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Cite this article: Byrne BW, Houlsby GT. 2015 Helical piles: an innovative foundation design option for offshore wind turbines. *Phil. Trans. R. Soc. A* **373**: 20140081. http://dx.doi.org/10.1098/rsta.2014.0081

One contribution of 17 to a theme issue 'New perspectives in offshore wind energy'.

Subject Areas:
civil engineering, ocean engineering

Keywords:
helical piles, geotechnical engineering, offshore wind, soil mechanics, pile foundations

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Helical piles: an innovative foundation design option for offshore wind turbines

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Offshore wind turbines play a key part in the renewable energy strategy in the UK and Europe as well as in other parts of the world (for example, China). The majority of current developments, certainly in UK waters, have taken place in relatively shallow water and close to shore. This limits the scale of the engineering to relatively simple structures, such as those using monopile foundations, and these have been the most common design to date, in UK waters. However, as larger turbines are designed, or they are placed in deeper water, it will be necessary to use multi-footing structures such as tripods or jackets. For these designs, the tension on the upwind footing becomes the critical design condition. Driven pile foundations could be used, as could suction-installed foundations. However, in this paper, we present another concept—the use of helical pile foundations. These foundations are routinely applied onshore where large tension capacities are required. However, for use offshore, a significant upscaling of the technology will be needed, particularly of the equipment required for installation of the piles. A clear understanding of the relevant geotechnical engineering will be needed if this upscaling is to be successful.

1. Introduction

In UK waters, as of September 2014, there are 1075 offshore wind turbines installed and operating, with a net capacity of over 3.6 GW. There are approximately 1000 more turbines being constructed or with planning permission. Many thousands more are currently being designed, and there are plans for perhaps up to 10 000 to be installed over the next few decades.

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Table 1. Notation.

D	diameter of helical pile shaft
D_p	diameter of helical plate(s) on helical pile
H	horizontal load
L	length of helical pile (ground surface to top of tip detail once the pile is fully installed)
n	number of helical plates
p	pitch of the helical plates
s	vertical spacing of helical plates (centre-to-centre)
s_u	undrained strength of fine-grained soil
T	installation torque
V	downward vertical (compression) load on pile
V_t	upward vertical (tension) load on pile
W_{pile}	pile weight
γ	soil bulk unit weight
γ'	soil effective unit weight $= \gamma - \gamma_w$
γ_w	water unit weight

In addition, to maintain the stock of operating turbines, a very significant programme of maintenance and renewal will be required. There is the potential for a substantial manufacturing and construction industry to be developed in the UK, and there are similar plans in other countries around Europe as well as worldwide. One of the main challenges for building offshore wind turbines is the design and installation of the foundations, as this represents a significant fraction of the installed cost, with estimates up to 35% [1]. More efficient foundation design, leading to lower costs, will contribute to a faster development of the offshore wind sector and consequently a more sustainable and secure energy supply for the countries involved. Geotechnical engineers have a significant role to play in this process and will need to develop new foundation concepts if the foundation costs are to be reduced. In this paper, we propose the use of helical piles as one such concept. Table 1 provides notation referred to in discussion of this problem.

2. Loading conditions for offshore wind turbines

The loading conditions on offshore wind turbines have significant differences when compared with standard offshore engineering design for the oil and gas industry. There are significant loads from the wind acting on the turbine blades, and the height at which this force acts leads to large moments across the base. In addition, there are the wave and current loads acting closer to the base, similar to those in standard offshore engineering design. Typical loads for a 3.5–5 MW turbine, in water depths from 20 to 50 m, are shown in figure 1. Typically, the extreme horizontal loads may be 60% of the net vertical load. Although the absolute loads on most oil and gas structures are much larger, as a proportion of the vertical load they are smaller, rarely more than about 15%. Both horizontal loads and overturning moments are therefore of more importance for the design of offshore wind turbines.

