Assessing Novel Foundation Options for Offshore Wind Turbines

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SYNOPSIS

Offshore wind farms will contribute significantly to the renewable generation of electricity for the UK. The economic development of windfarms depends, however, on development of efficient solutions to a number of technical issues, one of these being the foundations for the offshore turbines. We review here the results of a recent research programme directed towards the design of caisson foundations as an option for wind turbine foundations. The possibilities of using caissons either in the form of monopod foundations or in the form of a tripod/tetrapod arrangement are discussed.

INTRODUCTION

The seas around the UK could provide a plentiful supply of renewable energy if wisely exploited. Possible sources of energy are wind, waves, currents and tides, and of these wind power is the only one to be exploited on a commercial scale at present. Three major offshore windfarms around the UK have been completed (North Hoyle, Scroby Sands and Kentish Flats) and others are in the process of construction or planning. The costs of offshore wind are currently, however, significantly higher than onshore wind. A significant contributor to this higher cost is the cost of the foundations for the turbines. By comparison with onshore foundations these must:

- support a taller tower (because of the additional height due to water depth),
- withstand forces and overturning moments from waves and currents as well as from wind,
- be capable of being constructed offshore.

In order to satisfy these requirements a number of possible designs are feasible, as illustrated in Figure 1. There is of course extensive experience on design of offshore foundations for the oil and gas industry, and as far as possible existing knowledge and technology should be employed for wind turbine foundations. It must be recognised, however, that the loading conditions and certain economic drivers are very different in the two industries[1,2]. Specifically, for the wind turbine foundations:

- the vertical loads are typically much smaller, whilst as in proportion to the vertical load the horizontal loads and moments are much larger,
- many, relatively cheap, foundations are required rather than single “one off” structures,
- the design is dominated by considerations of dynamic response and fatigue under working loads, rather than by ultimate conditions.

In shallow waters a simple concrete “gravity base” foundation (Figure 1(a)) may be possible, and has been used for instance at the Middelgrunden and Nysted windfarms in the Baltic Sea. These foundations resist overturning forces largely through action of their own self weight. Although constructed differently (by construction onshore and

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Author’ Biography

Dr Byron Byrne is currently a University Lecturer in Engineering Science at Oxford University and a Tutorial Fellow at St Catherine’s College. Prior to this he was a Research Fellow and then a Departmental Lecturer, both in Oxford. His current interests are in mechanics of soil and applications relating to offshore engineering.

Professor Guy Houlsby has been Professor of Civil Engineering at Oxford University since 1991. His main work is in geotechnical engineering, where he has considerable research experience on *in situ* testing, offshore foundations and tunnelling. He has a particular interest in the development of offshore renewable energy. He has published over 160 papers in journals and conference proceedings and regularly lectures in the U.K. and abroad. He has acted as a specialist consultant in civil and geotechnical engineering on many projects, especially in the offshore sector. He is a Fellow of the Royal Academy of Engineering.

installation offshore as a single unit) they are similar in concept to concrete pad foundations constructed *in situ* onshore. In some materials special foundation preparation may also be required. The performance of the foundation may be enhanced by adding ballast after placement. Such foundations are likely, however, to be too expensive for deeper waters in which the waves as well as the wind contributes significantly to the overturning moment on the foundation.

The commonest form of foundation at intermediate depth is the "monopile" foundation shown in Figure 1(b). Such foundations were used at Horns Rev off Denmark, and at all three windfarms constructed around the UK to date. The piles, typically 4m or more in diameter and 20m to 35m long are installed by either drilling and grouting, or by driving (or a combination of drilling and driving). In either case very substantial equipment is required for installation of the piles. A specialist jack-up barge is usually required, and the cost of the foundation depends as much on the cost of installation as on the materials used.

