed which combine several foundation elements to create a 'hybrid' system. In this way it is possible to develop a foundation system which is more efficient for the combination of vertical and lateral loads associated with wind turbines while maintaining the efficiency and simplicity of the design. Previous studies have reported the results of single gravity tests of the hybrid system where the benefits of adding the footing to the pile are illustrated. This paper prevents experimental results on the performance of skirted and unskirted monopile-footings. A simplified design approach based on conventional lateral pile analysis is presented.

RÉSUMÉ : Alors que monopiles se sont révélés être une solution économiquement viable pour les fondations des éoliennes, en particulier dans les eaux relativement peu profondes, leur installation dans des eaux plus profondes et dans un sol dur peut exiger une conception des fondations plus complexes afin de satisfaire les conditions de chargement. Une approche possible est que les systèmes de base sont développées qui combinent plusieurs éléments de fondation pour créer un système hybride. De cette manière, il est possible de développer un système de fondation qui est plus efficace pour la combinaison de charges verticales et latérales associées aux éoliennes, tout en maintenant l'efficacité et la simplicité de la conception. Des études antérieures ont rapporté les résultats d'essais simples de gravité du système hybride où les avantages de l'ajout du pied à la pile sont illustrés. Cet article empêche résultats expérimentaux sur la performance des jupes et non jupée semelles monopile. Une approche de conception simplifiée basée sur l'analyse pile latéral classique est présentée.

KEYWORDS: Hybrid monopile footing, offshore piles, laterally loaded piles, wind turbine foundations

1 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. Similarly the expansion of the offshore wind sector involves the development of deepwater sites, together with requirements for heavier high capacity turbines. Conventional offshore foundations are not always economical or practical for this new generation of turbines, and there remains a requirement to develop foundation solutions which can better satisfy future developments in the offshore wind sector.

The foundations of a typical offshore wind turbine are subjected to combined loading conditions consisting of the 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, which has the advantage that it can be employed in a variety of different soil conditions. However, a disadvantage in the use of monopiles in deep water sites is that the system can be overly compliant. For sites with intermediate water depths, it may be possible to stiffen the lateral response of the monopile at the mudline.

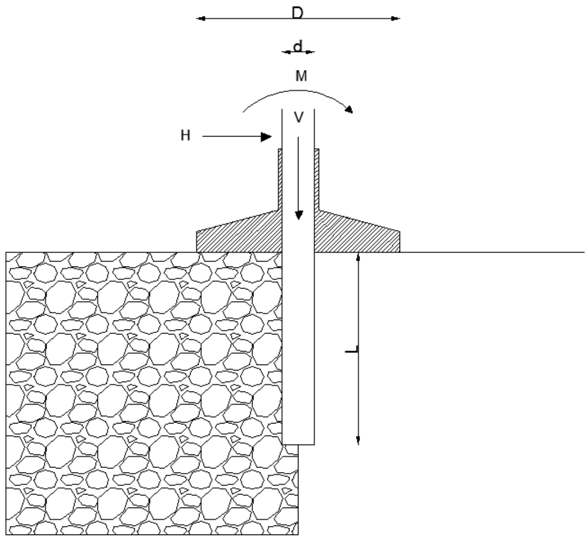

Figure 1. Schematic illustration of the prototype hybrid system

One such approach to increase the lateral resistance of a monopile is the 'hybrid' monopile-footing system. As schematically represented in Figure 1, this foundation system comprises of a circular footing attached to the monopile at the mudline. A 2-D analogy of this system is that of a retaining wall with a stabilising base (Powrie and Daly, 2007). 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).

Analysis of the hybrid system would involve both lateral pile analysis and bearing capacity analysis. 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 (1971), Reese et al. (1974), Randolph (1981), Duncan et al (1994) and Zhang et al. (2005). 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, 1983), 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 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).