As the seabed moment increases (e.g. owing to increasing water depth), it is likely that a multi-footing structure will be preferred, as shown in figure 2, such that the moment is supported by 'push–pull' reactions across the base. Structural engineers will be seeking to minimize the weight of the structure, and a weight in the region of 6–10 MN is typical for a structure of this size. They will also seek to minimize the foot-print, as this minimizes both material requirements

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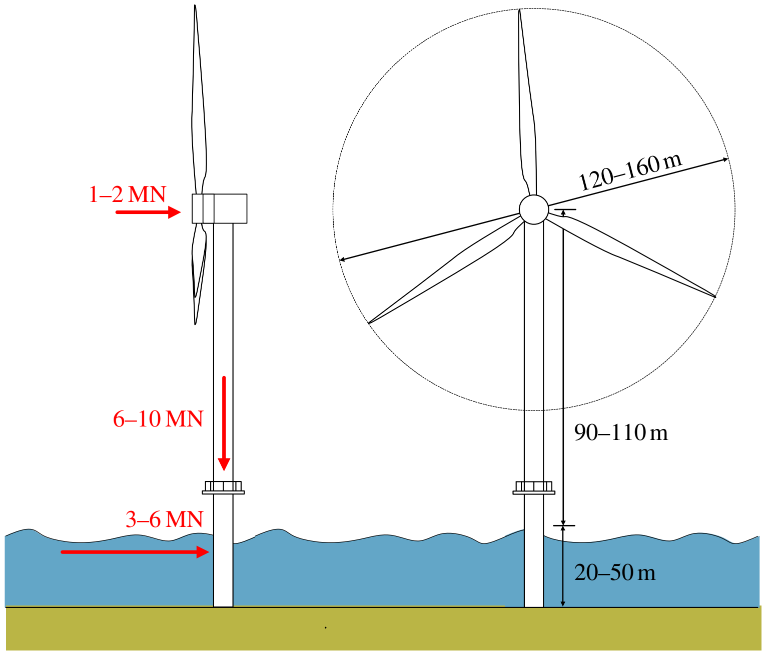

Figure 1. Loading on offshore wind turbines. (Online version in colour.)

and transportation and installation costs. Given these design drivers, the upwind footing will probably be under a (significant) tension load for the ultimate limit state. Simple calculations, using the forces shown in figure 1, and constraining the structural foot-print, would indicate a tension load on each upwind foundation of between 5 and 20 MN. This could be accommodated by using standard piling, as used for an oil and gas structure of similar loading. However, the offshore wind farm may consist of more than 100 structures, and for a four-legged structure, this would lead to driving more than 400 piles into the ground. Significant noise pollution is generated by this pile-driving, which has consequential environmental effects. Specifically, strict limits on noise levels are being imposed in some sectors because of concerns about lasting damage to marine mammal populations. Alternative, quieter methods of anchoring may be needed, and suction-installed foundations may be used [1]. However, the purpose of this paper is to explore the possibilities of using large-diameter helical piles, installed using large hydraulic torque motors. These piles are routinely used onshore for a variety of applications which involve lightweight structures subjected to large overturning moments (e.g. overhead gantry signs on motorways). The installation by torque means that noise pollution is significantly reduced, and the burial of large plates into the soil provides the required tension capacity.

Helical piles are not new to the offshore environment, and as discussed (as well as patented) by Mitchell [2] they were used as the foundations for the Maplin Sands lighthouse as long ago as 1838. The lighthouse was founded on nine screw piles (eight forming an octagon plus one in the centre). The piles each had a single helical plate, 1.2 m diameter on a shaft 0.125 m in diameter, and they were installed by manual effort to a depth of 7 m below the mudline. The lighthouse operated for over 90 years until 1931, but the foundation was eventually undermined by scour, and the structure collapsed in 1932.

Since the pioneering work of Mitchell, screw piles have been used for a range of offshore and onshore structures. Recently, however, they have not seen significant use offshore, and specifically they have not been used for offshore wind turbines, in spite of the fact that their characteristics would seem to lend themselves rather well to this application.

