

The Application of Suction Caisson Foundations to Offshore Wind Turbines – Extracts from a proposal to the DTI

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Sub Contractors: Oxford University (Department of Engineering Science), HR Wallingford, Marine Operations (TBA)

1. TECHNICAL BACKGROUND TO THE PROJECT

The market for offshore wind farms in the UK is expected to be substantial. The initial sites proposed for such structures are predominantly near shore shallow water sites (less than 15 m water depth). Unlike onshore wind farms, the cost of the foundations, including installation, is a significant fraction of the unit cost for an offshore wind turbine. This is recognised in the DTI's initiative, which places the highest priority on innovative foundation solutions and improved offshore installation techniques.

It is anticipated that each offshore wind farm development may require the installation of up to fifty similar or identical units. Commercial viability of such developments are therefore sensitively dependent on the cost of marine equipment and logistics and the critical path duration required for the installation of each unit.

Suction caissons are a technology which provides the prospect of a foundation solution that would be particularly attractive for application on offshore wind farms for the following reasons:

- Suction caissons are simple steel fabrications that can be designed to be lighter and cheaper than the steel required for an equivalent pile foundation. This has been demonstrated in a number of offshore oil and gas projects.
- The installation method is potentially much quicker and simpler than for other solutions. A foundation incorporating suction caisson(s) is a single unit that can be deployed and installed within a matter of hours as a single simple operation. It is not significantly weather dependent. By comparison, installing driven piles, for example, would involve multiple operations, and delays associated with grout curing, that could take several days to complete and also risk additional weather delays, especially in winter. Complete unit installation also offers potential for savings on commissioning.
- The installation method requires only a simple marine spread including a crane of sufficient capacity to lift units into place. Additional costs of ancillary equipment such as pile driving hammer spreads, grouting spreads and consumables required by other installation methods, can be saved.
- Suction caissons are expected to be particularly suitable for foundations in the type of seabed sediments found around the coast of the UK. A number of offshore wind farm developments in Europe to date have been founded in/on rock. The foundation designs used in these developments may not be cost effective in the majority of the UK sites.
- Suction caisson foundations can be flexibly adapted to a variety of structural forms thus enabling designs to be adapted to maximise accessibility by boat and accommodate a variety of water depths and tidal conditions.
- At the end of a wind turbine's life, a suction caisson may be removed completely from the seabed, unlike piled foundations.

There is a large body of accumulated knowledge and expertise (not least in the UK) on the design of suction caisson foundations for oil and gas projects undertaken in recent years. Designs for wind turbine foundations can exploit this experience. However, by comparison with typical offshore oil and gas applications, wind turbine foundations will differ in respect of their environmental conditions and required performance. The important differences include the following:

- Vertical loading on the foundations will be relatively small. Consequently the horizontal and moment loading are a much larger fraction of the vertical loading and are also highly dynamic. This is important as the capacity of suction foundations to resist tensile and moment loading is sensitively dependent on the dynamic characteristics of the loading.
- Sediment movement and local scour are important phenomena in coastal waters due to high currents and shallow water wave effects. The performance of caissons in a partially eroded seabed and effective means of scour mitigation therefore become important design issues.
- The dynamic interaction between wind-induced loading of the turbine rotor and the wave induced loading on the structure results in complicated dynamic loading on the foundation, which is very different the wave and current loading that dominates the design of typical oil and gas installations.

The understanding of the static strength behaviour of suction caisson foundations is reasonably well established. However, to date, design of oil and gas foundations for cyclic loading has been achieved by either adopting overly conservative assumptions, or by reference to case specific empirical data. The loading environment discussed above means that this approach cannot be transferred to the design of economic wind turbine foundations. Theoretical models based on a fundamental understanding of the soil mechanics are required. Models of this type have been developed by Oxford University. One of the key aims of this project is to develop and validate this theory to the point where it can be applied to the design of actual wind farm development projects.

2. AIMS AND OBJECTIVES OF THE PROJECT

The overall aim of the project is to develop suction foundation caisson technology to the point where it can be applied to the design of economically optimised and reliable foundations for actual offshore wind farm developments.