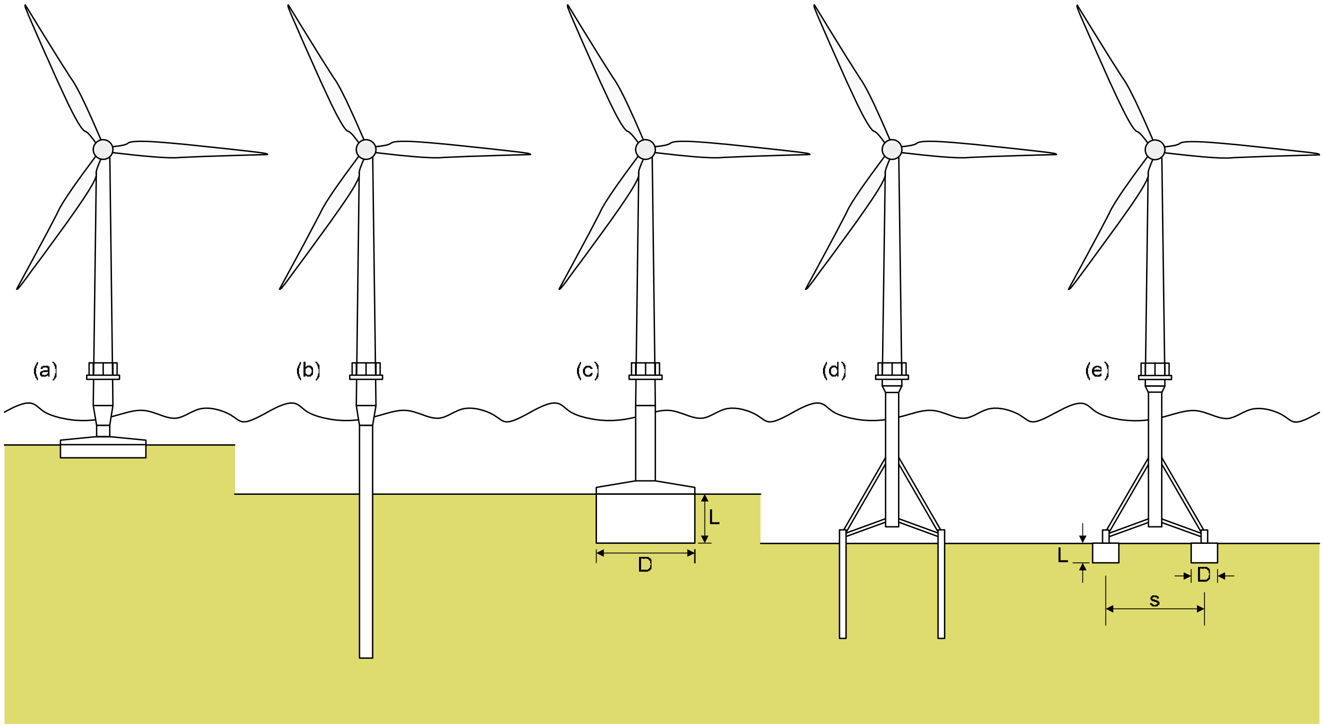


Figure 1 Options for wind turbine foundations

An alternative would be to use a "suction caisson" foundation of the type shown in Figure 1(c). These foundations are like large upturned buckets. On lowering them to the seabed they cut in a small distance. The water trapped inside the caisson is then pumped out, sucking the foundation to its final position. The advantage of such a construction lies not so much in the saving of materials, but in the possibilities it offers for a simpler construction procedure. Indeed if the caisson could be floated to site, it would need little more than a large pump for installation. A trial foundation of a suction caisson for a wind turbine has been constructed at Frederikhavn, Denmark.

As water becomes deeper and turbines larger a monopile would be come so large that it could not be handled and installed using current technology, and equally well a caisson would become uneconomically large. For deeper water a multiple footing option would be more attractive, either in the form of a tripod (three foundations) or tetrapod (four foundations). Figure 1(d) illustrates a tetrapod pile foundation. The foundation would support a simple steel structure which in turn would support the turbine tower. Details of the steel structure are not shown in the figure, but one advantage is that, by shortening the free length of the tower, a stiffer overall structure can be made, hence making it easier to meet dynamic requirements. A structure and foundation of this sort is likely to be adopted for the two experimental turbines in deep water at the Beatrice field off Scotland.

An alternative to the piled design in deep water would be to use a tripod or tetrapod caisson structure, as illustrated in Figure 1(e). Again there would be advantages in the installation procedures.

The subject of the remainder of this paper is to report some of the main findings from a research project directed towards development of design guidelines for suction caissons for offshore wind turbines, in either of the configurations illustrated in Figures 1(c) and 1(e).

EPSRC / DTI RESEARCH PROJECT

During 2005 a £1.5m, three-year research project aimed at developing design guidelines for suction-installed foundations for offshore wind turbines was completed. This project was principally funded by the DTI and EPSRC, as well as a number of industrial partners as shown in Figure 2. A large component of work was co-ordinated and completed by personnel at Oxford University, and some key conclusions from the project are reported in this paper. The industrial partners are listed in the Acknowledgements: they represent parties with expertise in site investigation, geotechnical design, offshore operations, wind farm design and supply, as well potential operators of offshore wind developments. A steering committee ensured that the project remained in touch with relevant issues in what is a rapidly changing technological area.