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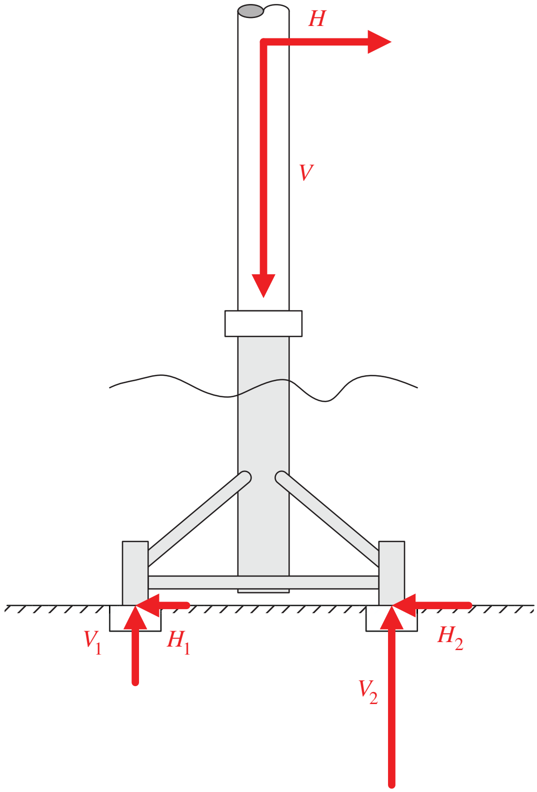

Figure 2. Distribution of loading on a multi-footing structure. (Online version in colour.)

3. Helical pile geometry

A typical helical pile is shown in figure 3. Dimensional analysis indicates that the following dimensionless groups would be useful:

— in clay $V/s_{\mathrm{u}}D_{\mathrm{p}}^2, V_{\mathrm{t}}/s_{\mathrm{u}}D_{\mathrm{p}}^2, H/s_{\mathrm{u}}D_{\mathrm{p}}^2, T/s_{\mathrm{u}}D_{\mathrm{p}}^3$
— in sand $V/\gamma' LD_{\mathrm{p}}^2$, $V_{\mathrm{t}}/\gamma' LD_{\mathrm{p}}^2$, $H/\gamma' LD_{\mathrm{p}}^2$, $T/\gamma' LD_{\mathrm{p}}^3$.

In the following, we shall assume that the screw pile is used in 'push–pull' mode as in figure 2, so that vertical loads become of primary concern. We shall not, therefore, discuss further the role of the horizontal load, although clearly in a detailed design this too would have to be addressed.

In addition to the groups defined above, there are other important dimensionless groups governing the problem. For geometric similitude, for example, the ratios L/D_{p}, p/D_{p} are relevant. It is common in the literature to make use of correlations between torque and capacity [3], and a factor that is often used is the ratio capacity/installation torque which inconveniently has dimensions of (length)$^{-1}$. Some typical values range from 10 to 33 m^{-1}, and depend on the type of helical pile being used (e.g. square shaft, circular shaft). More obviously, these dimensioned parameters depend on the size of the helical pile. While individual companies have their proprietary interpretation of the relevant factors for design, there are also standard recommendations for the factors. Much more logical, as would be apparent from the above dimensionless groups, would be to use capacity × plate diameter/installation torque ($V_{\mathrm{t}}D_{\mathrm{p}}/T$), which is dimensionless. Greater confidence can be placed in the use of this factor for exploring pile designs outside the empirical database. The other useful ratio,

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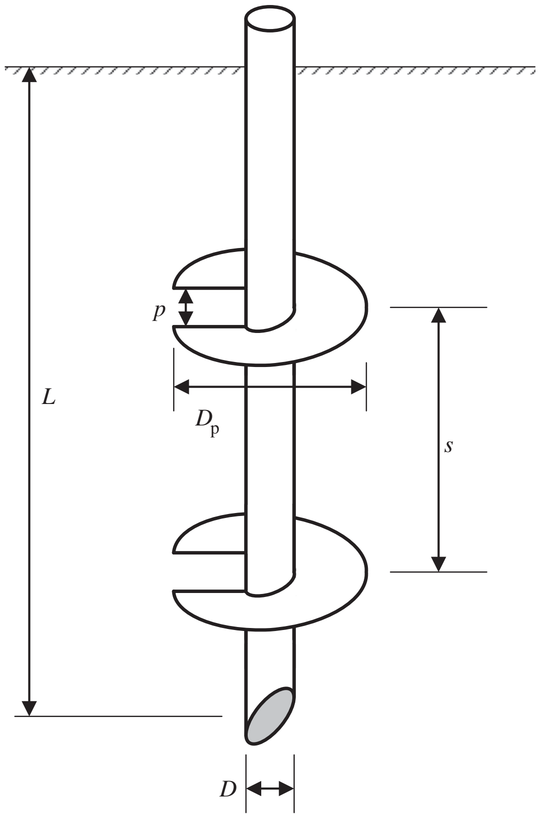

