Tilting of monopiles
Long, heavy and stiff; pushed beyond their limits

Christopher Golightly — Go-Els

Introduction
In the newly developing northern European offshore wind industry, it is becoming apparent that driven tubular steel piles, and monopiles in particular, will continue to be used in what some would regard as excessive water depths of greater than about 25m with diameters of the order of 5m to 7m.

This depth was often used as a general rule-of-thumb in the early days of UK Rounds 1 and 2 and the first Danish, Swedish and German projects for the transition from monopiles to jackets/tripods. However, the DONG/Carbon Trust “Pisa” Project aims to demonstrate the feasibility of 10m or larger diameter monopiles in up to 40m water depths and 1,200t in weight.

There have even been recent statements anticipating giant “XL” monopiles in up to 60m water depths. As an example of this trend, monopiles of 73.5m length, 930t and 6.5m diameter were recently fabricated for 39 of 80 Siemens’ 3.6MW turbines for the German Baltic 2 project, with the remainder founded on jackets, in water depths of 23m to 44m.

The debate is whether the move towards heavier, longer monopiles is desirable for the offshore wind industry. Alternative foundation solutions, including mono and multi-suction caissons, leaner lightweight jackets and tripods and concrete gravity bases may all suffer as a result. Many of these alternative solutions may be more suitable for the prevailing conditions and also cheaper than giant monopiles.

Larger, heavier trend
In an increasing number of cases in the UK and Baltic, larger and heavier offshore monopiles are being driven and sometimes even drilled into bedrock and the likelihood is that this will also occur at the majority of the six French sites currently being planned.

For example, at the RWE Gwent Y Mor 160-turbine site in the UK every monopile was “bespoke” designed, with weights exceeding 70t and target depths of up to 64m dependent upon bedrock level at each location, which was often difficult to determine from geophysical survey results and geotechnical drilling. There are several other examples of projects in UK waters where the time-consuming drive-drill-drive technique has had to be adopted, either as a planned technique, as it was at Gwent Y Mor and Teeside, or completely unplanned, as at LINCS where there were unexpected pile refusals in chalk.

Drilled piling is not limited to monopiles. The Samsung 7MW turbine at a test site in shallow water at the Fife Energy Park near Methil in Scotland, completed in September 2013, is founded on four 3m diameter steel piles placed in 37m long drilled holes grouted into bedrock. This time-consuming and costly method of large diameter pile installation would not usually be considered in the onshore civil engineering industry where foundation designers usually look at shallow foundations and other alternatives first, with driven or drilled piling with rock grouting regarded as the final and most expensive option.

The use of the term “monopile” is something of a misnomer, since in a structural engineering context these
should more properly be described as large diameter, thin-walled steel caissons. In the initial stages of the offshore wind industry, with smaller wind turbines in shallow water depths of up to 25m founded within the sands or clays prevalent on the continental shelf of the North Sea, it seemed entirely logical to adopt monopiles as these structures simply migrated from land to nearshore.

In scaling up from typically 4m to 6m diameter piles, there are likely to be economies of scale in the fabrication and transportation of large quantities of very heavy – up to 1,200t – and very large – up to 10m diameter – steel tubular piles. However, there is a reluctance in the industry to adopt alternative “smarter” foundations such as Gravity Base Structures (GBS) or single/multiple suction caissons in suitable seabed conditions. This is mainly due to conservatism, risk aversion, a wish to stick with “proven technology” despite stated support for innovation and an often severe lack of experience on the part of many developers.

**Monopile disadvantages**

There are now several reasons to move away from deeper water (>25m) monopiles, particularly where the local geology shows bedrock or hard glacial soils to be present at shallow depths, where drive-drill-drive techniques may be required, with subsequent increases in cost and schedule.

The main problems can be summarised as follows:

a) Use of monopiles in these conditions increases the potential for driven pile early refusal and catastrophic tip buckling. This results from excessive hard driving of relatively thin-walled steel caissons with diameter/wall thickness ratios (D/t) in excess of 50 to 60. Many monopile projects have D/t values greater than 100, which may be adequate in loose to medium dense sands or soft to firm clays, but which could be dangerously high in dense to very dense sands or weathered bedrocks encountered at greater depths for the larger monopiles now proposed in deeper water for 5MW-plus turbine sizes.

b) The possibility of “floating” monopiles where the piles are not end bearing in hard/dense soils or bedrock or piles in unconsolidated sands or softer clays/silts settling and tilting excessively in the long term, exacerbated by wind/wave cyclic loading. Gearbox turbines usually have a 0.5° out of vertical tolerance defined by the manufacturer and piles are usually installed at an allowable 1° out of vertical, with transition pieces and towers installed straighter by means of grout or a bolted flange. Few researchers – and even fewer designers – have assessed the likelihood of long-term tilt leading to turbines requiring remediation. Achmus et al have developed theoretical work relating lateral behaviour to magnitudes and numbers of load cycles.

