Novel Foundations for Offshore Wind Farms

Research Proposal to EPSRC (August 2001)

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1. PREVIOUS RESEARCH AND TRACK RECORD

The Principal Investigator has wide experience of managing research in geotechnical engineering (including offshore foundations, *in situ* testing, tunnelling and reinforced soil). Only projects on shallow foundation behaviour are described here:

1. Extensive studies have been made of the moment fixity of spudcan footings for jack-up units. The assessment of jack-up units depends significantly on this foundation fixity. Initial research was part of a Joint Industry Study (Trickey *et al.*, 1991), in which the research at Oxford involved 46 tests of model spudcans on clay (de Santa Maria 1988, de Santa Maria and Houlsby 1988). The work was extended (with support from Shell Expro and MTD) to a further 21 tests on cyclic loading. This work led directly to the section on foundations in clay in the current recommended practice in this area (SNAME, 1993). This document forms the basis for the ISO standard currently under consideration, and Prof. Houlsby is a member of the drafting panel.
2. Further testing (Houlsby and Martin 1992, Martin 1994, Martin and Houlsby 1999, 2000, 2001) using a sophisticated computer-controlled rig have led to the development of more accurate theories for spudcan foundations, based on plasticity theory ('Model B' and 'Model C'). These models represent the current state-of-the-art of the understanding of jack-up foundations. They were, for instance, used in recent studies sponsored by HSE, IADC and Global Maritime on various aspects of jack-up unit behaviour. The models developed have been incorporated in full non-linear analyses of the dynamic response of jack-up units (Thompson 1996, Williams *et al.* 1998, 1999, Cassidy and Houlsby 1999, Cassidy 1999, Cassidy *et al.* 2000, 2001).
3. In parallel with the above, more fundamental studies have been made on the general problem of a shallow foundation under combined vertical, horizontal and moment loading. Finite element studies (Bell 1991, Bell *et al.* 1991, Ngo Tran 1996) have been complemented by fundamental theoretical work (Houlsby and Puzrin, 1999). The capacity of foundations on sand (Gottardi *et al.* 1999, Cassidy and Houlsby 2001) and loose carbonate sand (Byrne and Houlsby, 2001) have also been found to fit well within the framework of plasticity theory.
4. Recently the work has focussed on the important problem of the effects of partial drainage on the response of shallow foundations on sand. This work began with commercially confidential work for Statoil related to a specific site (Houlsby, 1995). It has been extended to more general studies of flat circular foundations (Mangal 1999, Mangal and Houlsby 1999) and to caisson foundations on dense sand, with sponsorship from EPSRC GR/L67547 (£36k) (Byrne 2000, Byrne and Houlsby 1999, 2000, 2001, Houlsby and Byrne 2000). A further small EPSRC grant GR/M55657 (17k) was for instrumentation of a field trial of an offshore caisson. Some preliminary large-scale laboratory tests have also been completed in the Structural Dynamics testing facility at Oxford University (Johnson, 1999). This facility allows large transient loads to be applied to model foundations with full control of load paths at frequencies up to 25 Hz. This allows the partial drainage effects, which occur in the field, to be realistically modelled.
5. Complementing the work on the partial drainage problem has been work on the development of a new family of plasticity models based on a framework termed 'continuous hyperplasticity' (Houlsby and Puzrin 2000, Puzrin and Houlsby 2001a,b,c,d). These models have been found to

simulate well the load–displacement response of footings subjected to combined cyclic loading (Byrne, 2000). The next generation of models for cyclic foundation response (termed 'Model D') will be based on developing these new plasticity theories.

6. The research group at Oxford University has recently developed a strategic collaboration, funded by the Australian Research Council (AU$44k under the IREX scheme), with the Centre for Offshore Foundation Systems at the University of Western Australia and researchers at the Technion in Haifa, Israel. The focus of this collaboration, which funds short visits by researchers, is the development of theoretical models for cyclic loading of foundations for use in the offshore industry.

The above projects have contributed significantly to the understanding of offshore foundations, with the main emphasis recently on shallow (*i.e.* not piled) foundations. This has been achieved by sponsorship from a variety of sources, involving close contact with industry.