Figure 3. Geometrical parameters for a helical pile.

less commonly seen in the helical pile literature, is the ratio of tensile to compressive capacity V_t/V.

Current applications of helical piles are mostly limited to onshore applications, and are relatively small in scale. There is some offshore application, such as for anchoring of pipelines, for which the helical piles are also relatively small. Onshore pile helix diameters are about 0.2–0.5 m, and shaft diameters are about 0.05–0.3 m. The largest known helical piles have helix diameters of 1.2–1.5 m. Helical piles are usually fairly short; usually less than 10 m long and occasionally up to 20 m. This is due to the relatively light loading applied, with the overall size being comparable to bored pile or driven pile designs for the same loading. Contractors have a significant amount of experience of helical pile design and installation. Many empirical design methods, based on this experience, can be found in the public domain. In addition, there are numerous small-scale model test studies reported in the literature [4,5], as well as a very small number of larger-scale field tests [6,7]. Some details of these studies are shown in table 2, focusing on the dimensionless torque group ($V_t D_p/T$). A more comprehensive summary of existing work can be found in Perko [11], and is summarized in table 3. The data are split into tension and compression, and the number of data points in each category is typically over 150, so the data can be considered representative of current experience. The key observations, from this dataset, are that the plate diameter to shaft diameter is between 2 and 4 and the pitch-to-plate diameter is about 1/3. As a result, the dimensionless torque factor is in the region of 8. It is also noted that in this database the maximum plate diameter is about 1 m, with a maximum capacity in the region of a few MN and maximum torque required for installation of about 0.25 MNm.

Given the loading conditions for offshore wind turbines, the helical piles required will be substantially larger than those used onshore, both in helix diameter and in length. They will also require considerably more torque for installation. For example, taking the torque factor as 8

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Table 2. Selected results from the literature on helical piles.

source	test type	soil	V_tD_p/T min.	V_tD_p/T mean	V_tD_p/T max.	V_t/V
Tsuha *et al.* [8]	centrifuge	sand	6.0	8.3	12.5	
Rao *et al.* [5]	laboratory	soft clay				0.64
Sakr [6]	field	oil sand		5.2		0.52
Livneh & El Naggar [9]	field	clayey silt	6.4	8.0	10.9	
Ghaly *et al.* [10]	laboratory	sand	3.2	5.0	6.1	
Cerato & Victor [7]	field	layered soil	2.6	14.4	23.3	
Perko [11] (table 3)	various	various	1.6	8.5 (mean); 6.9 (median)	24.6	0.8–0.96 (implied)

Table 3. Summary data from Perko [11].

	shaft, D (m)	pitch, p (m)	helices, D_p (m)	depth, L (m)	torque, T (kNm)	load, V (kN)	VD_p/T	VD/T	D_p/D	p/D_p	L/D_p
compression											
count	178	152	341	148	148	178	148	148	176	152	148
st. dev.	0.059	0.011	0.121	4.1	23.9	372.1	4.6	1.0	1.8	0.10	30
min.	0.025	0.025	0.076	0.9	1.2	0.7	2.3	0.5	1.6	0.08	3
average	0.089	0.073	0.283	7.0	16.3	287.1	8.8	2.1	4.1	0.28	30
median	0.075	0.076	0.305	5.8	7.8	186.8	8.5	1.9	4.0	0.25	21
max.	0.325	0.081	0.914	21.3	118.6	2491.0	30.7	7.7	9.3	0.58	156
tension											
count	135	131	140	129	110	140	110	110	135	131	129
st. dev.	0.048	0.022	0.126	5.8	28.9	256.3	5.1	0.7	2.1	0.10	43
min.	0.013	0.010	0.051	0.3	0.0	0.6	1.6	0.4	1.6	0.10	4
average	0.063	0.060	0.206	5.9	12.6	171.8	8.5	1.7	4.7	0.28	36
median	0.044	0.069	0.203	4.9	6.0	144.6	6.9	1.7	4.2	0.25	20
max.	0.219	0.081	0.762	43.0	257.6	2023.9	24.6	4.1	8.0	0.58	169

