Laboratory Testing of Shallow Skirted Foundations in Sand

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Introduction

Shallow skirted foundations are now considered to be a viable foundation option for a variety of offshore applications. One possible application may be as a foundation for offshore wind turbines, where the loading on the foundation is significantly different from that of more typical offshore structures. The vertical load is low, whilst the horizontal load and the applied moment are large compared with the vertical load. It is necessary to determine appropriate structural and foundation configurations that will allow these environmental loads to be transferred safely to the surrounding soil.

This paper presents results from a laboratory investigation of the monotonic loading response of skirted shallow foundations on sand, with particular emphasis on loads relevant to the wind turbine problem. The investigation includes varying the length of the skirt (L) compared with the diameter (D) of the foundation as well as varying the mineralogy and density of the sand deposits. Results from vertical bearing capacity tests are presented and compared with simple theoretical expressions based on standard bearing capacity formulae. Results from applied moment loading tests are also presented, from which it is possible to determine the limiting moment capacity for skirted foundations under very low vertical loads. This work forms part of a larger program of research at Oxford University aimed at defining guidelines for offshore wind turbine design (Byrne *et al*., 2002).

The Problem

Figure 1 presents a schematic of the problem. It shows a 95m high wind turbine with 96m diameter blades. This is representative of a 3MW wind turbine. The 9MN vertical force reflects the self-weight of the structure and foundation. The wind and waves combine to apply a net horizontal force of 6.2MN at a height of 31m above the mudline. This results in a net overturning moment at foundation level of 192MNm.

Figure 2 presents some typical structural configurations that could be adopted for these wind turbine structures (taken from Houlsby and Byrne, 2000). In considering shallow foundations there are two structural configurations that are possible. Appropriate designs must be developed in both cases. The first is a tripod or quadruped where the applied environmental loads are resisted by vertical reactions (compression and tension) at the foundations (Figure 2(b)). This problem has been studied by Johnson (1999), Byrne (2000), Byrne and Houlsby (2002) and Kelly *et al*. (2003) but will not be addressed specifically in this paper. The second option is a monopod where the applied environmental load is resisted by the moment capacity of the foundation (Figure 2(c)). This will be addressed here, and in particular a simple preliminary calculation procedure for estimating the ultimate moment capacity will be described.

Laboratory Work

The laboratory studies are designed to provide input for the development of plasticity models to describe the response of offshore foundations. These theoretical models have been shown, in recent studies of footings subjected to combined loads, to provide a successful description of the elasto-plastic deformation behaviour of the footing, at least under monotonic loading conditions (Tan, 1990; Martin, 1994; Gottardi *et al*., 1999; Byrne, 2000). This is useful in that the models can be incorporated within structural analysis packages, thus providing a realistic simulation of the foundation response. The postulate is that after a given footing penetration a yield surface is established within $\{V, M/2R, H\}$ space as shown in Figure 3; shown in Figure 4 is the sign convention that is used as defined by Butterfield *et al*. (1997). Any footing behaviour within this surface is assumed to be elastic; whilst elasto-plastic behaviour occurs once the load point reaches the yield surface. Four components are required for the development of these models: (a) a yield surface, (b) a plastic potential, (c) a hardening law, and (d) an elastic response. Roscoe and Schofield (1957) were the first to use elements of such an approach whilst Butterfield and Ticof (1979) were amongst the first to examine experimentally footing behaviour in this context. The results described in this paper cover aspects of hardening behaviour and the shape of the yield surface at low vertical loads, as these are critical for the wind turbine foundations.

Loading Rig

A three degree-of-freedom loading rig has been developed at Oxford. This was initially designed to explore the behaviour of spudcan footings on clay (Martin, 1994). It has been modified several times and is adaptable to any soil medium. The unique feature of this apparatus is that an arbitrary displacement path can be applied to the model footing, using computer controlled stepper motors. The independent control of the three components of displacement is accomplished by using separate bearing arrangements, and by superposition of the different motion systems. The vertical, horizontal and moment displacement ranges are 300mm, 50mm and 30° respectively. The response of the footing is determined by measuring the resultant loads using a 'Cambridge' load cell, whilst foundation displacements are accurately measured using a system of LVDTs. The primary advantage of using this displacement-controlled apparatus is the ability to explore strain softening behaviour. Figure 5 shows the loading rig and the associated equipment.