c) Environmentally unacceptable underwater piling noise has led to a great deal of research. Since 2011 there have been clear rules defined in Germany by the federal regulatory authority BSH, with strictly enforced limits of 160dBA allowed at 750m radius from the pile. Expensive bubble curtains and sleeves with variable rates of success have been proposed by organisations with something of a vested interest in maintaining driven piling offshore as the preferred solution. Work has been published in the UK by Cowrie, but strict mitigation measures in the UK are not yet obligatory. Mitigation measures are usually costly and cause delays in project schedules.

d) The unavoidable need for a physical connection between the pre-installed monopile and the tower transition piece. The mistakes and failures involved in grouting monopile connections are well documented and have been costly, with a great deal of secrecy resulting from numerous claims and litigations. There is a clear move towards more robust bolted flange connections, requiring almost vertical pile installation and guarantees that driving will not damage the flanges, but monopiles always require some form of physical connection to be formed in a difficult offshore environment with increased risks associated with such operations.

**Summary – overall cost and schedule**

The first major European markets to move into offshore wind were the UK and Germany and both have been somewhat bedevilled by cost and schedule overruns. These projects experienced issues with grouted connections, driven pile refusals, HDD crossing collapses and cable trenching installation in the early days and developers have tended to be somewhat reluctant to share the lessons learned with the industry and there is a huge need for less secrecy and greater cooperation.

When the increased risks involved are considered with the disadvantages outlined above at increased water depths, structure weights and sizes, it is difficult to see how driven/drilled large monopiles can be more cost effective.
effective and lower risk than other alternatives. It is uncertain whether this new industry has properly assessed the true final as-built costs for proper comparison with more appropriate foundation solutions for certain marine and geological conditions.

Long-term settlement and tilt
The technical issues and associated risks above now appear to be reasonably well understood. However, what does not appear to have been addressed for most projects is the prediction of long-term cyclic load generated tilt of monopiles embedded in sands and normally consolidated (usually soft to firm) clays and silts. These may not terminate in bedrock, which provides end fixity and the theoretical predictions can be imprecise.

It is likely that some projects include structures and turbines which will already have tilted considerable amounts, taking them outside the usual 0.25° limiting criteria, but where turbines continue to operate satisfactorily. Work has been done by people such as Achmus et al in predicting these long term movements for different sand density conditions and pile depths and diameters, but few projects appear to have performed this design check routinely.

Predictions show cyclic displacements could be two to five times the static single static load values, depending upon pile size, stiffness and depth. It remains to be seen at what point in time the tilts reach values which necessitate shutdown, but little to no monitoring of lateral movement is being carried out in this author’s experience – this may be a mistake.

Monopile designs for up to 8m in diameter and 6MW turbines demonstrate the design pile embedment depth is driven by the decision to adopt an almost random 0.25° limit on tilt at the naselle level. This is then back-figured to a value at the transition to tower interface. Finite element analyses are often performed, with considered usually given to ensuring that the lateral resistance “spring P-Y curves” in the seabed soils are maintained within the linear elastic section at all depths. This invariably leads to excessively long, over stiff heavy mono piles.

An alternative method sometimes adopted is to restrict mudline rotation to maintain the wind turbine within efficient operational levels. Wiemann, Lesny & Richwien (2004) state that in order for a monopile to continue to be considered a rigid foundation, the pile head rotation should not exceed 0.7° while the guideline standard quoted by de Vries & Krolis (2004) suggests restricting horizontal displacement at the mudline to 0.2m.

Few developers or designers in the industry appear to understand or have challenged where these values or the 0.25° limit originated, other than stating that it is a “manufacturer’s requirement”.

Chapter 10 of Sanjeev Malhotra’s book Selection, Design and Construction of Offshore Wind Turbine Foundations states in Section 2.4: “Deformation tolerances are usually specified by the wind turbine manufacturer and are based on the requirements for the operation of the wind turbine. Typically, these tolerances include a maximum allowable rotation at pile head after installation, and also a maximum accumulated permanent rotation resulting from cyclic loading over the design life.”