and assuming that a tension capacity of 20 MN is required for a single helical pile this gives the quantity torque divided by plate diameter of 2.5 MN. Choosing a plate diameter of 2 m gives an installation torque of 5 MNm. A lower plate diameter would give a lower torque, but might not deliver sufficient capacity. Groups of helical piles could be used, rather than a single helical pile, but interaction effects will need to be accounted for. The values described above are considerably greater than the database of current experience. Careful geotechnical input is required to develop robust design approaches.

4. Design methods

For the initial design of a helical pile, there are two main issues: (i) calculation of capacities (compression and tension) and (ii) assessment of the installation torque. For more detailed

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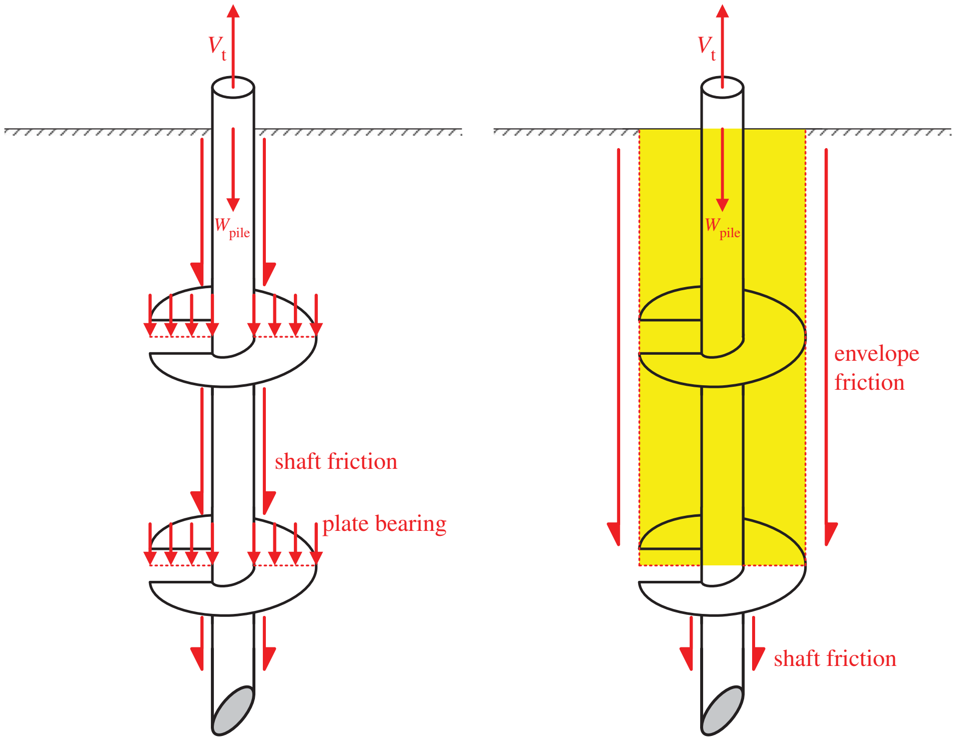

Figure 4. Possible failure mechanisms for a helical pile under tensile loading. (Online version in colour.)

design, there would be considerations of foundation stiffness, performance under cyclic loading, structural design and so on. Although these more detailed issues are of significant importance, we only focus here on the ultimate capacity and the installation torque.