Dry Sand

Two different types of sand have been used during the testing described here. The sand was tested dry so that only drained behaviour was investigated.
(a) White and Yellow 14/25 Leighton Buzzard Sand (Palmeira, 1987; Schnaid, 1990): these are very uniform silica sands (coefficient of uniformity of 1.3) with an angular grain shape, and have been used in a number of experimental studies. The yellow sand is coloured due to iron staining.
(b) Dogs Bay Sand (Nutt, 1993): this is a carbonate sand from the west coast of Ireland and consists of a large proportion of skeletal mollusc fragments in the form of plates, hollow globules and tubes with the carbonate content ranging from 87% to 92%. The sand has a D_{50} of 0.24mm and a coefficient of uniformity of 2.75.

Figure 6 shows the grading curves for these sands.

The loose samples were prepared by carefully placing the soil within the sample container from a scoop. This method enables very loose sand samples to be prepared with relative densities of about 20%. To prepare denser samples of sand a vibration is applied to the tank until the appropriate density is reached (Byrne, 2000; Lau, 1988). The main parameter used to characterise the dry sand samples is the relative density.

Vertical Loading Tests

Vertical loading tests are essential for developing expressions to describe the hardening law within the plasticity models. Typically, as suggested by Martin (1994) and Cassidy (1999), the vertical load-displacement relationship can be used as the simplest description of the hardening law. Villalobos *et al.* (2003) describe a series of tests investigating the load penetration curves for various skirted footings on dry sand. The footings are all of diameter 51mm and wall thickness of 1.6mm but with skirt lengths varying from 0mm to 102mm. Five series of tests were carried out, including tests on loose and dense silica sand and tests on loose carbonate sand. The results from a series of tests on the dense Leighton Buzzard sand are shown in Figure 7. The relative density was 88%. Initially, the tests all follow a common load-penetration curve as the skirts are forced into the sand. Once the base makes contact with the surface of the sand the load increases quickly until a peak is reached. There is a small amount of post peak softening before the load again increases as the footing is pushed further into the sand. These results can be compared with standard bearing capacity calculations. For instance as the skirts are pushed into the sand the response would be calculated as the sum of the friction on the outside and inside of the caisson skirts and the end bearing on the annulus. The end bearing is the sum of an N_q and an N_g term. The result is:

$$V = \frac{g'h^2}{2}\left(K\tan d\right)_o\left(pD_o\right) + \frac{g'h^2}{2}\left(K\tan d\right)_i\left(pD_i\right) + \left(g'hN_q + g'\frac{t}{2}N_g\right)\left(pDt\right)$$

which can be simplified to (assuming that the internal and external friction is equal):

$$V = g'\left(pD\right)\left(h^2\left(K\tan d\right) + htN_q + \frac{t^2}{2}N_g\right)$$

The factor $K\tan d$ might be taken as 0.5, and N_q and N_g are appropriate bearing capacity factors (strip footing factors). Although this provides a first estimate of capacity at shallow penetration, it is important that the enhancement of vertical stress within the caisson by the "silo effect" is accounted for at deeper penetrations. When the footing base makes contact with the sand the capacity of the foundation can be found using conventional bearing capacity theory:

$$V = \frac{g'h^2}{2}\left(K\tan d\right)_o pD_o + \frac{pD^2}{4}\left(g'LN_q + g'\frac{D}{2}N_g\right)$$

where the factors N_q and N_g are bearing capacity factors as determined for circular footings (such as those given by Bolton and Lau, 1993 or Cassidy and Houlsby, 2002) and the friction is taken only on the outside skirt wall. Results using these expressions and appropriate soil parameters are presented on Figure 7, showing reasonable agreement with the data.