2. EXPERIMENTAL INVESTIGATIONS

The potential performance of the hybrid system was investigated in single gravity studies (Stone et al. (2007)) and is illustrated in Figure 2. These studies suggested that the additional rotation restraint provided by the footing can result in a stiffer lateral response of the pile and greater ultimate lateral load. The degree of restraint at the pile head was dependent on the size of the footing, the initial contact between the soil and the footing and the stiffness of the soil beneath the footing. Observations of heaved and displaced soil in front of the edge of the footing also suggested that a degree of passive soil resistance is likely to be generated under the lateral movement and rotation of the footing.

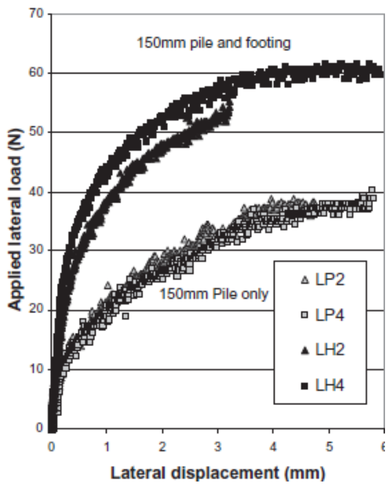

Figure 2. Lateral load response of the hybrid system (after Stone et al. 2007)

Arshi (2011), and Arshi and Stone (2012) reported the results of a comprehensive series of single gravity testes carried out on the foundation system where the elements affecting the overall performance of the foundation system was investigated in depth. It was reported that the size for the footing has a direct effect on the overall lateral load bearing capacity of the foundation system. Furthermore it was reported that the ratio between the vertical and horizontal load has a significant effect on the lateral performance of the foundation system where larger vertical loads tend to improve the lateral load bearing capacity of the hybrid system. The connection between the footing and the pile was also investigated where it was suggested that the hybrid foundation system tends to be more effective if vertical movements are allowed at the pile-footing connection. This movement allows the footing to act independently from the pile where the positive contact between the footing and the soil underneath is solely controlled by the vertical load acting on the footing.

Table 1. Notations for skirted hybrid foundations system

ID	Footing size (mm)	Skirt length (mm)	Dead load (N)	Footing to pile connection
P.W0	-	-	0	-
P.F80.W1.FR	80		100	Slipping
P.F80.S1.W1.FR	80		100	Slipping
P.F80.S2.W1.FR	80		100	Slipping
P.F80.S3.W1.FR	80		100	Slipping

More recent single gravity tests are presented in Figure 3 where skirts with different lengths have been added to the footing. The tests were conducted in sand and the results indicate that the presence of the skirts has a relatively significant contribution on the lateral load capacity of the system. The results show that adding the skirts to the footing and increasing the skirt length tends to increase the lateral load bearing capacity of the foundation system by about 50% in comparison to a non-skirted hybrid system. It is also apparent that footings with very short skirts do not tend to show any 'apparent' additional advantage to that without the skirt. This could be due to the fact that the stresses around the skirt induced by the soil are very small at 1g. Further studies in the centrifuge are in the taking place to investigate the effect of the skirts and the results will be reported soon.

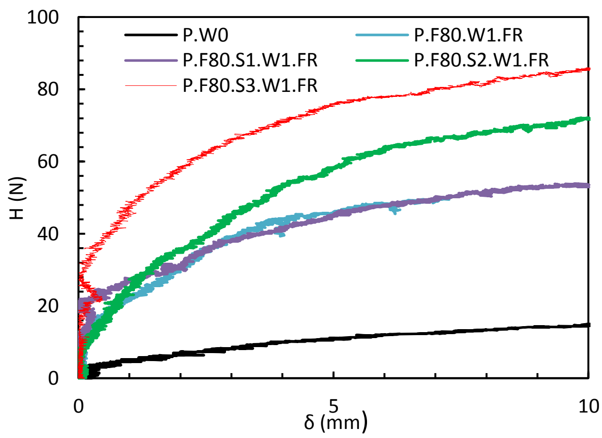

Figure 3. Load vs. deflection plot for the hybrid system with skirts

Stone et al (2011) reported the results of a series of centrifuge tests in sand. The results of the combined vertical and lateral loading tests are best represented through plots of lateral load versus lateral displacement. Figure 4 shows a plot of the lateral load versus lateral displacement for the monopile-footing (HL 1) and single pile (PL 1) with a vertical load of 600N at 50 g. It is apparent from this plot that the initial lateral stiffness of the monopile-footing and pile are similar for the first 1–1.5mm of lateral displacement. However the monopile-footing continues to exhibit a stiffer response than the single pile as the lateral displacement increases. Further analyses of these data provided information on the redistribution of bending moment in the pile due to the plate.

