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Model Tests on Suction Caissons in Dense Sand
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SUMMARY: A programme of research on the behaviour of “suction caisson” foundations for offshore structures is described. A large number of small-scale model tests were carried out in which the models were subjected to loading regimes relevant to the design of offshore foundations. The results of the tests were interpreted within the context of plasticity theory.

Introduction

Suction caisson foundations are a novel alternative to piled foundations for fixed offshore structures. They take the form of large upturned “buckets”, typically 10m-15m in diameter and 3m-5m deep. Their name arises from the fact that, after initial contact with the seabed is established, they are installed by applying a suction to the water trapped within the caisson (see Figure 1). They offer cost savings over more conventional foundations both in terms of material costs (steel) and in terms of the time and equipment required for installation. They have already been used for two jacket structures (Draupner E and Sleipner T) on dense sand in the North Sea.

Whilst research is necessary on the installation of suction caissons, this project was concerned entirely with the performance of the foundations once they are in place. Under typical storm loading the foundations are subjected to a combination of vertical, horizontal and moment loading. It is therefore necessary to understand their behaviour under cyclic combined loads. It is worth noting that design practice for offshore piled foundations has evolved gradually from onshore practice, and has for many years been codified in the API guidelines. Equivalent onshore experience does not exist for suction caissons, nor have design codes yet been established, so design must be based on fundamental research.

Some commercially confidential research had been conducted for the design of the rigs at Draupner and Sleipner, but this was directed towards the specific design problems at those sites. The purpose of this grant was to carry out generic research on the behaviour of suction caissons on dense sand, with the ultimate purpose of establishing more general design procedures. The method used for the research was small-scale laboratory model testing. Both monotonic and cyclic tests were carried out, and these have been interpreted within the context of plasticity theory.

Stages of Research

Equipment development

The principal equipment used for the model tests was a computer-controlled loading rig, capable of applying independently a vertical, horizontal and moment loading to a model foundation. The rig was initially designed by Martin (1994) for testing models of foundations on clay, and was modified for testing models on sand as reported by Gottardi, Houlsby and

Figure 1
Butterfield (1999) and Mangal (1999, thesis submitted). For the purposes of these tests further modifications have been made, which will be reported in detail by Byrne (1999, forthcoming thesis). In summary they involve:

- replacement of the data acquisition system with a faster and more versatile unit,
- replacement of the controlling PC with a faster machine,
- updating of the control software to use Visual Basic,
- implementation of feedback control systems to allow load-controlled testing,
- construction of new model foundations,
- design and construction of two larger testing tanks to allow multiple tests per tank,
- design and construction of an improved system for measuring displacements of the foundations,
- fitting of a new system for preparation of dense dry soil samples,
- design and construction of improved sample preparation equipment for oil-saturated tests,
- instrumentation for measurement of pore pressure response.

Monotonic tests

The first stage of testing involved a comprehensive set of monotonic tests of caisson foundations under combined loading. The purpose of these tests was to establish in detail the response of the caisson foundations to slow monotonic loading. These results serve as the baseline for comparison with the subsequent tests, which were to examine the behaviour under transient cyclic loading.

The approach taken to monotonic testing followed the pattern successfully employed by Martin (1994) for foundations on clay and Gottardi, Houlsby and Butterfield (1999) for tests on sand. A number of different types of tests are used, each specifically designed to explore a particular aspect of the behaviour of the foundation under combined loads. The theoretical framework used for the understanding of these tests is work-hardening plasticity theory, and the tests are designed to give information which can be used directly to derive plasticity models. The monotonic tests examined three different depth/diameter ratios of caissons, as well as flat surface footings. The main tests carried out were:

- Vertical loading tests (18 tests),
- Constant vertical load tests (11 tests),
- “Swipe” tests (see Martin (1994) for a description) to explore the shape of the yield locus in the \(V, H\) and \(V, M\) planes (161 tests),
- “Loop” tests to explore the shape of the yield locus in the \(M, H\) plane (41 tests),
- Miscellaneous additional tests (15 tests).

Full details of the tests will be given in the forthcoming thesis by Byrne (1999). The results are analysed in Byrne and Houlsby (1999). A supplementary series of tests were carried out on one design of caisson foundation on carbonate soils (40 tests) and are reported by Byrne and Houlsby (1998).

Cyclic tests

An essential element of the loading of an offshore structure is that it is both cyclic and transient. Cyclic tests were therefore carried out, in which similar loadings were applied to the monotonic tests, but with cycling at different rates. Both pseudo-random (“constrained NewWave”) cycles and regular cycles were used. All cyclic tests were on sand saturated with silicone oil with a viscosity 100 times that of water: this is to allow proper modelling of the rate of loading. Tests were carried out on three different depths of caisson and with different diameters to investigate scaling effects. The transient and cyclic tests involved:
Consolidation tests to establish the time scale for pore pressure dissipation (30 tests),
Vertical cyclic loading tests (70 tests),
Horizontal and moment cyclic tests at constant vertical load (90 tests),
Miscellaneous additional tests (70 tests).