Personnel

Prof. G.T. Houlsby, MA, PhD, FREng, FICE has worked in geotechnical research since 1977, and has been Professor of Civil Engineering at Oxford University since 1991. He has wide experience of managing research for both EPSRC and industry. A principal theme of his research has been offshore foundations, including piled foundations, jack-up units, gravity bases and caissons; and he supervised all the work described above. Recently he has been carrying out extensive research (funded by industry and EPSRC) on suction caisson foundations, concentrating particularly on their response to cyclic loads, and the effects of horizontal and moment loading. He has been invited to give the Geotechnique lecture on this subject at the ICE in September 2001. He acts as a consultant to a number of companies in the offshore industry. His wider interests include *in situ* testing, the interaction between tunnelling operations and adjacent structures, development of constitutive models for soils and structural dynamics. He has published over 120 journal and conference papers.

Dr B.W. Byrne, BE(Hons), BCom, MA, DPhil has been involved in research on shallow foundations for five years. He completed his doctorate at Oxford investigating the monotonic and cyclic loading response of suction caissons on dense sand. This has led to a number of technical publications. He has contributed to both EPSRC-funded and industry-funded research projects and is currently an 1851 Research Fellow and Fellow by Examination at Magdalen College. From October 2001 he will take up the post of Departmental Lecturer in Civil Engineering at Oxford.

Dr C.M. Martin, BE(Hons), MA, DPhil has been involved in research on theoretical and experimental aspects of shallow foundation behaviour for ten years. His doctoral work at Oxford underpins the development of 'Model B' (item 2 above) and forms part of the SNAME design guidelines for mobile drilling units. Since completing his doctorate he has worked in consulting for Ove Arup & Partners, in research at the University of Western Australia and more recently at Oxford when he was appointed as a University Lecturer in 2000. He has published a number of articles in the technical literature on shallow foundation behaviour.

Mr R.C. Sawala is a mechanical engineering technician with over 25 years experience of design and construction of equipment for high quality model and other testing in geotechnical engineering. He will provide technician support for the experimental work.

A **Research Assistant (RA1(A))** will be recruited to carry out the research. The level of the appointment is chosen so that someone with a proven record can be recruited to undertake this work. This would involve either a doctorate in an appropriate area, or wide experience in the offshore foundations sector.

2. DESCRIPTION OF PROPOSED RESEARCH

A. Background

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). The cost of the foundations for these developments is a significant fraction of the overall installed cost (current estimates suggest between 15% and 40%), and so the development of appropriate designs for the foundations is of importance to the financial viability of such projects. Early developments in offshore wind energy will most probably involve structures fixed to the seabed in shallow water (say 5m - 20m). The hub of a typical large turbine would be located about 60m above water level. The turbine and supporting structure, which would typically be a single column, might have a weight of about 2 - 3 MN. The structure would be subjected to large horizontal forces, due to wind, waves and current. The maximum horizontal force might be of the order of 2 MN, and would result in overturning moments at foundation level of say 50 - 80 MNm. Furthermore these loads would be pseudo-random and repetitive in nature. Foundations must be designed to withstand these forces.

There is of course extensive knowledge and experience of foundation design for offshore structures within the offshore oil and gas industry. However, by comparison with typical oil and gas applications, the offshore wind turbine problem differs in several key aspects:

(i) the vertical loading is much smaller (by a factor of say 5 to 200), and as a proportion of the vertical loading the horizontal load and overturning moment are much larger. The loading pattern is complicated by the dynamic interaction between wind-induced loading of the turbine rotor and the wave induced loading on the structure.

(ii) the water depth is typically much smaller. Sediment movement and local scour are important phenomena in these coastal waters due to high currents and shallow water wave effects. The performance of foundations in a partially eroded seabed and effective means of scour mitigation therefore become important design issues.

(iii) multiple installations (say 10 to 100) of relatively economical designs are required, rather than “one-off” foundations for large high-cost structures. Since these may be spread over a large area, less detailed site investigation information may be available.

Therefore, while it will be possible to draw to some extent on existing offshore experience, new design concepts for both the finished structure and for installation procedures will be needed to meet the challenges of the offshore wind industry. Concepts under consideration are given in Table 1. Floating structures for possible application in deep water are excluded.

Concept	Application	Advantages	Disadvantages
Single piles	Most conditions other than deep soft material (very long piles required).	Simple, versatile.	Very expensive installation because of large size. Difficult to remove.
Multiple piles (tripod?)	Most conditions other than deep soft material. Deeper water.	Versatile.	Expensive construction and installation. Difficult to remove.
Concrete gravity base	Virtually all soil conditions.	Float-out installation.	Expensive (large weight).
Single suction caisson	Sands, soft clays.	Inexpensive installation. Easy removal.	Installation proven in limited range of materials.
Multiple suction caisson (tripod?)	Sands, soft clays. Deeper water.	Inexpensive installation. Easy removal.	Installation proven in limited range of materials. More expensive construction.