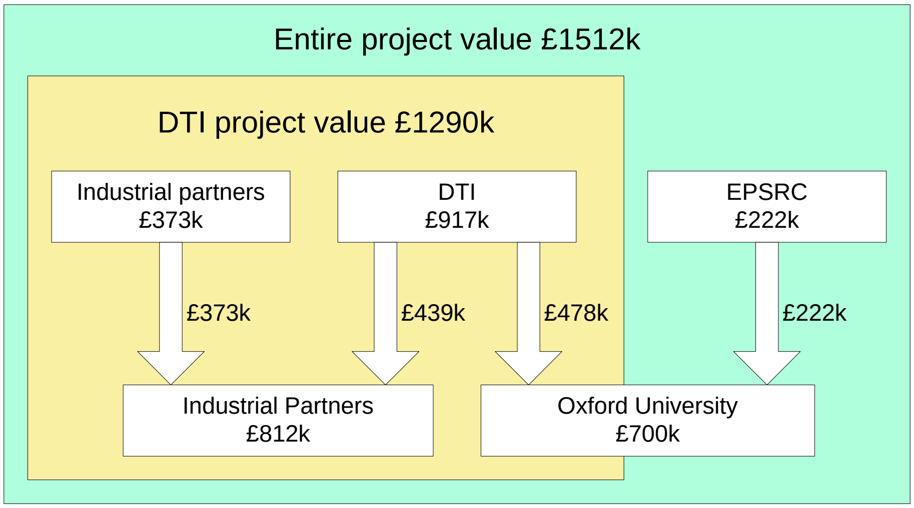


Figure 2 Funding arrangements for wind turbine foundation project.

The following areas of work were pursued in the project:

- Desk studies (by Fugro) of ground conditions at relevant sites, so that the laboratory tests were on appropriate soils. This results in an early decision to focus the testing on sands.
- Preliminary studies (by Garrad Hassan and HR Wallingford) to determine appropriate wind, current and turbine loads on the foundations, which were scaled for the model tests.
- Preliminary studies (by SLP Engineering) to determine appropriate structural forms.
- Development of understanding of the foundation response by carrying out laboratory scale tests specified by the initial studies.
- Assess scaling relationships by carrying out large scale onshore field testing.
- Develop the “force resultant” models on the basis of the laboratory and field tests to allow the modelling of cyclic loading[3].
- Linking of the “force resultant” computational model with the Garrad Hassan program “Bladed” for complete analysis of the turbine/structure/foundation system under realistic loading.
- Final studies of possible structure and caisson configurations on different soil types, making use of the analysis techniques developed.
- Experimental studies (by HR Wallingford) into the scour and liquefaction for different foundation configurations, and into possible preventative measures.
- Assessment of the methodology, equipment and logistics required to install the proposed designs.

A final report has been issued to the DTI on the project in 2005, and details combined with design guidance are to be presented in a forthcoming book by Byrne *et al.*[4]. The following sections outline some of the key outcomes from the research, and in particular relate to a large part of the work carried out by Oxford University. Houlsby *et al.*[5] outline in more detail some of the main technical aspects from the research.

It is important to note that the monopod caisson (Figure 1(c)) and tripod/tetrapod (Figure 1(e) resist the environmental loadings in quite different ways. In particular the overturning moment caused by wind and waves is of primary importance. The monopod resists this moment directly, and it is therefore essential to investigate the response of a monopod when subjected to moment load (but at approximately constant low vertical load). The essential outcomes are the required diameter *D* and length *L* of the caisson. The tripod/tetrapod, on the other hand, resist the moment primarily by "push-pull" action on downwind and upwind caissons, and so it is necessary to investigate their performance under cyclic vertical load. Of primary importance will be the onset of tension applied to the upwind foundation when the moment becomes sufficiently large to overcome the deadweight of the structure.

SUCTION INSTALLATION

The suction caisson foundation has advantages over other foundation types by virtue of the installation process. Whereas heavy duty equipment is required for the installation of piles it is likely that relatively light-duty equipment will be required to install the caisson foundations; simplistically all that is required is a pump of the appropriate capacity. The installation of the foundation should be completed faster than if the more traditional technologies, such as piling, are used. These two advantages should lead to a significant reduction in the up-front capital cost of installing the wind turbine, thus improving the economics of the entire operation. Whilst the suction installation process may well be beneficial, a designer will still need to give serious consideration to issues of transportation to site, assembly and connectivity of the sub-structure and tower.

The key design curve necessary for assessing installation of a foundation by suction is the relationship between suction within the caisson and the penetration of the caisson into the ground. Houlsby and Byrne[6,7] present design calculations which allow an assessment of this relationship for a variety of seabed materials. Installation in clay is considered in the first paper where the net suction provides an additional force on the caisson driving it into the seabed material. As the clay has a very low permeability it is not possible for steady state seepage gradients to develop within the soil, therefore the rate of installation will be related to the rate of water extraction from the caisson cavity. Installation in sand involves a slightly different process whereby the development of the suction within the caisson allows seepage gradients to develop within the soil[7]. These seepage gradients beneficially reduce the overall soil resistance to penetration and provide the main mechanism for the caisson penetration.