Selected Results

Monotonic Tests

The results of the monotonic tests, as reported by Byrne and Houlsby (1999) broadly confirmed that the patterns of behaviour observed for flat foundations (i.e. without the skirt which is present on the caisson foundation), and reported by Gottardi, Houlsby and Butterfield (1999), also applied to the suction caisson. The main difference was that the caisson tests concentrated on the region (highly relevant to the field case) where the ratio of the vertical load to the ultimate static bearing capacity is small (say less than 0.1). Under these conditions the earlier assumption that the “yield surface” for the foundation expands with vertical load but does not change shape is inadequate. Figure 2 shows the results of a set of horizontal loading “swipe” tests at different initial vertical loads. Each curve represents approximately the shape of the yield surface in the \((V, H)\) plane, and it is clear that the shape as well as the size changes. The proposed framework for understanding the change of shape is shown in Figure 3: an inner yield surface expands within a fixed outer yield surface.

Cyclic Tests

Preliminary work on loading of flat footings under transient (i.e. partially drained) conditions reported by Mangal and Houlsby (1999) had indicated that the effects of loading rate were relatively minor. This conclusion was supported strongly by this research. Rather surprisingly, the performance of the foundations was found to be remarkably similar for transient loading at a wide range of different loading rates. These rates were chosen to span the full range from almost “undrained” to almost fully “drained” as implied by the measured \(t_{50}\) for dissipation of pore pressures under the foundation. This result is almost certainly coupled to the fact that the peak pore pressures measured within the caisson during cyclic loading accounted for only a small fraction (typically 5%) of the applied vertical load. It was not possible in these tests to measure the pore pressures at the skirt tip.

The wave loading on offshore structures is random in nature. An efficient way of modelling extreme waves is the “constrained NewWave” approach, and this concept has been transferred to the loading on the foundation. Figure 4 shows a fragment from the time history of load applied in one of the moment tests. Within the random background of repeated loading (which in fact has well-defined spectral characteristics) are two extreme events which have been “constrained” into the time history. The corresponding displacement history is
shown in Figure 5. Finally the load-displacement plot for this fragment is shown in Figure 6. This shows clearly that at low amplitudes of cycling a stiff response with little hysteresis is observed, but at higher amplitudes there is a large amount of plastic deformation.

For vertical cycling the response is more complex. Figure 7 shows the extreme points of a cyclic vertical loading test, compared with a vertical monotonic tension test. The low tensile resistance is obvious, but the fact that the cyclic tests follow the same trend as the monotonic test is a useful simplification. Further research is going to be necessary to resolve the details of the tensile capacity and how it varies with static load and water depth.

**Theoretical Developments**

It is important that any experiments are interpreted within an appropriate theoretical framework, and not merely treated as an empirical collection of data. An appropriate framework for the understanding of the behaviour of foundations has been found to be plasticity theory. The reasons for this choice are (a) theories can be constructed which reproduce the behaviour of the foundations well, and (b) the resulting models can readily be included in a numerical analysis of a complete offshore structure.

Plasticity theories for slow monotonic loading of foundations had been established prior to this research, and the monotonic data were simply fitted within an existing framework (although they revealed that some aspects needed modification). The important theoretical developments relate to the understanding of cyclic loading. The results of a typical cyclic test have been shown in Figure 6. A remarkable feature about this result (which is typical of any cyclic horizontal or moment load test on a foundation) is that continuous smooth curves are obtained as the load is cycled. A conventional plasticity model could not model this type of
behaviour, but instead would result in well-defined yield points at which a sudden change of stiffness would occur. The magnitude of plastic deformation predicted on reverse loading would also be at least an order of magnitude smaller than that observed.

An obvious conclusion would be that plasticity theory is inappropriate for modelling cyclic loading, but given its proven success for modelling monotonic loading this is excessively pessimistic. After much searching for an appropriate framework to describe cyclic loading, a development termed “continuous hyperplasticity” has been made. An exposition of the theory would be inappropriate here as it involves a considerable amount of mathematical development, and this is fully documented in papers by Collins and Houlsby (1997), Houlsby and Puzrin (1999) and Puzrin and Houlsby (1999).