Table 1: Types of foundation for offshore wind turbine installations

Whilst piled foundations and gravity bases are adaptations of well-proven technology, the suction caisson solutions are in their infancy. As is clear from Table 1, there will be many applications for which the most economical design may be a piled foundation or gravity base. Because, however, these are both well-developed solutions in the offshore industry, the research proposed is on the more novel suction caissons. In oil and gas applications two recent structures, the Sleipner T and Draupner E steel jackets in the North Sea, used suction caissons rather than conventional piled solutions (Bye *et al*., 1995, Tjelta, 1995). In each case the foundation involved four caissons, one at each corner of the jacket. Suction caissons are essentially huge upturned steel buckets (see Figure 1). At the Sleipner T and Draupner E sites they were 15m and 12m diameter respectively.

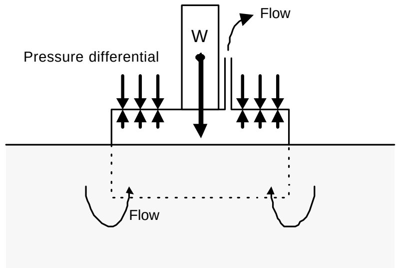

Figure 1: Suction-assisted installation of a caisson foundation

When the jacket is lowered to the seabed the rim of the caisson cuts into the soil. The weight of the jacket is insufficient to push the caisson entirely into the seabed, and a suction is then applied by pumping out the water trapped within the caisson. This creates a pressure differential across the top of the caisson. In clay soils this is sufficient to drive the caisson to its full depth, but in sands an important further phenomenon occurs. Because of the applied suction, water flows from outside the caisson to the inside. The upward flow within the caisson reduces the effective stresses in the sand, almost causing a 'piping' failure. This greatly reduces the bearing capacity around the rim of the caisson, and allows it to penetrate the sand (Erbrich and Tjelta, 1999); the sand regains its strength when pumping is ceased. Removal requires simply an overpressure within the caisson.

For the offshore wind farm application the suction caisson offers the following advantages:

i) 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.

ii) The installation method is potentially much quicker and simpler than piling. A foundation incorporating suction caisson(s) is a single unit that can be deployed and installed within a matter of hours as a single operation. It is not significantly weather dependent. By comparison, installing driven or socketed piles would involve multiple operations, and possibly delays associated with grout curing. These could take several days to complete and also risk additional weather delays, especially in winter. Complete unit installation offers potential savings on commissioning.

iii) Suction caissons are expected to be particularly suitable for foundations in the type of seabed sediments found around the coast of the UK. The small number of offshore wind farm developments in Europe to date have been founded in or on rock. The foundation designs used in these developments may not be cost effective in the majority of the UK sites.

iv) 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. It is emphasised, however, that a caisson is not ideal for all sites: it should simply be available as a possible option.

Structural Considerations

Perhaps the simplest concept for a foundation for an offshore wind turbine or anemometer mast is as shown in Figure 2(a). This is a 'monopile' foundation, in which a single pile is driven or socketed into the seabed. The supporting structure would be attached to the top of the pile either through an appropriate connection at seabed level, or above the water line. Foundations of this form, grouted into pre-drilled holes in the underlying bedrock, have been used for the UK's first offshore wind turbines at Blyth, Northumberland (Grainger 2000).

There are two main possibilities for a caisson foundation for a wind turbine. Firstly a tripod foundation could be used (Figure 2(b)). The large overturning moment would in this case be resisted by combinations of tension and compression on the upwind and downwind legs. The design of suction caissons to resist **transient tensile loads** is therefore of particular interest. The second possible design would involve a single "monopod" foundation (Figure 2(c)), and in this case the primary loading which is of interest is the **overturning moment**. The tripod offers possible advantages in that the caissons can be smaller, and that separate control of the installation of the caissons would allow levelling of the structure. The monopod foundation has the great advantage of simplicity.