Moment Loading Tests

Moment loading tests were carried out to investigate the ultimate moment capacity of the footing under low vertical loads. The footing sizes were chosen so that the loads investigated were within the constraints of the loading rig. One footing was diameter 293mm and skirt length 150mm representing an L/D ratio of 0.51. The majority of the results presented in this paper relate to results from tests on this footing. A second footing of diameter 202mm and skirt length of 200mm (representing an L/D ratio of 1) was also tested. The control program for the loading rig incorporates feedback control routines that enable complex loading tests to be carried out. The tests described here are ones where the footing is rotated whilst the vertical load is kept constant. The horizontal load is controlled so that it represents a chosen ratio of the moment load. For instance a time history of a test is shown in Figure 8 (in this test H is simply a constant multiple of M/D). This shows the vertical load kept approximately constant at

20N whilst the horizontal load and moment are cycled. The load displacement response for this test is shown in Figure 9. The test comprises cycles of increasing amplitude. Clearly at small displacement the response is very stiff, but on increasing displacements the response softens considerably. There is also considerable hysteresis in the loading and unloading loops. This response is consistent with the results reported by Byrne (2000) and is typical of material behaving in accordance with Masing's rules (Masing, 1926; Pyke, 1979). Figure 10 shows the response in the ($M/2R$, H) plane and the ($2R\theta$, u) plane. These data can be used to determine the plastic potential as they give the incremental displacement vector direction for this particular ratio of loads in ($M/2R$, H) space.

The data shown here will be used to develop plasticity models, once sufficient data have been collected. In the first instance, however, it is useful to develop simple design calculations based on the results so that preliminary foundation designs can be assessed. These calculations should be developed such that they are consistent with the more complex procedures that are being developed, such as plasticity models of foundation response. To interpret the load-displacement response as shown in Figure 9 it is necessary to focus on the initial loading curve. This is shown in Figure 11. There is significant noise in the measurement of the very small foundation displacements. The response is initially stiff before yielding occurs, and a much softer response follows. This yield point can be calculated by looking at the intersection of the tangents to the initial stiff section and the softer plastic section; this is a reasonably simple but consistent method of determining a yield point. As shown in Figure 11 the representative yield point is deduced as 32.6N. A similar process is required for horizontal load, so that eventually a point in three dimensional (V, $M/2R$, H) space can be determined. By carrying out a number of such tests it is possible to define a surface bounding these points to be used in preliminary calculations.

As the number of possible combinations of loading is large it is important to investigate only quantities relevant to the wind turbine problem. Two such quantities are:

(a) $M/2RH$: This varies between 0.5 and 2 for the wind turbine problem. The test program therefore focussed on ratios of 0.5, 1 and 2.

(b) $V/\gamma' D^3$: This varies from 0.01 to 0.5 for the wind turbine problem. The test program is therefore focussing on vertical loads of 0, 20, 50 and 100N on footings of diameter 293mm and 202mm.

The test results presented here are preliminary results which relate only to the footing of diameter 293mm and skirt length 150mm. The results are presented in Figure 12 in (V, $M/2R$) space. In the first instance a plane can be fitted through the points. Such a plane would have a form:

$$f_1 \frac{M}{D} + f_2 H = V + f_3 \gamma' \frac{\pi D^2 L}{4}$$

If we define the following quantities corresponding to the ratio of moment to horizontal load and the weight of the soil plug:

$$\frac{M}{DH} = k \text{ and } W = g'\frac{pD^2L}{4}$$

We can therefore arrive at an expression for the moment capacity as:

$$\frac{M}{D} = \frac{1}{f_1 + f_2/k}\left(V + f_3W\right)$$

The best fit parameters using a least squares regression of this preliminary data to the plane are f_1 = 3.03, f_2 = 1 and f_3 = 0.64. The third parameter represents proportion of the soil plug weight (W = 154N) 'mobilised' under the action of moment loading. The dotted lines represent lines of constant M/DH ratio and intersect the horizontal axis at –100N. An alternative way to view the data is in the ($M/2R$, H) plane and is shown in Figure 13. The dotted lines represent lines of constant vertical load corresponding to loads of 0, 20, 50 and 100N. The plane shows a good fit to the data. Also shown on the Figure are the incremental displacement vectors and their normals. For associated flow the displacement vector would be normal to the yield surface. At this stage the data are preliminary, and a number of further experiments are required to verify this approach. In particular the effect of skirt length, footing diameter and sand density are to be investigated.

Conclusions

A topical problem in civil engineering at present is the development of design calculations for wind turbines in the offshore environment. One area where cost-savings can be made is in the design of the foundations for these structures. To this end an experimental research project, as described by Byrne *et al.* (2002), is currently being carried out to develop designs for shallow skirted foundations. This paper presents some preliminary results from the early part of the project. In particular some vertical loading results are presented that could be used for developing installation calculation procedures. The last part of the paper presented some results for determining the ultimate moment capacity of a shallow foundation when the vertical load is very low. These results will contribute to the development of plasticity models that can be used within structural analysis packages.