To achieve this aim the following objectives will be pursued.

- (1) Finalise the development of the current geotechnical models of suction caisson in-service behaviour.
- (2) Validate and calibrate the geotechnical models using laboratory testing.
- (3) Validate scaling assumptions for geotechnical models using large-scale onshore or offshore testing.
- (4) Implement geotechnical models into structural analysis and loading software suitable for checking design solutions.
- (5) Identify and validate methods for firstly predicting scour in the vicinity of suction caissons (including scour alternative protection measures) and secondly assessing the effect on the foundation performance.
- (6) Identify and assess novel solutions, as appropriate, to problems of caisson design and scour mitigation.
- (7) Develop conceptual designs for wind turbine structures, incorporating suction caisson foundations, which would be demonstrated to satisfy, as far as possible, the criteria of being simple and economic to construct, simple and quick to install, reliable, durable, maintenance free and widely applicable to the range of possible site conditions.
- (8) Outline specification of the methodology, equipment and logistics required to install the proposed design.
- (9) Economic validation of the proposed design by comparative desk studies of the construction and installation costs, risks and schedule.
- (10) Map applicability of solutions to the full range of potential site conditions.
- (11) Report the results of the project including reporting the lessons learnt and understanding gained in the form of outline design guidance.

3. BENEFITS

Benefits to participants can be summarised as follows:

- (1) SLP Engineering will expect to advance their capabilities and profile in the market to design and supply the structural and foundation components for offshore wind turbines.
- (2) Shell, Aerolaminates and Enron would expect to accrue benefits primarily in terms of savings on capital cost associated with implementing a significantly simpler and cheaper design for wind turbine foundations in their developments. There is a potential for savings of the order of £200,000 per turbine on installation costs compared to mono-pile designs. The immediate market for offshore wind turbine foundations (supply and installation) in the designated development areas is worth approximately £270 million in total, based on the 30 turbines at each of the 18 sites. The total European market for turbine foundations could grow to £2 billion annually if predictions that 40% of the EU energy consumption could be supplied from offshore wind farms within 30 years are achieved.
- (3) Garrad Hassan and Fugro would expect to advance their capabilities and therefore sustain their competitiveness in the market to supply engineering consultancy in the field of offshore wind turbine design and analysis.

The benefits to the country can be summarised as follows:

- (1) The project will create and disseminate to a group of UK institutions and companies expertise that has the potential to give the UK a technical lead in a technology that can not only be applied to a large and growing market for offshore wind farms in the UK and the EU, but can also be applied to a variety of other applications in the UK and worldwide, including oil and gas minimum offshore structures and anchors for floating production vessels. Exploitation of this should be beneficial in terms of UK competitiveness, growth, tax revenue etc.
- (2) By developing this new technology, opportunities will be created for the UK steel fabrication industry to compete in the market for supply of foundation steel, which is currently dominated by continental organisations, who have invested in plant suitable for fabrication of large mono-piles.
- (3) The risks and cost associated with installing traditional foundations for offshore wind turbines are sufficiently large to make the economics of development marginal in most typical cases. Suction caissons offer the prospect of significantly reducing the risk and cost associated with installation. Consequently, making this technology available would be expected significantly to increase the number of licence areas that become economic and hence the rate at which they are developed.
- (4) It may be that suction caisson foundations can be applied to site conditions that are not economically suitable for development using any other foundation design. Making previously unsuitable sites available for development would again tend to increase the rate of development.
- (5) Advancing suction caisson technology has the potential to significantly increase the chances of the Government reaching its targets for offshore wind farm development on schedule.
- (6) Significantly reducing costs of development and making previously unsuitable sites more attractive for development should result in an increase in the revenue the Government might expect to accrue from any future licence rounds.

4. PROGRAMME OF WORK: PROJECT ACTIVITIES, TIMESCALE AND COSTS

4.1 Activity Description

(a) Design Basis

This activity will aim to identify, describe and bound the site characteristics that will need to be considered in both the subsequent experimental work and design studies. This will include the following tasks:

- Use BGS and Admiralty charts to determine the range of near surface soils that might be encountered at the 18 sites given licences for development by the Crown Estate, as well as other potential sites in the EU. Describe a number of

generic soil profiles, to a depth of 15m, for use in studies, which are representative of the range of potential sites of application.