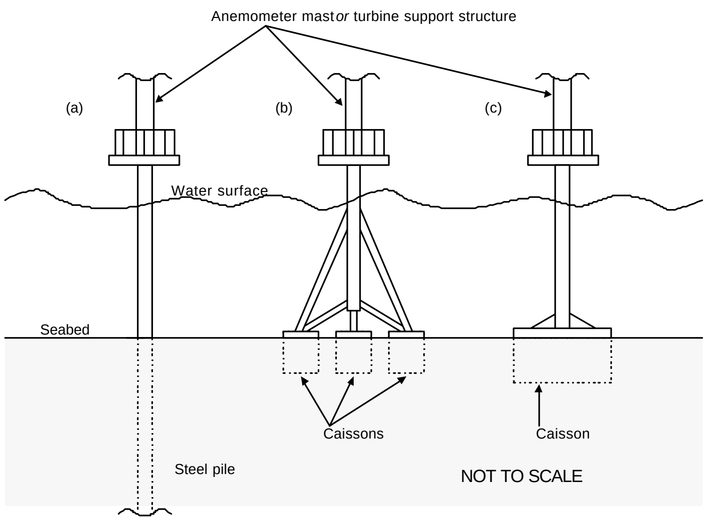

Figure 2: Alternative designs for foundations for offshore developments

B. Programme and Methodology

This activity will form part of a larger project "The application of suction caisson foundations to offshore wind turbines" for which an application for funds has been made to the DTI under their New and Renewable Energy Programme. An outline bid has been accepted, and a full proposal submitted to DTI. The total cost of this parent project is £1.9 million, of which £1.29 million has been sought from the DTI through ETSU. The participants in this programme are SLP Engineering Ltd, Aerolaminates Ltd, Garrad Hassan, Fugro Ltd, Shell Renewables Ltd, Enron Wind Overseas Development Ltd, Oxford University and HR Wallingford. The proposed work involves a coordinated programme of nine tasks. Three major tasks (laboratory testing, field testing and theoretical development) are to be led by Oxford University. This EPSRC proposal is for the first of these three tasks, the other two would be funded from the DTI. Other tasks in the programme include identifying appropriate soil conditions, loading conditions and refined structural configurations using the resources of the consultants above, the results of which would feed directly into this study.

The work proposed here is an integral part of the DTI programme, but represents the 'underpinning science' for that programme. Hence it can be viewed as a stand-alone proposal which does not depend on the DTI work going ahead (although it would clearly be much enriched if it does).

To date the design of oil and gas foundations for the cyclic loading has been achieved by either adopting conservative assumptions, or by reference to case-specific empirical data. The loading environment discussed previously 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 based on plasticity theory. However, to date they are principally for monotonic loading. Recent advances in developing a theory called 'continuous hyperplasticity' have provided a rigorous yet simple means of constructing theoretical models that can deal with cyclic loading. This has provided the impetus to carry out further testing on the cyclic loading problem in the laboratory. Most of this recent testing of model caissons has focussed on offshore oil and gas applications, and has included tests on footings up to 300 mm in diameter. It is necessary to carry out testing aimed directly at the special aspects of wind turbine foundations. These tests would provide an extensive database for the development of design methods.

The key design issue for a tripod design will be the tension response of the upwind leg, whilst for a monopod it will be the overturning moment. In each case the major concern in design will not be the ultimate load capacities (which will be huge) but the accumulated displacements under cyclic loading. For the tripod, from the few data that have been obtained to date, it appears that as the foundation goes from compresession into tension there is a transition to a much softer, i.e. less stiff, response. 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 field tests proposed in the DTI project. It will be possible with laboratory equipment at Oxford to apply loads from 200N up to 500kN on the footing, which could be from 100mm up to 400mm in diameter. Loading rate, liquefaction and water depth are key issues that need to be investigated. A number of potential sites are on a medium loose sand where the possibility of liquefaction is high, particularly during early storms before the foundation has sufficiently bedded into the seabed soils. The ambient water pressure affects the possibility of cavitation beneath the foundation. Tests will be carried out in a pressurised testing tank so that this effect on foundation performance can be quantified.

