

# Performance of Shallow Foundations on Sand

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## Abstract

Novel foundation systems, such as suction caissons, are increasingly being considered for use as foundations in a number of offshore applications. These applications include the typical oil and gas industry structures as well as emerging applications in the renewable energies sector (for example offshore wind turbines). It is important to understand the performance of the foundation under a wide variety of loading regimes relevant to these cases so that appropriate design calculations can be carried out.

## Experimental Equipment

A three-degree-of-freedom loading rig has been developed at the University of Oxford so that the study of foundations subjected to combined loading can be carried out. This loading rig is computer controlled so that independent PID control can be maintained on the three components of load ( $V$ ,  $M/2R$ ,  $H$ ) or displacement ( $d_v$ ,  $2Rd_\theta$ ,  $d_h$ ) that are applied to the foundation. This enables experiments to be carried out, within the context of formulating theoretical frameworks, such as work hardening plasticity theory. The testing to date has mainly used high friction angle samples of sand to imitate typical offshore conditions (in the North Sea for example). Dry sand has been used so that long term behaviour (current and wind loading) can be investigated, whilst oil saturated sand samples have been used to study transient behaviour. The sample container used for these tests is large enough to accommodate eight individual tests on the same sample of sand. The footings used were representative of suction caissons and were of diameters ranging from 100 mm to 300 mm with embedment ratios (skirt depth / diameter) ranging from 0 to 0.66.

## Monotonic Loading Conditions

A large amount of testing was devoted to determining the response under monotonic loading conditions. The tests were performed so that work hardening plasticity models could be developed. For these models there is a need to define (i) a yield surface (such as shown in Figure 1), (ii) a work hardening relationship, (iii) a plastic potential, and, (iv) the elastic response for load states within the yield surface. Such models have been developed previously and this new research was aimed at response at low levels of vertical load compared to peak bearing capacity. This is a typical condition encountered for offshore foundations. A majority of the tests performed were 'swipe tests' which indicate the yield surface shape for given ratios of  $H$  and  $M/2R$ . Under these conditions it was found that the yield surface changes shape as well as expanding with increases of vertical load. The advantage of developing plasticity models such as these is that they can be incorporated into structural analysis packages. The response of structures to various wave histories can therefore be evaluated with more realistic foundation models than either pinned or linear springs.

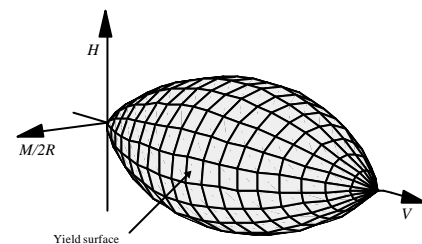


Figure 1

## Transient Loading Conditions

Shallow foundations for offshore structures are exposed to cyclic wave loading and confidence in performance can only be obtained by examining behaviour under similar conditions. In the initial development of the research it was expected that extreme events (such as that associated with the 'monster wave') would cause or precipitate failure. An approach called 'Constrained NewWave', a state-of-the-art deterministic random-wave loading theory, was used for the construction of the extreme event loading time histories (Taylor *et al.*, 1995). This technique enables an extreme event

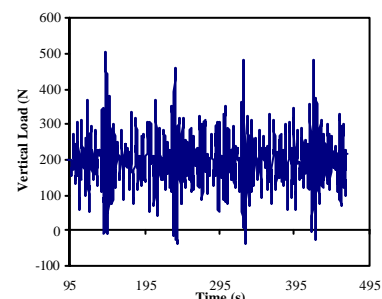


Figure 2

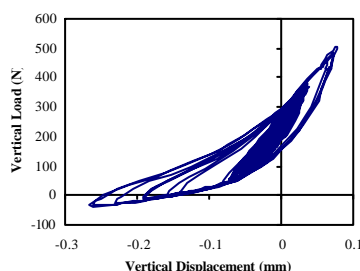


Figure 3

to be placed within a sequence of random loading such that it is statistically indistinguishable from a random occurrence of that event. Such a loading sequence for vertical loading is shown in Figure 2 and the load displacement response for this loading event is shown in Figure 3. This is a more satisfactory representation of the physical reality than the

usual application of many sinusoidal cycles. The load displacement response is asymmetric with a much softer response observed for tension than for compression. This was investigated further by conducting monotonic pull tests where it was observed that upon successive small displacement pulls (<1 mm) the response remained constant regardless of loading rate. On the application of larger displacements the capacity (at small displacements) degraded to that observed for drained tension. On the application of large displacements (>10 mm) the capacity was rate dependent, and limited by cavitation of the pore fluid. Cyclic loading and monotonic behaviour was also examined for the combined load cases where typically the vertical load was held constant.

Due to the large amount of cyclic loading data, a method of data reduction was developed which encapsulated each loading test. Normalising quantities were determined, based on dimensional analysis, so tests could be compared across mean loads and caisson diameters. The normalisations indicated a scaling relationship, although data collected from tests at higher stress levels will be necessary to confirm this. Surprisingly, there was little evidence of the effect of loading rate on the response. This is perhaps because small displacements are required to mobilise the typical loads. The dilation induced negative pressures do not occur except where displacements are so excessively large that they probably breach serviceability requirements. In all cases there was good agreement with the Masing (1926) rules. This may lead to cost effective testing, requiring only monotonic tests to infer cyclic behaviour with few high quality cyclic loading tests to confirm inferred behaviour.

## Theoretical Developments

The availability of the experimental data has verified a new development in theoretical modelling termed

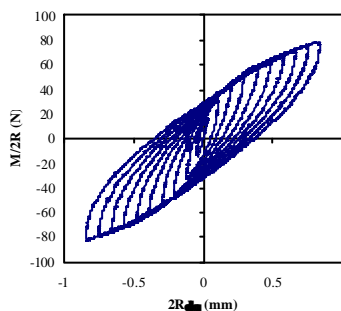


Figure 4

'continuous hyperplasticity' (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. 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 3 can be modelled. The mathematical structure of the theories is relatively simple, although unfamiliar to those used to conventional plasticity. For example, Figure 4 shows the result of a moment test in which cycles of increasing amplitude have been applied. Figure 5 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 hysteretic behaviour shown in these Figures.

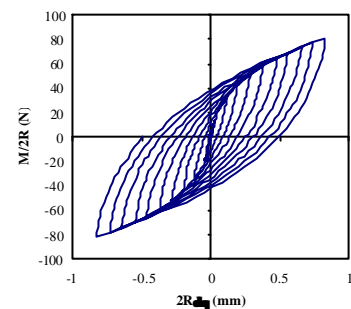


Figure 5

## Conclusion

An experimental programme has been carried out aimed at identifying important mechanisms and behaviour patterns for shallow foundations in sand (particularly suction caissons). A large number of tests were carried out, both on dry sand, and on an oil saturated sand, which has enabled the development of theoretical modelling techniques. The transient tests indicated that Masing behaviour was applicable and the effect of rate was minimal, whilst a scaling relationship was also identified. It was observed that design for tensile loading is likely to be governed by serviceability requirements as opposed to capacity requirements.

## Acknowledgements

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