- Collate oceanographic and wind speed data for the development sites from Government reports, Admiralty and other public domain sources as well as Participants involved in wind farm development. Identify ranges of key parameters such as mean water depth, tidal range, current velocity, wave climate statistics and wind speed climate statistics. Establish a set of representative site condition definitions, for use in studies.
- Collate existing information about seabed mobility and bed forms around the UK using HR Wallingford databases. Potential ranges of global seabed movement will be identified for a range of typical development sites.
- Identify and describe the loading and dynamic characteristics of alternative turbine designs. Select one or two representative turbine characteristics to be considered in the following studies. These will include consideration of the potential for developments using large (say 3.5MW) turbines.
- The above information will be assembled and compared to identify broad correlations. Design guidance in relation to target reliability criteria, risk, design conditions, partial factors, etc. will be established.

This activity will deliver the Design Basis report, which will be used as an input into subsequent activities.

(b) Design Studies (Initial)

This activity will aim to highlight key design issues so that testing work can be targeted towards critical loading regimes and caisson arrangements. This activity will also identify the novel solutions, which will be investigated by the project. This will include the following tasks:

- Perform preliminary comparative sizing of suction caissons applied to two or three potential conceptual structural configurations. This will include consideration of single caisson foundations and foundations consisting of three caissons in a triangular arrangement. The full range of site environmental conditions defined in the design basis will be simulated using Garrad Hassan's Bladed for Windows software. Caisson load time histories will be analysed and characterised and correlations between the three components of caisson loading (vertical load, moment and horizontal load) will be identified in each case.
- Issues of caisson aspect ratio will be studied to identify appropriate ranges of aspect ratio for different structural forms and different site conditions.
- Potential novel solutions for caisson design and scour mitigation will be identified and screened. Conceptual designs will be undertaken for solutions identified as being suitable for further investigation and testing.
- The constraints on the design resulting from wind turbine functional and technical objectives will be assessed and implemented in the conceptual structural configurations. These will include turbine performance constraints, the need for easy boat access and the need for easy and simple installation.

This activity will deliver a report, which defines the technological solutions, which will be investigated in the following activities. It will also describe functional and performance criteria that need to be achieved.

(c) Numerical Model Building

There is extensive experience at Oxford University on development of "force resultant" models for the behaviour of shallow foundations. "Model B" (for clay) and "Model C" (for sand) have been developed and used in finite element analyses of jack-up units under wave loading. In these models the behaviour of the foundation is reproduced in terms of the relationship between the resultant forces (vertical, horizontal, moment) on the foundation and the corresponding displacements. These models are based on work-hardening plasticity theory and are among the most advanced worldwide in this particular field.

In this activity new models would be developed for the caisson foundation with the following work being of prime importance:

- Merger and enhancement of Models B and C to allow them to model 6 degrees of freedom, required for implementation in a 3 dimensional analysis package.
- The further development of these models to allow the prediction of displacements under cyclic loading (the current models are focused more on the monotonic failure problem). This will almost certainly be based on "continuous hyperplasticity" research and will involve collaboration with Dr A.M. Puzrin of the Technion, Haifa.
- The modelling of the detailed behaviour at the tension/compression transition for the caisson.
- Validation and calibration of models against data from laboratory tests and field trials.
- Results of the "Oxford Model" will be compared with the results obtained using other analytical methods, including geotechnical finite element simulations or the Fugro CANCAP analysis programme.
- Assessment of the importance, and analysis, of wave-induced liquefaction on the performance of suction caissons. This will involve HR Wallingford undertaking both numerical modelling using DIANA-SWANDYNE and laboratory experiments. These would aim to assess changes in pore pressure in the seabed due to wave induced stresses. These would subsequently be compared with pore pressure changes predicted due to caisson movement and assessments of caisson stability will be made.
- The models in the form of software modules would be included in Garrad Hassan's program "BladeD for Windows" for analysis of the complete turbine/structure/foundation system.