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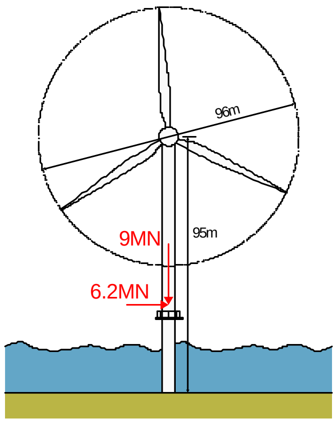

Figure 1 Schematic of wind turbine problem

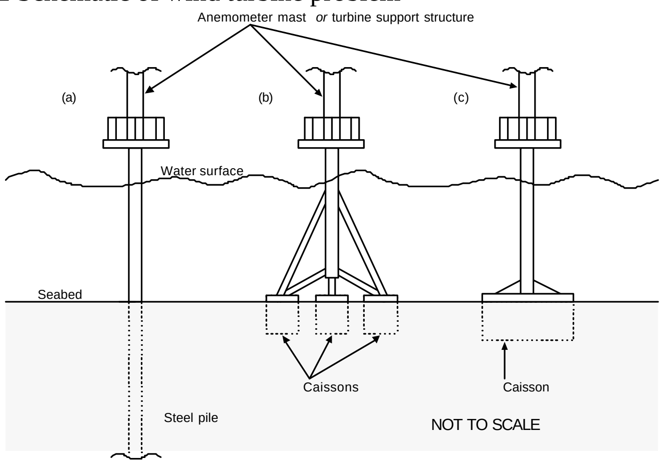

Figure 2 Different structural configurations (after Houlsby and Byrne, 2000)

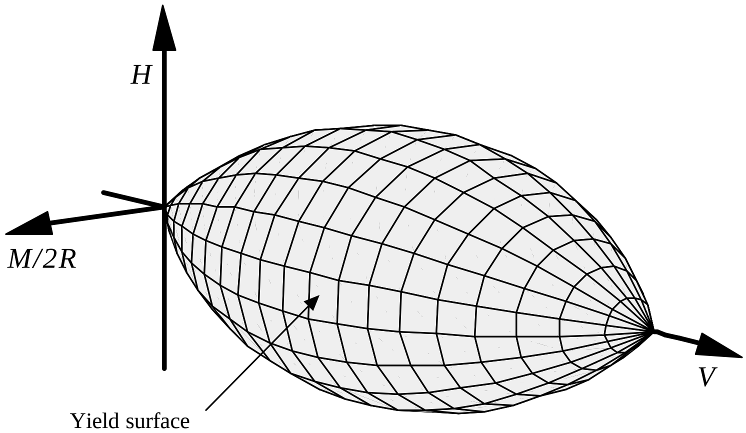

Figure 3 A typical footing yield surface

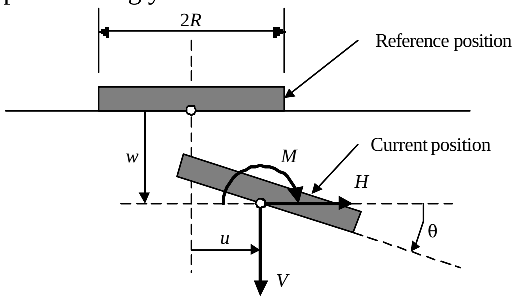

Figure 4 Footing sign convention after Butterfield *et al*. (1997)

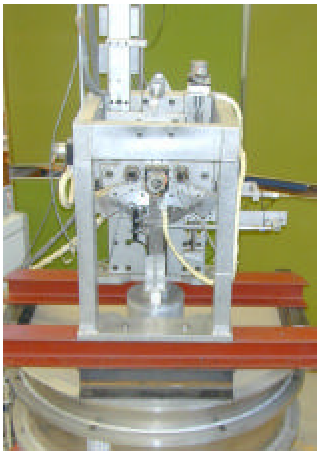

Figure 5 Experimental rig (left) and foundation models (right)