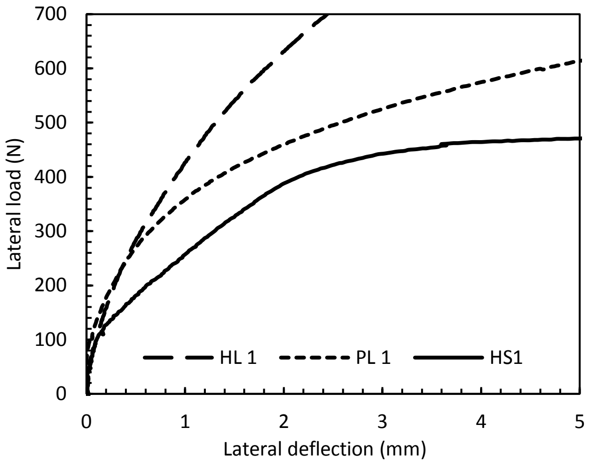

Figure 4. Load deflection graph for centrifuge tests carried out on the hybrid system (after Stone et al. 2011)

In Figure 5, the bold lines represent the bending moments at 5% and 20% of the maximum deflection for the pile only case and the dashed lines show the behaviour of the hybrid system. The results show that adding the footing to the pile reduces the bending moment at any given deflection, and as a result increases the moment capacity of the system at any given applied lateral load. The results indicate about 25% improvement in the bending moment for at both deflections.

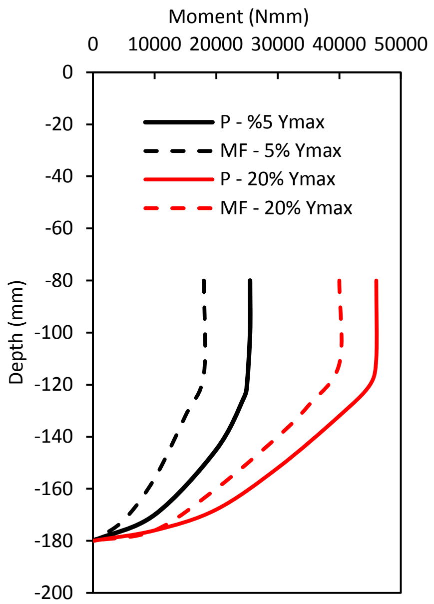

Figure 5. Bending moment distribution along the pile length for the hybrid system

3. ANALYSIS

Whilst some advanced numerical modelling of monopiled footings has been undertaken (El-Marassi et al. 2008; Stone et al. 2010; Arshi et al. 2011; Arshi and Stone 2012), the method presented here utilises conventional lateral pile analysis methodology where the hybrid system is idealised to a lateral pile with a resisting moment applied at the mudline. The resisting moment capacity provided by the footings were estimated analytically using conventional bearing capacity theory and applied at the mudline acting in the oposite dirtection to the loading. This approach only considers the ultimate condition of the system and does not allow the moment developed by the footing to be generated as a function of the footing rotation.

The results generated by this approach are illsutetared in Figure 6 where it is shown how different pile to footing diamater increses the moment capacityof the piles, where this variation lies between a fully free and a fully fixed pile.

The dashed lines in Figure 6 show the ultimate moment capacities of the hybrid system. Although this method successfully leads to obtaining the ultimate load bearing capacity of the hybdegree of rigidity (D.O.R 75%, 50% and 25% showing the the ultimate capacity of the system when %75, 50% and 25% of the ultimate moment at pile head is applied to the free headed pile) of the system are shown as a benchmark for comparing how differenet pile to footing diameters relate to the fully fixed moment. As apparent in Figure 6, increasng the sie of the footing tends to increse the lateral load bearing capacity. As the footing size increases, it gets close to the fully fixed head condrion. This also indicates that there for a given pile diamater and length, there ought to be a footing size afterwhcih increseing the footing size further will not enhance the lateral load bearing capacity of the foundation system.