The capacity is calculated by considering two different failure mechanisms—the independent plate mechanism and the envelope mechanism. For tension, these are shown in figure 4. There are of course possible combinations of the two mechanisms, and these would need to be checked. For the independent plate mechanism, the capacity will principally consist of (i) friction along the shaft and (ii) bearing capacity of each of the helical plates. For the envelope mechanism, it is assumed that a soil-on-soil shaft failure occurs at the diameter of the helical plates. Depending on the depth of the top plate, there may be a bearing failure at the top plate or the envelope may extend to the soil surface. There will also be some contribution from the shaft friction below the bottom plate and (for compression) a contribution from end bearing on the pile. A considerable amount of work is available to aid development of design approaches (for example, uplift plate factors from Merifield [12] or Llamparuthi *et al.* [13]), and standard calculation approaches from the American Petroleum Institute or Det Norske Veritas pile design methods may also be applicable [14,15]. For pullout in undrained soils, there needs to be a careful consideration of the response at the base of the pile, particularly if the water depths are sufficiently shallow that cavitation may occur.

Although the primary foundation design calculations for multi-footing structures relate to tension and compression loads, it will also be necessary to check that the lateral capacity, provided by the main shaft of the helical pile, is sufficient. This can be assessed using standard lateral pile capacity calculations [14,15], although this would not account for any contribution of the helical plates to the lateral capacity. The lateral capacity can be enhanced either by increasing the diameter of the main shaft near the soil surface or by using a winged sleeve or a skirted collar, where vertical plates provide additional lateral resistance. This detail would need further

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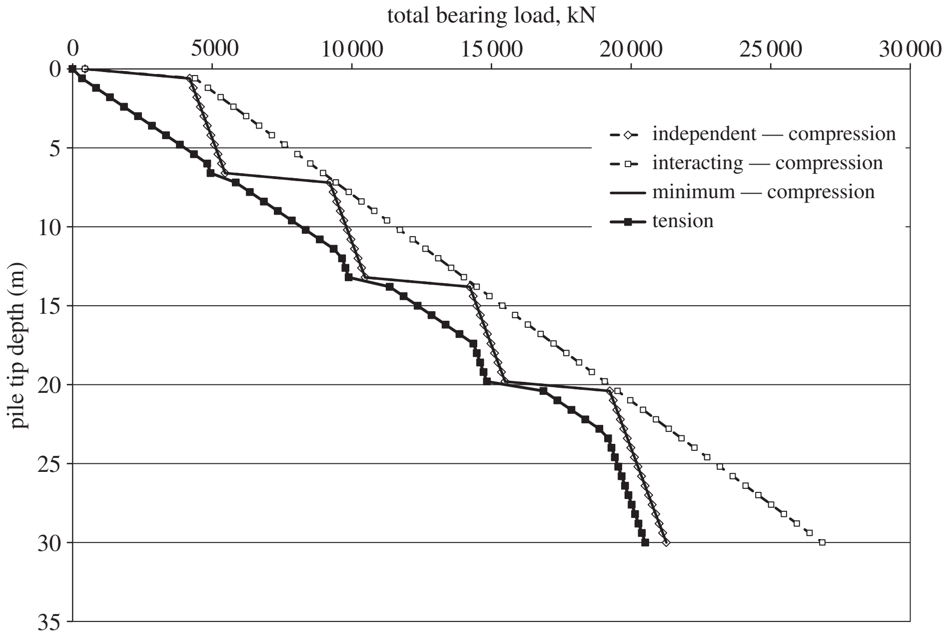

Figure 5. Output from calculations for compression and tension capacities.

consideration, along with the connection arrangement between the helical pile and the jacket structure, during detailed design.

It is possible to use the torque correlations, in combination with the capacity calculations, to determine the installation torque. For onshore helical pile design, the installation torque is probably not critical, and the installation torque is measured during the installation process principally for quality control purposes. For use offshore, however, a robust calculation for the installation torque is necessary, so that the installation equipment is sized accordingly. A calculation of the installation torque based on an independent plate mechanism and an envelope mechanism, as for capacities, has been developed. In the independent plate mechanism, the resisting torque from the helical plates and from the shaft is calculated. The effect of the advance of the pile into the ground is also included in the calculation. The second mechanism is the envelope mechanism, but this is less plausible, as it would require the helical plates to be so closely spaced that a cylinder of soil is rotated with the pile. These methods are relatively straightforward for helical piles in clay, but are still under development for piles in sand. The required installation torque can be reduced by addition of some vertical downward load during installation (so-called crowd force). Relationships between the applied torque and the applied load could be developed for screw pile installations, in a similar way to those developed for shallow foundations.