The installation of caissons into layered material is slightly less well understood though preliminary experiments would suggest that, broadly, installing a caisson into a layer of sand over clay should be possible whilst installing a caisson into clay over sand may be more problematical. Houlsby and Byrne[6,7] discuss installation into a range of other materials and also give calculation procedures for assessing flow rates both for the clay case where no seepage occurs and also for the sand case where seepage occurs.

The calculation procedures have been compared to a number of case studies derived from the literature and at a variety of scales, though further work is required to further verify a number of the key parameters. As an example of a result for such a calculation Figure 3 presents the relationship of suction pressure with depth for a trial installation at Tenby Harbour[7]. The caisson was 2m in diameter with a 2m skirt depth. In this particular instance the head of water was limited to about 2m and due to a combination of conditions the caisson only penetrated to 1.4m. The calculation procedures predict both the suction – penetration curve and also the limit to suction installed penetration (*i.e.* at 1.4m).

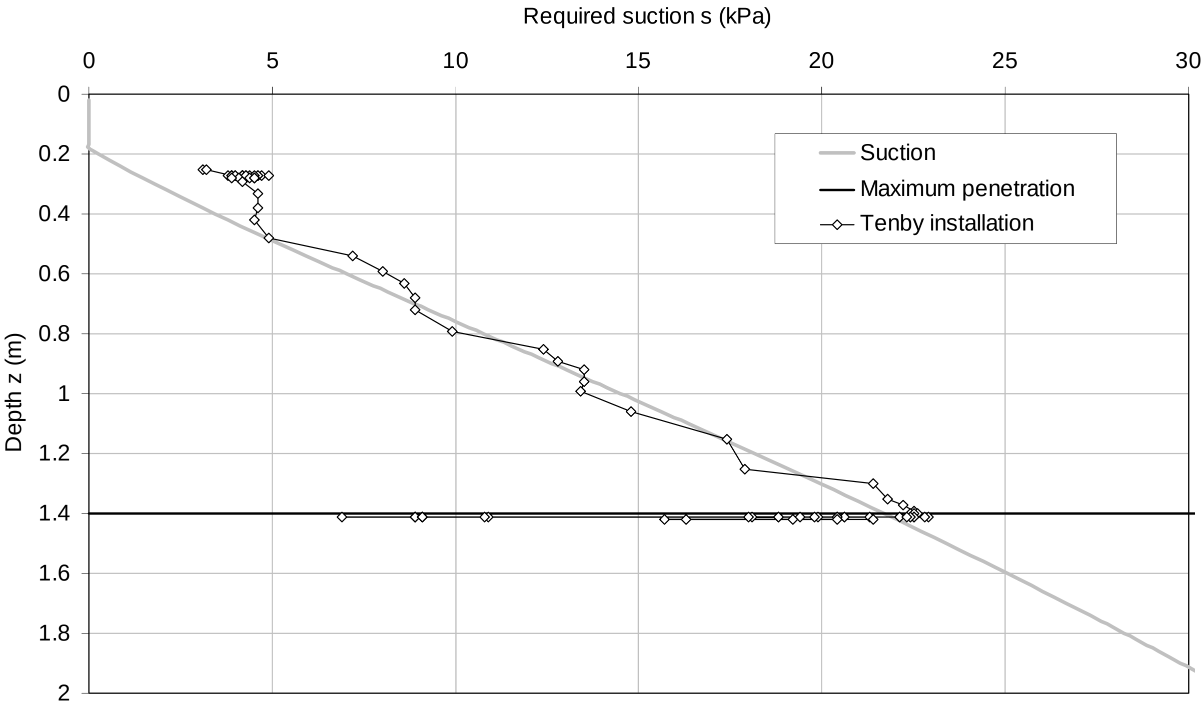


Figure 3 Actual and predicted behaviour for the installation of a suction caisson into sand at Tenby Harbour[7].

It should be noted that it is possible to install caissons in very shallow water (little or no head of water) as evidenced by a small number of field studies[6,7,8,9]. The limitations to installation will derive from an insufficient pump capacity, or in sand from a piping failure due to the suction being increased too rapidly (or the hydraulic gradients in the soil reaching critical values) or in clay a reverse bearing capacity failure. The latter two require consideration of the *L/D* ratio in conjunction with the soil parameters.