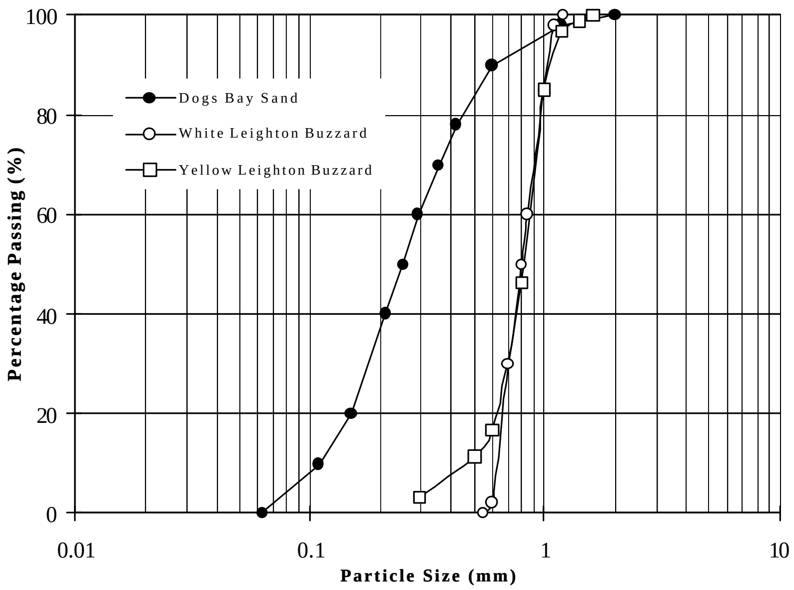

Figure 6 Grading curves for soils used during the experiments

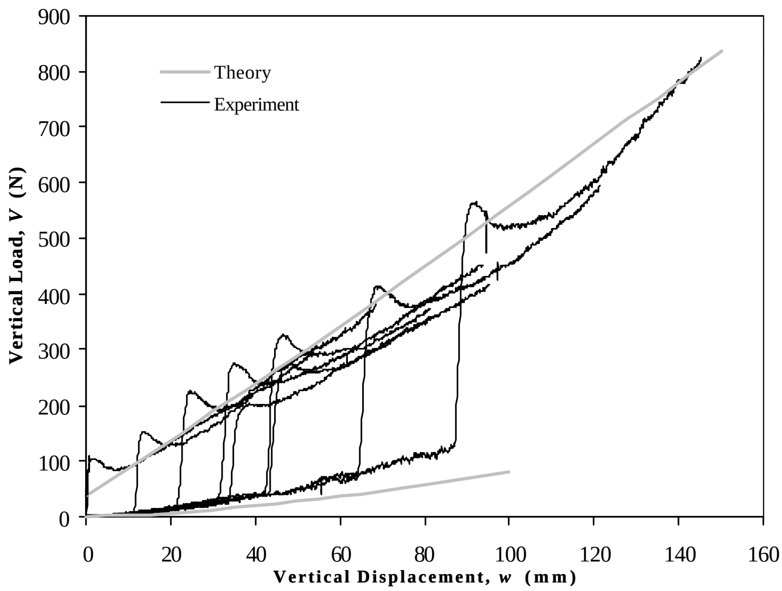

Figure 7 Vertical load-displacement response for different L/D ratios

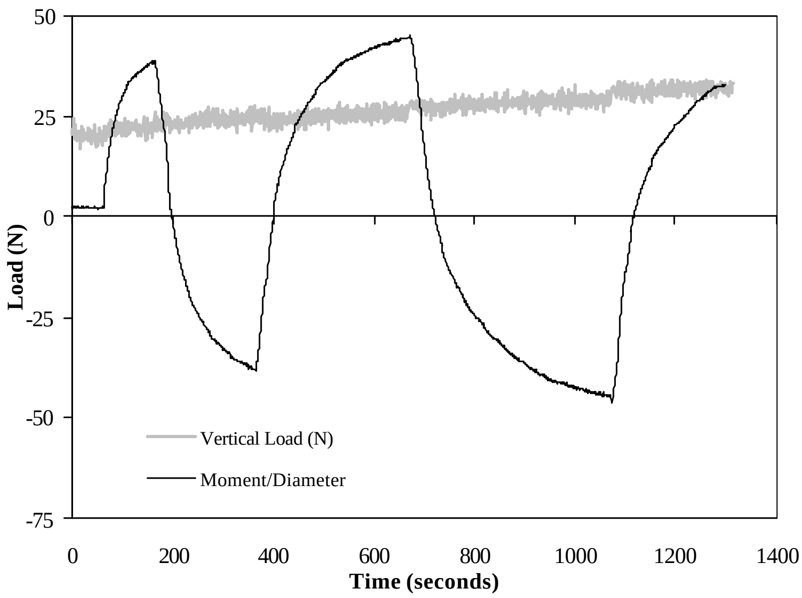