In essence the theory replaces the “plastic strain” in conventional plasticity theory with a continuous field of an infinite number of plastic strain components, each associated with a separate yield surface. This is achieved within a manageable mathematical framework by deriving the plasticity theory entirely from two potentials. For the case of the infinite field of plastic strains these potentials are functionals (“functions of functions”) of the plastic strain. Conventional plasticity theory is a special case of the new approach. The result is that theories can be constructed in which responses of the character shown in Figure 6 can be modelled. The mathematical structure of the theories is relatively simple (although unfamiliar to those used to conventional plasticity). For example, Figure 8 shows the result of a moment test in which cycles of increasing amplitude have been applied (this test was carried out specifically to aid model development). Figure 9 shows the fitted response using the continuous hyperplastic model. Whilst the fitting is not exact, the model captures the main features of the cyclic test. Only three parameters are required to define the behaviour shown in Figure 9.

**Technical Conclusions**

An extensive programme of both monotonic and cyclic test have been carried out on model “suction caissons”. These will provide a valuable database for the development of design methods for suction caisson foundations for offshore developments. The tests have been modelled using plasticity theory, and new developments have been made so that realistic modelling of the response to cyclic loading can be achieved. This latter work has many applications in more general problems in soil mechanics.

**Dissemination**

One paper (Byrne and Houlsby, 1999) has been presented on the results of the monotonic test programme. An abstract for a further paper has been submitted to the Offshore Technology Conference 2000 summarising the cyclic test programme. Other papers and reports related to
directly this programme are Houlsby and Puzrin (1999), Puzrin and Houlsby (1999), Butterfield, Houlsby and Gottardi (1997) and Gottardi, Houlsby and Butterfield (1999).

This research has been communicated to companies working in the offshore area, including Odebrecht Oil and Gas, Offshore Data Ltd. and Renewable Energy Systems Ltd.

An application that has emerged during the course of this work has been the use of suction caissons for offshore wind energy applications. Information on the research has therefore been disseminated via the EPSRC-funded Offshore Wind Energy Network (OWEN).

The work described here has been a major part of the doctoral research of Mr B.W. Byrne, a Rhodes Scholar at Oxford University. Mr Byrne’s thesis is expected to be submitted towards the end of 1999, and will include a much more detailed presentation of this research.

Trained Manpower

Mr Byrne has been awarded a two year Research Fellowship, one of six awarded annually by the Royal Commission for the Exhibition of 1851, to be held from October 1999. The research he will be carrying out during the Fellowship will in part be an extension of the work carried out under this grant.

Future Research

Interest in the use of suction caissons for offshore foundations continues to expand, and the possible applications have widened significantly during the course of this research. The latest area where they are expected to find an application is for the foundations for offshore wind turbines. A project involving proposed instrumentation of a small caisson used as the foundation for an offshore anemometer mast has been funded as EPSRC grant GR/M/55647. A further proposal has been made to EPSRC for research on foundations appropriate for offshore wind developments (application GR/N/04690), and a significant part of this work would involve studies of suction caissons under the loading regimes relevant to offshore wind turbines. These loadings involve much smaller vertical loads, but relatively larger horizontal loads and overturning moments than the cases relevant to the oil and gas industry. An application is also pending with the EU, for funding of the development of an offshore wind farm in the Mediterranean. Oxford University would carry out the relevant research on the foundations, for which suction caissons are currently proposed.

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This project was concerned with the performance of the foundations once they are in place. Under typical storm loading the foundations are subjected to a combination of vertical, horizontal and moment loading. It is therefore necessary to understand their behaviour under cyclic combined loads. It is worth noting that design practice for offshore piled foundations has evolved gradually from onshore practice, and has for many years been codified in the API guidelines. Equivalent onshore experience does not exist for suction caissons, nor have design codes yet been established, so design must be based on fundamental research. The purpose of this grant was therefore to carry out generic research on the behaviour of suction caissons on dense sand, with the ultimate purpose of establishing more general design procedures. The method used for the research was small-scale laboratory model testing.

The first phase of the work was to modify existing equipment to allow a wider range of tests to be carried out on model foundations. Following this a series of monotonic loading tests were carried out. The tests were compared with existing approaches to combined loading on foundations, which use plasticity theory. Broadly the existing framework was found to be appropriate, with some minor modifications being necessary.

Since the loading on offshore foundations is cyclic and transient in nature, cyclic testing was then carried out at a number of different loading rates. These tests provide an important database for design. An important feature of these tests was that pseudo-random cycling using the “constrained NewWave” approach was used to simulate extreme events within a random background. The cyclic loading tests show a pattern in which a stiff response to small amplitude cycling progresses through a gradual transition to a response with a large amount of hysteresis at large cycles. This type of transition cannot be modelled with conventional plasticity theory, but a new approach called “continuous hyperplasticity” has been developed which can model the main features of the cyclic response.

Key References


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List of publications