This activity would deliver preliminary foundation simulation software modules (excluding the cyclic loading capability) implemented for a commercial analysis package after 9 months. A final report describing the theory and its validation against laboratory testing and field trials would be delivered.

(d) Laboratory Caisson Tests

Recent testing of model caissons at Oxford University has focused mainly on loading appropriate to oil and gas installations and included tests on footings up to 300 mm in diameter. It will be necessary to carry out further testing aimed more directly at the wind turbine applications. These tests will provide an extensive database for the development of design methods. The key design issue for a tripod design is the tension response of the upwind leg whilst for a monopod it is the overturning moment. In each case this is not a matter of ultimate load capacity (which will be huge) but of accumulated deformations under cyclic loading. For the tripod it appears that as the foundation goes into tension there is a transition to a much softer response. The data are, however, rather few at present. It is necessary to explore (a) different sizes of foundation to investigate scaling, (b) different soil types (sand at different densities, clay at different strengths), (c) different possible loading regimes, and, (d) tests directly shadowing the proposed field tests. Oxford believe that with equipment at their disposal it would be possible for loads up to 500kN to be applied to a footing up to 400mm in diameter. Additionally it is proposed to do some tests in a sealed chamber, as the issue of the ambient water pressure is a key one.

Tasks will fall into the following categories:

- Tension and compression cyclic loading tests
- Overturning moment cyclic loading tests
- Tests shadowing field tests
- Pressurisation tank design and commissioning
- Pressurisation tank tests
- Installation tests (as part of in-service tests)
- Sample tests incorporating novel solutions (option)
- Sample tests investigating capacity degradation due to scour

This activity will deliver a report detailing the results of all testing categories, excluding pressure tank tests, at the end of 18 months. A final report including all test results will follow.

(e) Scour Investigation

Understanding the consequences, and optimal means of mitigation, of scour around a suction caisson is essential to assessing the applicability of the technology to areas where seabed movement is significant. Suction caissons penetrate the seabed to relatively shallow depths and so are more prone to being compromised by scour than say piled structures. Protection against scour could be a significant element of the installation cost of a suction caisson if say blanket rock-dumping is adopted. This activity will aim to develop the tools necessary to predict scour in the vicinity of a suction caisson including the means to design optimised mitigation measures. This will include the following work, which is to be undertaken by HR Wallingford:

- HR Wallingford will present a methodology identifying techniques, procedures and data sources for determining seabed mobility at an offshore wind farm location. This will be a summarisation of existing knowledge held within HRW.
- HR Wallingford has considerable expertise in the prediction and solution of local scour problems. HRW's existing database of experimental measurements and predictions will be used to identify key issues and predictive methods applicable to the caisson geometries being considered.
- There are gaps in the available techniques with respect to scour due to waves and currents, in general, and with respect to wind farm structure and foundation geometries, in particular. Computational fluid dynamic simulations, using CFX, will be undertaken to assess the scour magnitude around a wind farm structure in realistic wave and current conditions. This may be supplemented by laboratory wave tank tests. These simulations will be used to derive an empirical predictor for local scour around wind farm caisson structures.
- Existing scour mitigation measures will be identified and screened for effectiveness and cost, based on existing knowledge. Possible novel solutions will be identified and screened for practicality and cost. The effectiveness of preferred novel mitigation methods will be tested in the laboratory. Results will be compared with limiting scour profiles derived on the basis of caisson geotechnical performance. Design guidelines for preferred mitigation measures will be presented.

This activity will deliver a report detailing predictive methodologies, design guidelines and all test results.

(f) Large-Scale Caisson Tests

Although model tests can cover a wide variety of conditions, it is always necessary to establish their relevance to the field through larger scale tests. It is therefore intended to carry out tests at two or three sites (including one sand and one stiff clay), in which intermediate scale caissons (of size to be determined, but probably 2m diameter) would be installed. It is planned that three foundations would be installed in line, with a cross beam linking them. Loading devices on the cross-beam would allow the central foundation to be subjected to (a) cyclic tensile/compressive loading and (b) cyclic overturning moment. Appropriate instrumentation would be installed, including pore pressure sensors, strain sensors and applied load sensors. The tests would be used to establish appropriate scaling factors from model tests for both displacements and loads.