Figure 8 Time history of a typical moment loading test

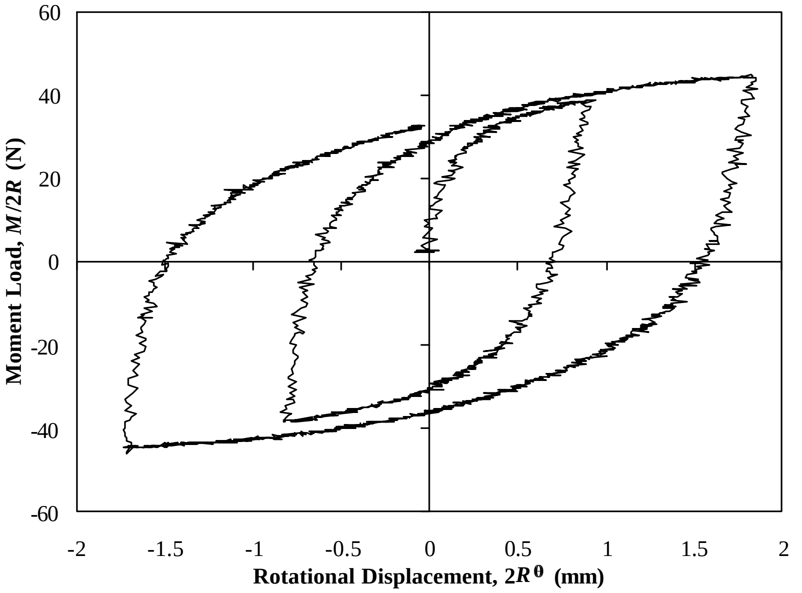

Figure 9 Load-displacement response for a typical moment loading test

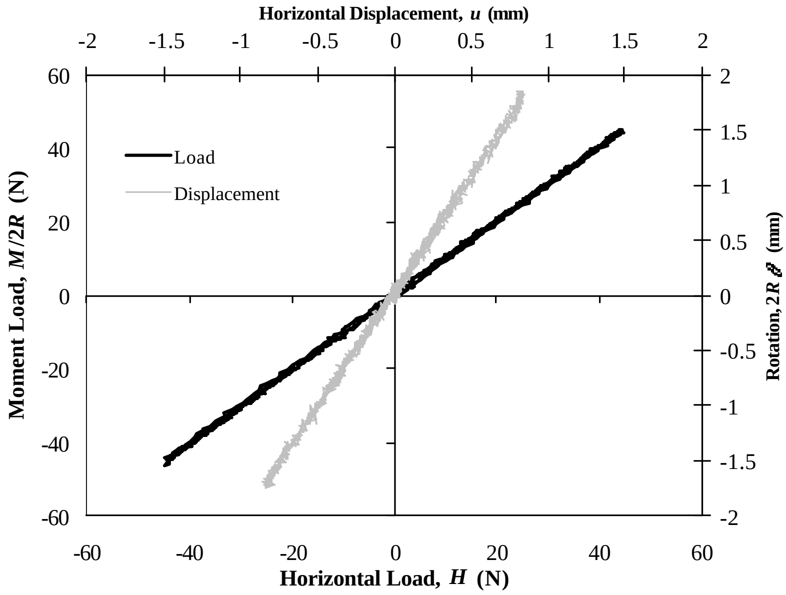

Figure 10 Load and displacement response in the $M/2R$:H and u:$2Rq$ planes

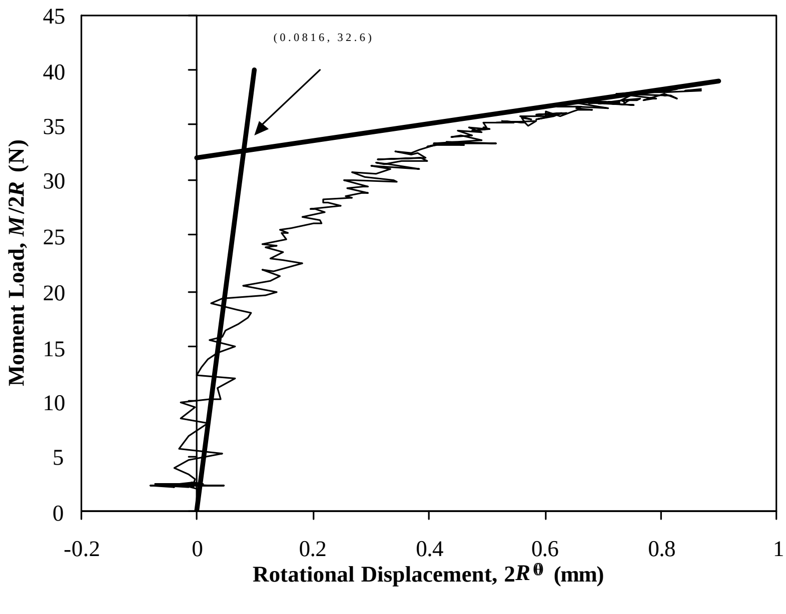