Specifically the testing will involve applying detailed load paths to a model foundation and measuring the displacement response. The load paths will be constructed with reference to the typical loading conditions, and, with serviceability of the structure in mind. These load paths will be applied at rates applicable to typical offshore loading conditions (in sands a viscous silicon oil pore fluid will be used to enable realistic modelling of transient effects). Other load paths will be applied, such as ramped sinusoidal loading, so that details necessary for the construction of theoretical models are obtained. Many of the testing techniques that will be used, as well as data reduction and analysis procedures, have been developed in previous research projects by the Investigators (Martin 1994, Byrne 2000). Initially tests will be conducted using an existing small scale three-degree of freedom loading rig that has been developed to investigate foundation behaviour (Martin 1994, Mangal 1999, Byrne 2000). This piece of apparatus will require little modification and should be ready to use at the commencement of the project. Larger scale forces will be applied using equipment in the recently established Structural Dynamics Laboratory at Oxford. It will be necessary to design and construct a large reaction frame, a testing tank, as well as develop control software for the loading actuators. For the pressurized tank testing it will be possible to modify an existing 1m diameter calibration chamber. Water depths of up to 20m will be simulated which is the range of depths at the potential sites. In this phase of testing only vertical loading will be applied as this is the critical component of loading with respect to cavitation.

In summary the 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 testing
- Installation tests (as part of in-service tests)
- Tests incorporating novel solutions
- Tests investigating capacity degradation due to scour

The testing described above will be conducted on the laboratory floor at one gravity so that complex testing designed to develop theoretical models can be carried out. A separate project (being carried out by Dr B.W. Byrne and funded by the Royal Commission for the Exhibition of 1851 and the IREX funds) is examining the issue of scaling model tests to prototype behaviour using the geotechnical centrifuges at the University of Western Australia. These results will be compared with this programme of research and will complement the data obtained from the field scale tests.

C. Management and Resources

The work would be carried out principally by a Research Assistant RA1(A). A starting point at spine point 9 on this scale is estimated. This grade is proposed because it will be necessary to recruit an experienced engineer to carry out this work, which will require not only skills in carrying out high quality experimental research, but also a good awareness of the offshore industry. A postdoctoral researcher with appropriate skills would be ideal, but someone without a doctorate but with particularly good industrial experience could also be appointed. The main cost is for salary for the research assistant and the associated overhead. The project will be managed by Dr B.W. Byrne who is co-ordinating the Oxford University component of research in the parent DTI project. There will be quarterly meetings of the participants of the DTI project to ensure the effectiveness of the research programme. The project will last for 36 months. However, key results will be made available early in the programme so that strategic decisions can be made by wind farm developers.

For the experimental work the main costs are for 12 months of technician time (R.C. Sawala, TE, scale point d2) and for the direct costs of additional equipment that will be required (loading frame, testing tank, transducers, model footings, sand, pressurised testing tank). Note that the main equipment used for the tests will be the existing structural dynamics testing facility (which represents an investment of over £300k of equipment) and an existing multi-degree of freedom loading rig. Resources are also sought for travel and subsistence (for meetings with collaborators, OWEN workshops and to attend relevant conferences e.g. the British Wind Energy Association annual conference). The costs of computing support include a contribution to the annual maintenance and upgrading of the group's computing facilities. A small allowance is also made for consumables.

RA1(A) salary, NI and superannuation for 36 months	£93225
Technician salary, NI and superannuation for 12 months	£23655
General testing equipment (loading frame, testing tank, sand, silicon oil)	£15000
Pressurised tank testing (modification of existing calibration tank, loading actuator, waterproof load cell, waterproof LVDT, 3 pressure transducers, signal conditioning, data acquisition card, desktop computer)	£20000
Travel and subsistence	£2000
Computing support and consumables	£4000
Overhead (46% on salary costs)	£53765
Total	£211645

D. Relevance to Beneficiaries, Dissemination and Exploitation

The main beneficiaries from this research are expected to be the windfarm developers. For example Shell, Aerolaminates and Enron are supporting the parallel DTI proposal as they 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 with 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 planned 30 turbines at each of the 18 sites. The total European market for turbine foundations could even grow to £2 billion annually if optimistic predictions that 40% of the EU energy consumption could be supplied from offshore wind farms within 30 years are achieved. The research is highly relevant and likely to be heavily exploited.

The project has the potential to give the UK a lead in a technology that can be applied to a large and growing market for offshore wind farms in the UK and the EU. It can also be applied to a variety of other applications in the UK and worldwide, including oil and gas minimal facility offshore structures and anchors for floating production vessels. Exploitation should be beneficial in terms of UK competitiveness, growth and tax revenue.

Other means of dissemination will be through publications presented at a number of annual conferences (Offshore Technology Conference, Offshore and Polar Engineering, Offshore Mechanics and Arctic Engineering, BWEA conferences, OWEN network) as well as refereed journal publications. The journal "Wind Engineering" offers rapid publication of material in this area. A set of web pages describing the work would be maintained.