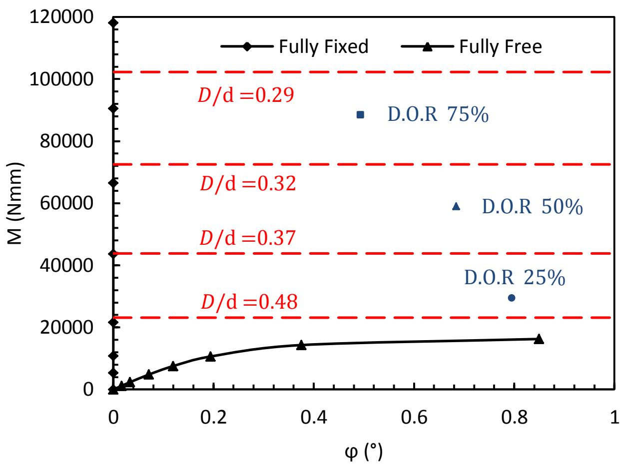

Figure 6. Moment vs. rotation plot for the hybrid system with different pile to footing ratios

In addition to this, design charts have been developed which relate the pile embedment length to pile and footing diameters. Numerous design charts have been developed covering a wide range of pile diameters, pile lengths, footing diameters and normalized moment capacities an example of which is shown in Figure 8 where the L/D ratios vary from 1 to 10 and the footing to pile diameter ratios varies from 0 to 1. The moment capacity of the hybrid system has been normalised and is shown against footing to pile diameter ratio. The lines in between represent different pile embedment depth where for a given moment capacity the designer could utilise this graph to choose the appropriate pile length as well as pile and footing diameters. It is also notable that for any given value of normalized moment capacity the designer has the option of choosing a short pile relatively large footing diameter, or long pile with relatively small footing diameter. The flexibility in this design approach is beneficial in particular designing the hybrid system in difficult soil conditions.

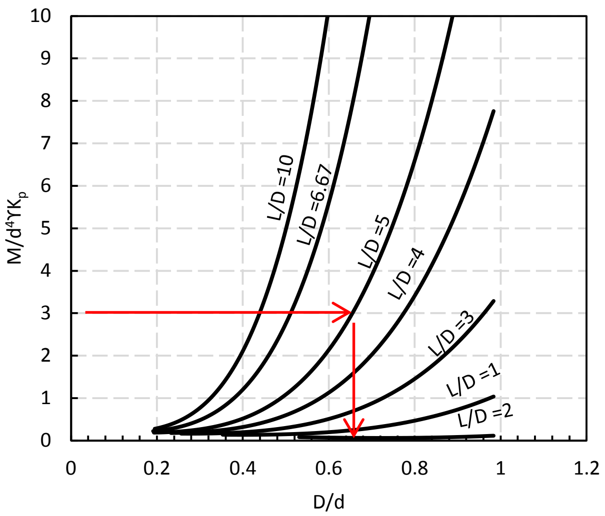

Figure 7. Example of a design chart for the hybrid system developed using analytical and numerical methods

4. DISCUSSION & CONCLUSION

It is apparent that the ultimate lateral response of a single monopile foundation can be enhanced by the presence of a footing resulting in a greater ultimate lateral capacity. This improvement was observed at both load versus deflection as well as the bending moment versus depth plots. Whilst the effect on the initial lateral stiffness may not be significant, the lateral stiffness beyond this initial movement was significantly enhanced through the presence of the footing.

The effect of adding skirts to the hybrid system has been shown to further increase the lateral performance of the hybrid system, and centrifuge tests are planned to investigate the skirted system in more detail.

A simple analytical approach using conventional lateral pile analysis methods is presented from which preliminary design charts can be generated. This approach can be developed to generate realistic design charts where the lateral capacity of the hybrid system is related to the development of bearing capacity coupled to the lateral resistance of the pile shaft.

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