Figure 11 Initial yield of footing in load displacement space

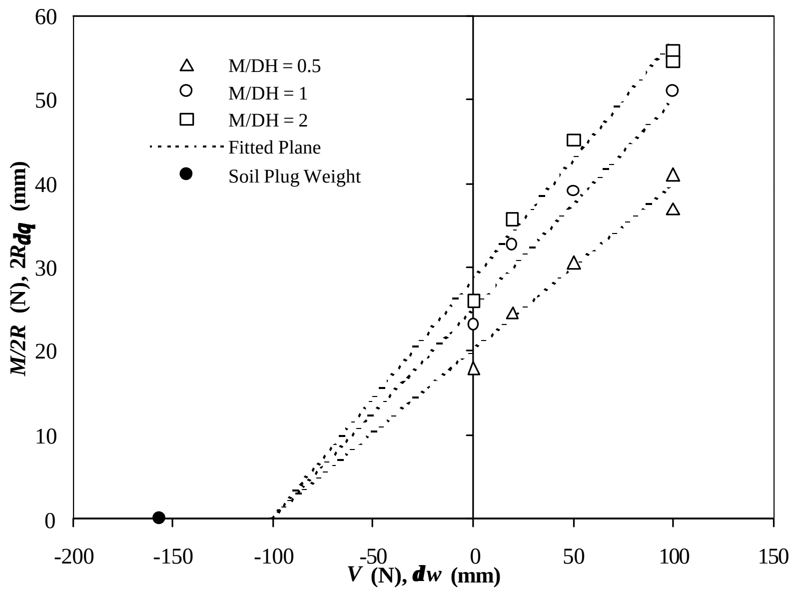

Figure 12 Ultimate moment capacity as a function of vertical load

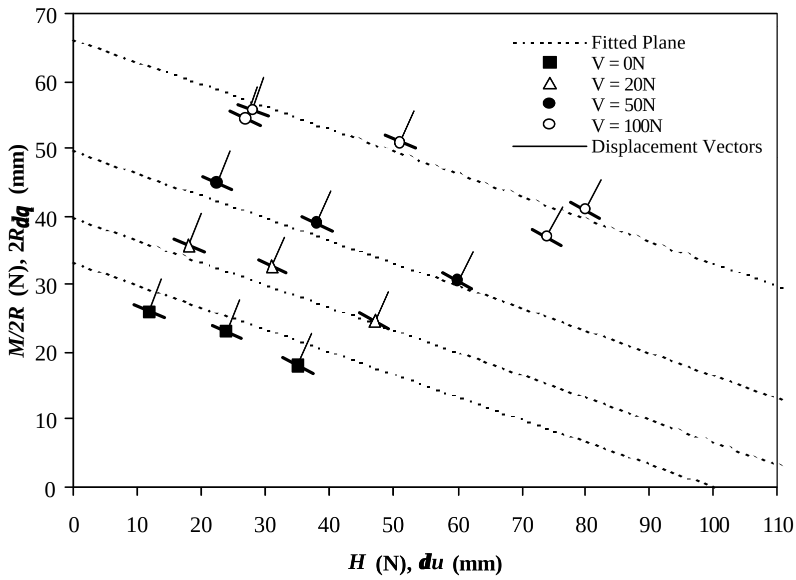

Figure 13 Yield points plotted in $M/2R{:}H$ space