It is envisaged that monitoring will also be performed during caisson installation and removal. The budget will provide for a pumping skid for this purpose. The tests could (for economy) be carried out at onshore sites, in a shallow flooded excavation.

This activity will include the following work:

- Field trial site selection and specification
- Design, engineering and supply of apparatus
- Engineering of test procedure (2 or 3 tests)
- Testing and data acquisition (2 or 3 tests)
- Data analysis
- Reporting

This activity will deliver data input to theory calibration and validation and a report detailing the results of the testing.

(g) Design Study (Final)

This activity will aim to identify practical and reliable design concepts that satisfy all functional, performance and economic criteria. This will be the opportunity to test the implications of understanding gained during the previous theoretical and experimental work. This activity will include the following work:

- Conceptual design of suction caisson founded wind turbine mast structures using the validated numerical foundation model. A range of sample designs will be undertaken representative of the range of soil types, site met-ocean conditions and turbine types selected for investigation. The aim would be to identify one, or at most two, preferred structural configurations, which would be easily installed, practical, reliable, durable and could be adapted to most conditions. The designs will include dynamic fatigue assessments of the supporting structure and mast.
- Existing alternative foundation designs for comparable conditions will be identified or developed. These might include driven piled foundations, bored mono-pile foundations and or gravity base foundations. Development of alternative designs will be sufficient for order of magnitude cost comparisons.
- Order of magnitude economic modelling of the costs of wind farm developments incorporating suction caissons as compared to traditional foundation designs will be undertaken. This will include detailed consideration of installation costs, risks and timescales. Costs and benefits will be discounted on a net present value basis.
- Conceptual design of an effective scour mitigation device that can be deployed simply and quickly. The costs and practicality of the design will be compared with conventional scour mitigation methods method such as rock dumping.
- The results of the conceptual design task will be used together with a parametric study of caisson performance to map the applicability of suction caissons to the range of conditions found around the coast of the UK.

This activity will deliver a report defining the proposed designs and detailing the design calculations, cost benefit and applicability assessments.

(h) Installation Study

This activity would aim to outline the specification of the procedures, equipment and logistics required to install the proposed suction caisson foundation. Criteria to be used in the development and optimisation of the conceptual design would also be developed. The work would include the following:

- Assessment of geotechnical constraints on suction caisson installation in shallow water utilising theory and test data obtained in preceding activities.
- Specification of Jack-up (or spud-leg) crane barge suitable for the installation operation. The current availability of suitable equipment will be reviewed and spread hire rates estimated.
- Outline procedures for the operation will be worked up including identification and costing of any ancillary equipment and logistic requirements. Weather constraints on each task will be assessed.
- Offshore operations will be scheduled and risks associated with weather down time, etc. will be assessed. This will be based on appropriate environmental data for year round operations.

This activity will deliver two reports, one summarising the results of the geotechnical constraints study, the other summarising the results of the above marine operations studies.

(i) Project Management and Reporting

Project management organisation will undertake the following responsibilities:

- Coordination of contributions from the various participants
- Detailed scheduling and control of the project timescale including preparation of progress reports.
- Project accounting including preparation of project financial reports.
- Liaison with funding authorities.
- Arranging and chairing steering group meetings.

This activity also includes responsibilities for technical reporting as follows:

- Summarising technical results in the form of Milestone Reports at stages through the project.
- Collation of reports produced in the technical activities for the final Report
- Preparation of the Final Technical Report, which will include summaries of the results of the technical activities together with "lessons learnt" and "understanding gained" in the form of outline design guidance.

This activity will deliver Management Reports, summarising progress and expenditure, to Participants and Funding Authorities. It will also deliver the Final Technical Report.

5. COMPLETION OF THE PROJECT

5.1 Risks

Technical Risks

The main technical risks for the project are associated with the specific areas of uncertainty that the project aims to clarify. In all the areas of study where technical advances are sought, there is the potential that unforeseen phenomena could be identified that limit the potential applicability or cost effectiveness of suction caissons for offshore wind turbine mast foundations. Mitigating these risks is the fact that suction caisson technology is well established for other applications and the experience from these has been used to identify the key remaining issues, which this project aims to target.