“For an onshore wind turbine, the maximum allowable tilt at pile head after installation is typically between 0.003 to 0.008 radian (0.2° to 0.45°). A somewhat larger tilt 0.009 radian (0.5°) may be allowed for offshore wind turbines. Any permanent tilt related to construction tolerances must be subtracted from these specified tolerances. Typical values of construction tolerances range from 0.003 to 0.0044 radians (0.2° to 0.25°).” Allowable rotation of the support structure/foundation during operation is generally defined in terms of rotational stiffness which typically ranges between 25GNm/radian to 30GNm/radian.

It is unclear how manufacturers originally arrived at these values and why they have apparently been adopted...
for all turbines at all locations, regardless of size and height, with gearboxes, onshore or offshore, direct drive or otherwise.

For several completed projects and presumably future planned monopile designs, it seems almost certain that the foundation piles are, or will be, too long and too heavy due to designers blindly adopting the 0.25° to 0.5° serviceability criterion and then back-figuring the resultant required pile stiffness and length from that. A lot of extra steel is being and will be hammered into seabed unnecessarily as a result. Whoever can define and justify a less stringent lateral deflection criterion will save a lot on foundation costs and installation time, not to mention considerably reduced vessel and equipment spread costs.

For example, the Principle Power wind floater off Portugal is reputedly permitted to be allowed to shift by up to 7° in the worst sea states, which begs the question as to why the 0.25° to 0.5° value is considered valid for up to 7° in the worst sea states, which begs the question as to why these values were originally selected, in order to control and limit:

- Fluid levels and cooling fluid movements
- Yaw motor capacity (riding the rotor uphill)
- Yaw break capacity (maintaining a rotor uphill)
- Movement criteria related to bearings.

These criteria appear to date back to arbitrary values set in the early days of onshore turbine construction and appear to have been conservatively accepted by the offshore industry without attempts to understand why these onerous and costly values are justifiable. A limiting value of 0.25° represents a horizontal movement of only 400mm for a typical transition piece joint to nacelle distance of about 95m.

To date it is the turbine manufacturers, with little incentive for change, who have specified the maximum tilt angles and consequently this has had, and may continue to have, a major impact on foundation and structure costs. That will influence the overall business case of the turbine technology applied. Whether this is different for gearbox versus direct drive is not fully known, but any manufacturer developing a direct drive turbine with a tilt tolerance of say 2° to 3°, leading to shorter, lighter foundation piles for fixed structures which may also be adopted for floating platforms will be onto a winner. There is an urgent need for all parties in offshore wind to assess these criteria and derive more realistic practical values.

Following the grouted connection design issues, the increasing requirement for expensive piling noise reduction "bubble curtains" or other noise mitigation measures, ever heavier/larger over-conservative pile design, more prevalent expensive unplanned drilling out and re-driving, and the uncertain prospect of future tilt and settlement problems, the adoption of even large diameter monopiles should be more readily challenged in many cases.

The associated risks can only increase with pile size, despite the obvious advantages in economies of scale in manufacture, transportation and installation. Whether or not developers have been retrospectively costing the whole exercise comprehensively to benchmark against smarter, better engineered foundation alternatives tailored to specific site conditions is uncertain.

Before developers consider adopting larger diameter monopiles in even deeper water, it would perhaps be a good idea for national and European wind organisations to initiate and carry out industry-wide projects with the cooperation of all parties. The research should aim to determine the extent to which European offshore monopiles have settled and tilted to date and what measured data is available within the industry.

On the basis of these findings and, after proper consideration of how much movement offshore turbines can really tolerate, the industry should work with all the large turbine manufacturers and certification bodies to determine a more sensible and realistic set of long-term tilt criteria for different ratings, types and weights of turbine.

References

www.dongenergy.com/EN/Media/Newsroom/News/Pages/ DONGEnergyentersintooperationwithUniversityofOxford. aspx
www.igth.uni-hannover.de/fileadmin/igbe/doku/ar_17.pdf
www.windpoweroffshore.com/article/1194713/first-100- foundations-completed-gwyn-t-y-nor
www.bsh.de/de/Produkte/Buecher/Standard/Measuring_ instruction.pdf
www.spiegel.de/international/germany/german-offshore- wind-offensive-plagued-by-problems-a-852728.html
www.renewableenergyfocus.com/view/3152/how-can-the- offshore-wind-industry-overcome-o-m-obstacles/
www.a2seanews.editionmanager.com/2013/02/20/the- power-of-working-together/
www.noordzee.nl/soundsolutions/mitigation-measures/ reduction-of-transmission/bubble-curtains/
www.lorc.dk/offshore-wind/foundations/a-working-noise- mitigation-system
www.rechargenews.com/wind/offshore/article1339749.ece
www.renewableenergyworld.com/reanews/article/2013/10/ securing-the-worlds-largest-wind-turbine?cmpid=WindNL- Thursday-October3-2013