E. References

Bell, R.W. (1991) "The Analysis of Offshore Foundations Subjected to Combined Loading", M.Sc. Thesis, Oxford University.

Bell, R.W, Houlsby, G.T. and Burd, H.J (1991) "Finite Element Analysis of Axisymmetric Footings Subjected to Combined Loads", Proc. Int. Conf. Comp. Meth. and Adv. in Geomech., Cairns, May, Vol. 3, pp 1765-1770.

Byrne, B.W. (2000) "Investigations of Suction Caissons on Dense Sand", D.Phil. Thesis, Oxford University.

Byrne, B.W. and Houlsby, G.T. (1999) "Drained Behaviour of Suction Caisson Foundations on Very Dense Sand", Offshore Technology Conference, 3-6 May, Houston, Paper 10994.

Byrne, B.W. and Houlsby, G.T. (2000) "Experimental investigations of the cyclic response of suction caissons in sand", Offshore Technology Conference, Houston, Paper 12194.

Byrne, B.W. and Houlsby, G.T. (2001). "Observations of footing behaviour on loose carbonate sands." Géotechnique, Vol. 51, No. 5, pp 463-466.

Byrne, B.W. and Houlsby, G.T. (2001) "Experimental investigations of the response of suction caissons to transient vertical loading." Submitted to the ASCE Journal of Geotechnical and Geoenvironmental Engineering.

Bye, A., Erbrich, C., Rognlien, B., and Tjelta, T.I. (1995) "Geotechnical design of bucket foundations", Offshore Technology Conference, Houston, Paper 7793.

Cassidy, M.J. (1999) "The Non-Linear Dynamic Analyses of Jackup Platforms under Random Ocean Waves", D.Phil. Thesis, Oxford University.

Cassidy, M.J. and Houlsby, G.T. (1999) "On the Modelling of Foundations for Jack-up Units on Sand", Offshore Technology Conference, 3-6 May, Houston, Paper 10995.

Cassidy, M.J., Eatock Taylor, R., Houlsby, G.T. (2000) "Analysis of jack-up units using a constrained NewWave methodology", Accepted for publication in Applied Ocean Research.

Cassidy, M.J., Taylor, P.H., Eatock Taylor, R., Houlsby, G.T. (2001) "Evaluation of long-term extreme response statistics of jack-up platforms", Submitted to Ocean Engineering.

de Santa Maria, P.E.L. (1988) "Behaviour of Footings for Offshore Structures under Combined Loads" , D.Phil. Thesis, Oxford University.

de Santa Maria, P.E.L. and Houlsby, G.T. (1988) "Model Tests for Offshore Foundations under Combined Loads", Proc. Symp. New Concepts in Lab. and In Situ Tests in Geotech. Eng., Rio de Janeiro, May, Vol. 2, pp 425-438.

Erbrich, C. and Tjelta, T.-I. (1999) "Installation of bucket foundations and suction caissons in sand: geotechnical performance", Offshore Technology Conference, Houston, Paper 10990.

Gottardi, G., Houlsby, G.T. and Butterfield, R. (1999) "The Plastic Response of Circular Footings on Sand under General Planar Loading", Géotechnique, Vol. 49, No. 4, pp 453-470.

Grainger W. and den Rooijen, H. (2000) "Blyth offshore wind project", Proc BWEA 22 Conf, MEP, London (to be published).

Houlsby, G.T. (1995) "Geotechnical Model Testing of Plated Foundations on Sand", report C034-A-N-RE-011 to Kvaerner Engineering.

Houlsby, G.T. and Byrne, B.W. (2000) "Suction caisson foundations for offshore wind turbines and anemometer masts." Journal of Wind Engineering, Vol. 24, No. 4, pp 249-255.

Houlsby, G.T. and Cassidy, M.J. (2001) "A Plasticity Model for the Behaviour of Footings on Sand under Combined Loading", Submitted to Géotechnique.

Houlsby, G.T. and Martin, C.M. (1992) "Modelling of the Behaviour of Foundations of Jack-up Units on Clay", Proc. of the Wroth Memorial Symp. Predictive Soil Mechanics, Oxford, July 27-29, pp 339-358.