FOUNDATION RESPONSE - MONOPOD STRUCTURES

The detailed response of suction caissons to various loadings has been studied in the laboratory at Oxford University. Studies have been carried out on dense and loose sand, dry and saturated sands as well as clays. The main emphasis of the testing has been for sands as this is relevant to a number of proposed wind farm development sites. The testing has investigated monotonic response, cyclic loading response, fatigue loading response and the effects of installation procedure on response. A large proportion of the testing was devoted to providing evidence for developing the “force resultant” plasticity models. The results of the tests can also be interpreted to give outline design guidance for particular structural solutions and in particular, as discussed earlier, there are two main structural configurations being explored for offshore wind turbines. The monopod structure is the obvious initial choice of structure for shallow water sites and therefore initial testing has focussed on the response of model foundations to moment loading. There are three key issues that must be addressed for the monopod foundation:

(a) Capacity – The foundation must be designed so that the one-off large event can be sustained by the structure/foundation without any appreciable movement. The foundation must also be designed with sufficient margin that over time there is no degradation of the response due to the cyclic loading applied. In particular the cyclic loading for this type of application is likely to be very uni-directional and so it is important that the structure does not start to tilt over time. To explore the capacity of the foundation a series of monotonic tests were carried out in dry sand (so as to simulate a drained soil condition). The tests allowed a relationship to be developed between the vertical load of the structure (dead weight) and the allowable combinations of applied horizontal and moment loads (which would be derived from the environmental conditions). Within the theories of “force resultant” models this set of relationships would be referred to as a yield surface. A typical set of results is shown in Figure 4 which shows in non-dimensional form a series of results for the moment capacity as a function of applied vertical load (for a particular ratio of horizontal to moment load). Note that the results indicate that considerable moment capacity is possible even if the foundation is in tension. Of course for the monopod structure the foundation will always remain in compression and the range of appropriate vertical loads is shown on the Figure. These types of results have been gathered for a range of moment to horizontal load ratios as applicable to the wind turbine application. These data can also be presented as in Figure 5, which shows the relationship between horizontal and moment load for different levels of vertical load. Again the range of potential monopod designs is given on the plot. Also shown on Figure 5 are the plastic displacement vectors at yield; another component necessary in the “force resultant” models, and which allows the vertical movements that result from overturning loads to be determined.

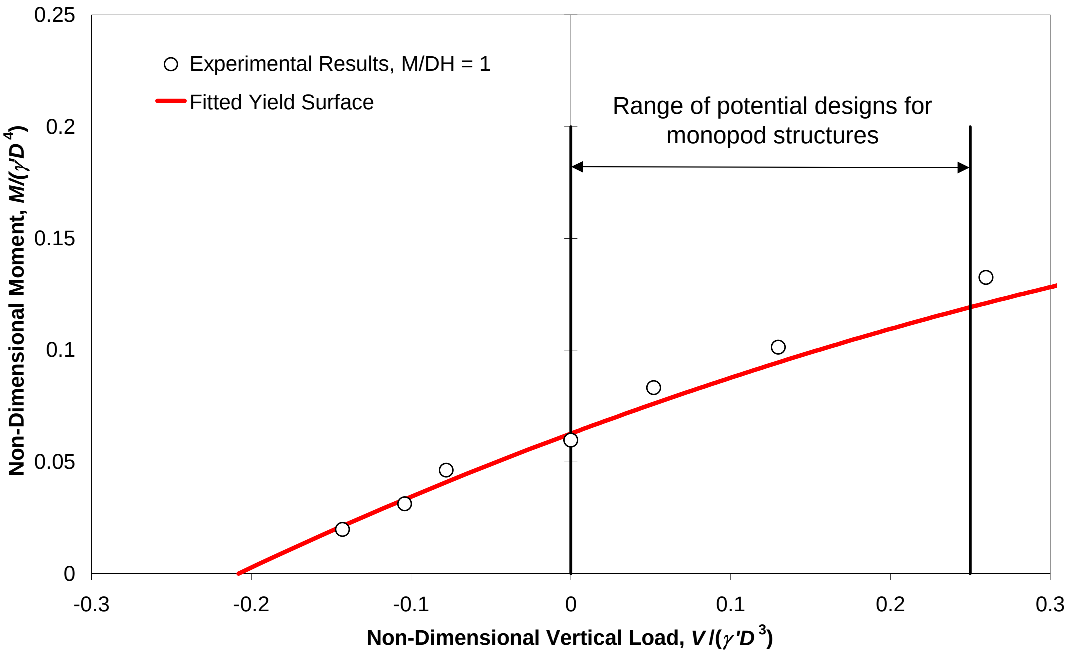


Figure 4 Relationship between moment and vertical load[10].