An example geotechnical calculation is carried out for a helical pile in stiff clay with a uniform undrained strength of 100 kPa. The pile is designed to have a length of 30.0 m, helical plates of diameter 2.4 m and a main shaft diameter of 0.8 m. The four helical plates are spaced 6.5 m apart starting from just above the pile tip. Note that there is an optimal spacing of plates, and typical calculations for clay lead to s/D_p between 2 and 3 [16]; for this example, calculation s/D_p is equal to 2.7 and determines the plate spacing. Note that typical assumptions have been made for the bearing capacity and adhesion factors for the purpose of this calculation. Significant engineering judgement will be required to assess appropriate values for these, in relation to specific site conditions and the actual design. Factors of safety are not considered in the calculation. The compression capacity for this pile is about 21.5 MN, the tension capacity is about 20.5 MN and the torque required for full installation is about 4.7 M Nm. Figure 5 shows the increase of capacity, in both compression and tension, with depth of pile tip, whereas figure 6

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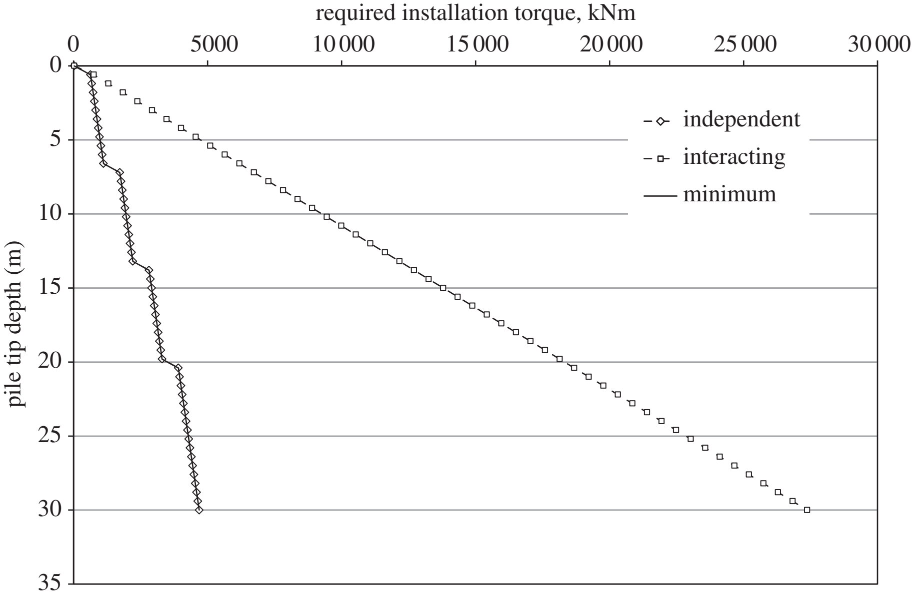

Figure 6. Required installation torque against depth for helical pile example.