Houlsby, G.T. and Puzrin, A.M. (1999) "Closed Form Solutions for the Bearing Capacity of a Strip Footing on Clay under Combined Loadings", Proc. Roy. Soc., Series A, Vol. 455 No. 1983, March, pp 893-916.

Houlsby, G.T. and Puzrin, A.M. (2000) "A Thermomechanical Framework for Constitutive Models for Rate-Independent Dissipative Materials", International Journal of Plasticity, Vol. 16 No. 9, pp 1017-1047.

Johnson, K. (1999) "The Behaviour of Partially Drained Footings under Axial Load", Part II project report, Dept. of Engineering Science, Oxford University.

Mangal, J.K. (1999) "Partially Drained Loading of Shallow Foundations on Sand", D.Phil. Thesis, Oxford University.

Mangal, J.K and Houlsby, G.T. (1999) "Partially-Drained Loading of Shallow Foundations on Sand", Offshore Technology Conference, 3-6 May, Houston, Paper 10991.

Martin, C.M. (1994) "Physical and Numerical Modelling of Offshore Foundations Under Combined Loads", D.Phil. Thesis, Oxford University.

Martin, C.M. and Houlsby, G.T. (1999) "Jackup Units on Clay: Structural Analysis with Realistic Modelling of Spudcan Behaviour", Offshore Technology Conference, 3-6 May, Houston, Paper 10996.

Martin, C.M. and Houlsby, G.T. (2000) “Combined Loading of Spudcan Foundations on Clay: Laboratory Tests”, Géotechnique, Vol. 50, No. 4, pp 325-338.
Martin, C.M. and Houlsby, G.T. (2001) “Combined Loading of Spudcan Foundations on Clay: Numerical Modelling”, Géotechnique, in press.
Ngo Tran, C.L. (1996) “The Analysis of Offshore Foundations Subjected to Combined Loading” ”, D.Phil. Thesis, Oxford University.
Puzrin, A.M. and Houlsby, G.T. (2001a) “A Thermomechanical Framework for Rate-Independent Dissipative Materials with Internal Functions”, International Journal of Plasticity, in press.
Puzrin, A.M. and Houlsby, G.T. (2001b) “Fundamentals of Kinematic Hardening Hyperplasticity”, International Journal of Solids and Structures, Vol 38, No 21, pp 3771-3794.
Puzrin, A.M. and Houlsby, G.T. (2001c) “On the Non-Intersection Dilemma in Multi-Surface Plasticity”, Géotechnique, Vol 51, No 4, pp 369-372.
Puzrin, A.M. and Houlsby, G.T. (2001d) “Strain-based plasticity models for soils and the BRICK model as an example of the hyperplasticity approach”, Géotechnique, Vol 51, No 2, pp 169-172.
SNAME (1993) “Guidelines for the Site Specific Assessment of Mobile Jack-up Units”, Society of naval Architects and Marine Engineers, New Jersey.
Thompson, R.S.G. (1996) “Development of Non-Linear Numerical Models Appropriate for the Analysis of Jack-up Units”, D.Phil. Thesis, Oxford University.
Tjelta, T.-I. (1995) “Geotechnical experience from the installation of the Europipe jacket with bucket foundations”, Offshore Technology Conference, Houston, Paper 7795.
Trickey, J.C., Osborne, J.J., Houlsby, G.T. and James, R.G. (1991) “Findings from a Joint Industry Study on Foundation Fixity of Jack-up Units”, OTC, 6-9 May, Houston, Paper 6615, pp 517-533.
Williams, M.S., Thompson, R.S.G. and Houlsby, G.T. (1998) “Non-Linear Dynamic Analysis of Offshore Jack-up Units”, Computers and Structures, Vol. 69, pp 171-180.
Williams, M.S., Thompson, R.S.G. and Houlsby, G.T. (1999) “A Parametric Study of the Non-Linear Dynamic Behaviour of an Offshore Jack-up Unit”, Engineering Structures, Vol. 21, pp 383-394.

3. PROJECT ORGANISATION

Management:

- Day-to-day management by Dr B.W. Byrne.
- Weekly meetings of investigators and the 3 Research Assistants to be appointed (2 under DTI funds, 1 from this proposal).
- Steering committee to meet quarterly (Prof. G.T. Houlsby, Dr B.W. Byrne, Dr C.M. Martin, Research Assistant, industrial representatives). If the DTI proposal goes ahead this steering committee will be subsumed within the committee steering the larger project.

Timing (in months):