These key areas of uncertainty are:

- The behaviour of suction caissons under cyclic tensile and moment loading.
- The susceptibility of caissons to scour in shallow waters and economic means of mitigation.
- Exact optimum geometry of a caisson design and its ease of installation.

Additional to the above there are potential technical risks associated with the productivity of the testing and field trials. These risks are expected to be very low, as the procedures and equipment used in this experimental work are similar to those used in numerous previous investigations.

Financial and Commercial Risks

The financial and commercial risks associated with the project are expected to be small. Obviously Participants are investing in the project in the anticipation of a positive outcome, which is dependent on the technical risks.

The risk that the project cannot achieve its objective due to budget overrun is expected to be very small due to the fact that the project is composed of numerous small activities with relatively small investment in hardware.

5.2 Exploitation

The aim of this project is to take the technology to the point at which it can be applied to the design of an actual offshore wind farm prototype utilising definitive design rules and commercially available modelling tools. The Participants in the project who are in the business of developing wind farms will anticipate to use the results of the project to enable them to implement suction caissons as the foundations for turbine masts installed in their development areas.

There is a potential saving of £200,000 per turbine on the installation operations. On the assumption that a wind farm may have 30 turbines this amounts to a prospective saving of £6 million on the development of a field. For the 18 development areas currently under consideration around the coast of the UK, the potential saving could be £108 million on a total development cost of £1.1 billion.

Obviously, savings on foundation installation could also be applied to future wind farm developments, either round the coast of the UK or abroad. Some analysts have suggested that there is the potential for 40% of European energy consumption to be supplied by offshore wind farms within a timescale of 30 years. To achieve this the industry would need to install, on average, 8 GW of generation capacity every year, resulting in a total market of £8 billion annually.

Participants who are in the business of engineering consultancy will be able to exploit the results of this work by using it to enhance their technical capabilities and profile in the emerging wind energy market. Costs of engineering foundations for a single wind farm may be of the order of £250,000, giving a total market for foundation related engineering services of £4.5 million for the current set of potential developments. Also, the technology could also be applied to other markets (offshore oil and gas, etc.).

Participants involved in the steel fabrication and EPIC contracting will be able to exploit the results of the project by also using it to enhance their technical capabilities and profile in the market. Adopting suction caisson foundations allows UK fabricators to compete for supply of foundation steelwork. Currently UK producers cannot compete with suppliers in Holland and Germany who have invested in plant suitable for supplying mono-pile tubulars. The cost of supplying foundation steelwork to a single wind farm

may be of the order of £7.5 million, giving a total market for supply of foundations for the current set of potential developments of approximately £135 million.

5.3 Publication of Results

A Project Profile and Project Summary (see 4.4 above) will be produced suitable for publication. In addition a Final report will be produced, which the DTI will publish as part of its New and Renewable Energy Programme. The final report will include all the test results from the whole project, but may exclude proprietary information.

It is anticipated that the following deliverables from the project will be treated as proprietary:

- The coding of the software modules to simulate the non-linear time history dependent load response of the suction caissons.
- Aspects of performance and specification of the wind turbines selected for investigation may be considered to be confidential by Participants in the business of supplying these units.
- For any novel solutions identified by the project that are patentable, publication of any details will be postponed until application for patents has been made. It should be noted that if any patentable solutions are identified, they are likely to relate to peripheral aspects of the project such as scour prevention and will not prevent publication of suction caisson design guidance.

Publication of the main results of the project will undertaken as the end of the project in the form of a Final Report together with papers presented at industry conferences.

It is also anticipated that the work undertaken in the proposed project will lead to a number of academic papers together with up to three PhD theses in the field of geotechnics.

The Design Basis may be published as soon as it is produced to enable cross fertilisation of relevant basic site and environmental data between projects being funded by the DTI.

5.4 Further Work

The aim of this project is to take the technology to the point at which it can be applied to the design of an actual offshore wind farm prototype utilising the optimised configurations, definitive design rules and commercially available modelling tools developed during the project.