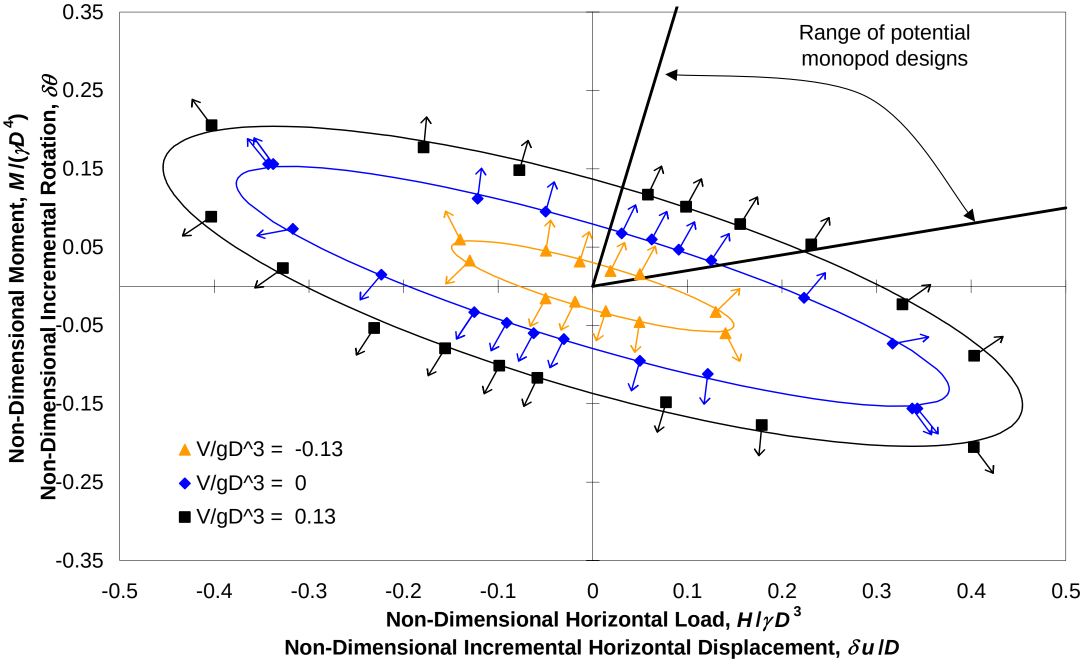


Figure 5 Relationship between H and M for different vertical load levels[10].

(b) Stiffness – Whilst the ultimate capacity is important for the one-off event, a more important issue for the operational life of the structure is the stiffness of the foundation response. In particular the dynamic characteristics of the structure can depend significantly on the stiffness that can be attributable to the foundation. A number of the laboratory tests were aimed at exploring this issue and the result of an example test is given in Figure 6. This shows a test where two cycles of increasing strain amplitude were applied to the model foundation. The results are shown in model scale units. Clearly at the low strain levels the stiffness of the response is high compared with the stiffness at larger strain amplitudes. Equally the response of the foundation is hysteretic in that on unloading the stiffness of the response is initially high and reduces on increasing strain. As well the openness of the hysteresis changes with strain amplitude. Clearly it is very important to be able to model this change in stiffness with strain amplitude closely so that any analysis of dynamics will take due account of it. Most recently new advances to the "force resultant" models have occurred and a new theory termed "continuous hyperplasticity" has been developed that takes due account of the cyclic loading response[11]. This theory successfully replicates results such as that shown in Figure 6, but as yet has not been adapted to allow for degradation or improvement of response that might occur after many hundreds of thousands of cycles. This is an area of on-going research and development.

(c) Scaling of response – During the main research project a significant number of tests were carried out in the laboratory at model scale. Whilst these tests allow a very detailed understanding of the foundation response to be gained it is important to be able to scale the results from the laboratory to prototype. To gather information on this scaling relationship a number of tests were carried out at mid-scale onshore in the field. These tests have been reported in detail by Houlsby *et al.*[8,9]. On the basis of the results of the field tests and laboratory tests Kelly *et al.*[12] have postulated a series of scaling relationships that can be used in the particular case of caissons applied to offshore wind turbines. An example application of the scaling relationships for a caisson is shown in Figure 7 where the response of a foundation in clay to applied moment loading is plotted.