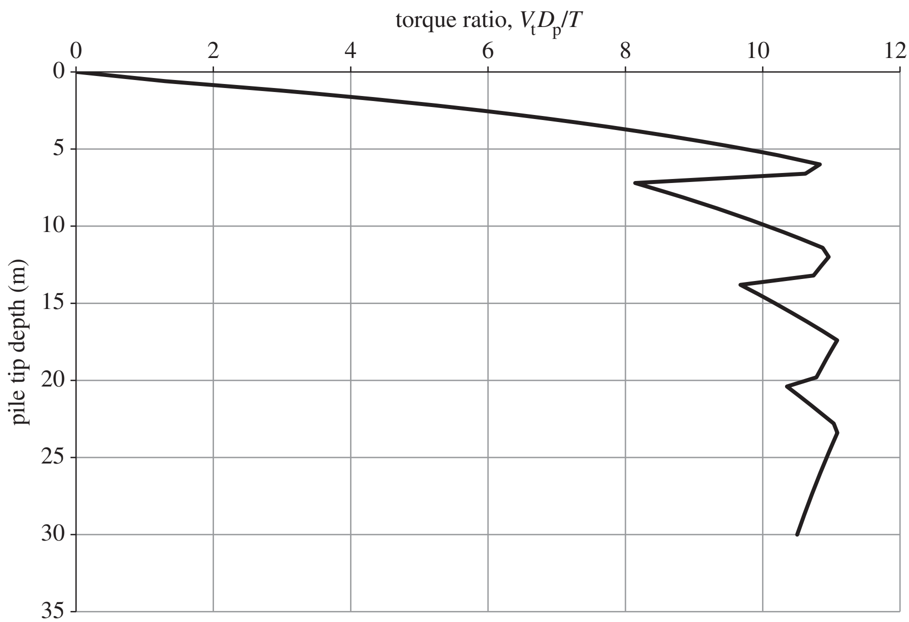

Figure 7. Calculated dimensionless torque ratio for helical pile example.

shows the increase of torque with depth. Note that the results from both the independent plate and the envelope mechanism are shown, with the limiting mechanism being the lower of the two. These calculations can be combined to give the dimensionless torque ratio, and this is shown in figure 7. This shows an average value just above the value of 8 identified in tables 2 and 3, indicating that the two calculations appropriately capture the observations from testing in the field and in the laboratory. The size of this helical pile, as determined by the diameter of the

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helical plates and the pile length, would be very similar to the size of a driven pile, principally owing to the similarity of the design methods.

We have not addressed here the structural issues in relation to the design of the pile. Clearly, the pile–plate connection will be subjected to substantial stressing both during installation (owing to torque) and later during loading. This may demand plates of considerable thickness, particularly on the inner edge of the plate. Such design requirements may make solutions such as cast plate-and-pile segments attractive, rather than using the welded fabrication techniques used commonly for screw piles onshore.

5. Discussion and concluding comments

This short paper has outlined the possibility of using large-diameter helical piles for offshore wind turbines, for which there are many advantages. They have very good tensile loading characteristics, and can be used in a wide range of soil conditions as demonstrated by their use for onshore applications. They are reusable in the sense that they can easily be 'unscrewed', and this will aid the eventual decommissioning of the structures. The torque motors that could be used to drive the helical piles into the ground will be relatively quiet, at least when compared with conventional piling, and they could be sited over water or under water. Importantly, the measurement of the torque during installation will provide a quality assurance on the pile capacity, as good evidence exists (from current field measurements and theory) that relates torque resistance to vertical capacity. It is possible that CPT correlation methods could be developed, and indeed the design can be further refined from torque data gathered during pile installation, and this might lead to cost savings. Much evidence exists from onshore use that reassures developers, from a geotechnical perspective, that they are feasible for larger-scale use offshore. However, a considerable development of the technology is required; for example, the helical piles will be substantially larger than those used onshore, and will require an installation torque that is up to two orders of magnitude greater than that required onshore (although it is broadly comparable to the torque required for offshore drilling). A substantial market will develop for an installation contractor who can develop this type of technology. To develop the method at the offshore scale, it will be necessary to complete field trials to verify the analytical geotechnical design methods, as well as to explore issues such as pile group effects, cyclic loading, pile stiffness, potential plugging of the piles during installation and its remediation, installation effects, as well as to proof-test large-scale installation devices. A range of structural engineering issues will need to be resolved including the design and fixing of the helical plates as well as fatigue. However, such issues can be resolved using standard fabrication methods, and indeed it should be possible to develop a modular foundation system, based on the helical pile technology. The final area where further work is needed relates to the practical installation activities including the provision of the reaction torque, although the maximum torque is not reached until full penetration of the pile. Of course elegant solutions involving two counter-rotating helical piles may offer an attractive solution.

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