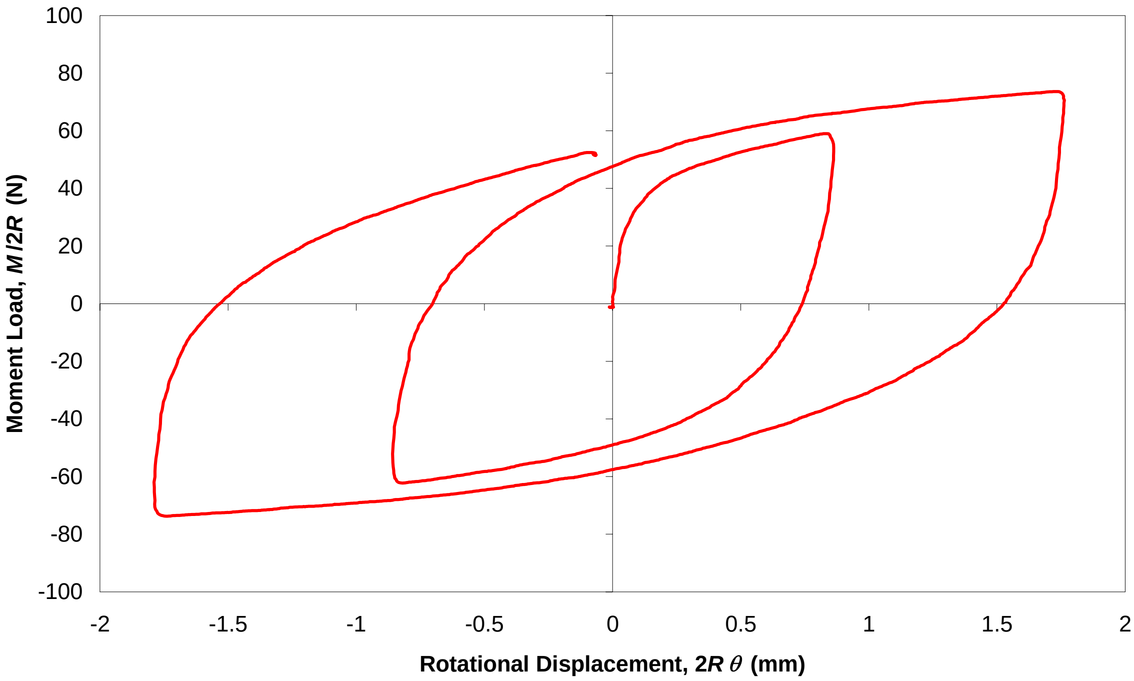
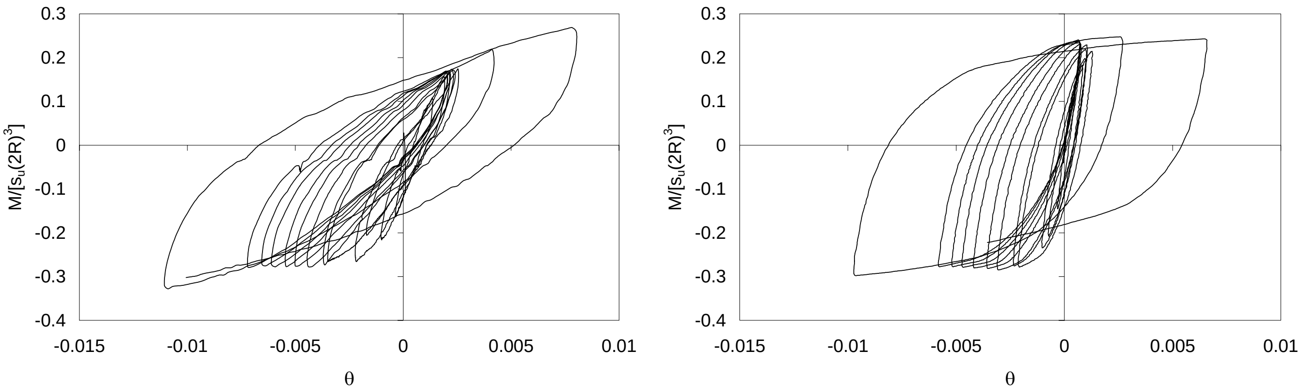


Figure 6 A cyclic loading test at low vertical load showing hysteretic behaviour.



(a) (b)

Figure 7 The results of moment loading of moment loading of a caisson in clay[12]:
(a) field test on caisson of diameter 3m, (b) laboratory test on 0.3m caisson.

TRIPOD/TETRAPOD CAISSON FOUNDATIONS

As stated above, the overturning moment on a tripod or tetrapod foundation is resisted primarily by "push-pull" action by opposing footings. In these circumstances the performance of the upwind caisson is of primary importance as the action of the moment reduces the vertical load. In particular there is the possibility that under extreme conditions tension might be applied to the upwind caisson. The testing of caissons for this application therefore focussed on the response under these conditions.

Figure 8 shows the result of a typical test in which, starting from a compressive load, cyclic vertical loads were applied to a caisson foundation. Packets of cycles at increasing amplitudes are applied. It can be seen that at low amplitudes of cycling the response is stiff, with relatively little hysteresis. As the amplitude increase the stiffness reduces and the hysteresis increases. There is also an accumulation of deformation during a number of cycles, but it should be noted that this deformation is always downward. This is thought to be an acceptable condition, as small additional embedment of the foundation is expected to cause a stiffening of response. Indeed, although few tests have been conducted to large numbers of cycles, there is evidence that the rate of additional settlement per cycle gradually reduces as the number of cycles increases.

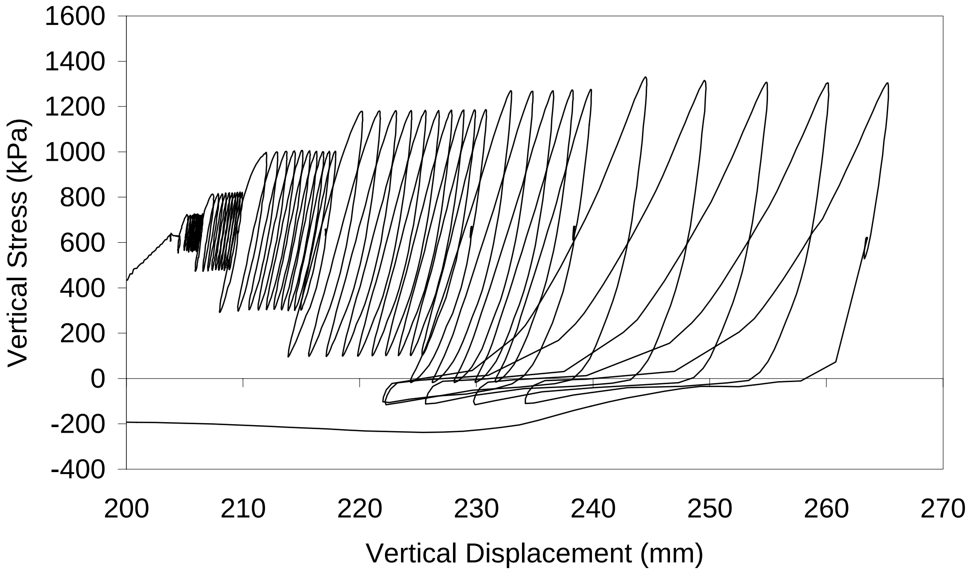


Figure 8 Cyclic vertical loading test on model suction caisson[13].

Once the cycles become sufficiently large that the foundation is subjected to tension it can be seen that there is a dramatic change in response. As tension is applied the foundation shows a much more flexible response and moves upwards markedly. As the compression is reapplied the footing moves back downward, with the overall hysteresis loop for the cycle becoming a characteristic "banana shape". Such behaviour would clearly not be acceptable for a turbine, as the larger movements, although not in themselves representing failure of the structure/foundation system, would almost certainly cause operational problems.

It has been suggested that the low tensile capacity observed in the foundation tests could be due to:

- a low rate of loading, so that significant suctions could not be developed below the foundation,
- the low ambient pressure, allowing cavitation to occur beneath the foundation at lower differential pressures than would occur in the field.

Tests were carried out therefore to address these issues, and they reveal that higher rates of loading and elevated pressures do indeed result in a higher ultimate failure load. Satisfactory (although approximate) procedures have been developed to explain the variation of capacity with pressure and displacement rate[13,14]. The tests reveal, however, that although the ultimate capacity is affected by these variables, just as tension is applied to the foundation there is always a rather flexible response first encountered (followed by stiffening and then an approach to the ultimate capacity). Serviceability requirements will dictate that this zone must be avoided, so our strong recommendation is that tensile loads on the caissons must not be allowed.

Tension can be avoided by adopting one of two strategies. Either the separation of the footings (s in Figure 1(e)) can be increased, or the deadweight of the structure can be increased. Different solutions may be appropriate in different situations, but the provision of relatively cheap ballasting of the structure is an attractive possibility. One disadvantage is that the structures necessary to contain the ballast may themselves attract additional wave and current loading.

OTHER CONSIDERATIONS

There are a number of other considerations that need to be addressed in the design of caisson foundations for offshore wind turbines. The most important of these is scour. Turbines may be located at sites where there are highly mobile seabed conditions, and experience indicates that scour can develop very rapidly around these structures. It will be necessary to make allowance in the design for an appropriate depth of scour around the caissons and/or put in place preventative measures.

CONCLUSIONS

We have addressed some of the major issues in the design of suction caisson foundations for offshore wind turbines. As large monopod foundations in relatively shallow water these would be subjected to moment loading. Tests at laboratory and field scale show a pattern of gradually reducing stiffness as the foundations are subjected to progressively larger moment cycles. In deeper waters a tripod or tetrapod foundation would probably be more economical. In this case the design of the foundation would usually be dominated by the need to avoid tension on the upwind foundation. The conclusions drawn in this paper are based on laboratory tests and field trials, supported by analyses. The next stage required in this development is the measurement of the response of larger scale trial foundations offshore.

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