Experimental Investigations of the Response of Suction Caissons to Transient Combined Loading

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Abstract: Combined loading of foundations is a fundamental problem in civil engineering, particularly in the offshore industry where harsh environmental conditions occur. Large moment and horizontal loads may be applied to the foundation as well as vertical loads. Also, as the waves pass a structure, there can be rapid changes in the loads, so that transient effects need to be considered. When designing shallow foundations, such as suction caissons, there is uncertainty in the current understanding of how the foundation responds to these loads. This paper presents experiments, performed on model suction caisson foundations, where typical cyclic loading conditions are applied. The footing is embedded in oil-saturated sand so that dimensionless drainage times are comparable with the typical offshore conditions. Most of the testing was carried out with the vertical load held constant, to mimic the structural dead weight, while realistic ''pseudorandom'' moment and horizontal cyclic loads were applied. Experiments were carried out at different vertical loads, showing that the response depends on the vertical load level. Nondimensional relationships were established which accounted for this dependency. Surprisingly, the rate of loading had little impact on the load–displacement behavior for the experiments undertaken.

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Introduction

In the search for cheaper alternatives to piled foundations, the offshore industry has turned to novel types of shallow foundations. One foundation concept is referred to as a ''suction caisson'', this is a flat foundation with skirts around the periphery, rather like an upturned bucket. There are two aspects to the engineering design of this foundation: (i) installation (from which method the foundation derives its name) and (ii) in-service performance. During installation the skirt is partially embedded under the self-weight of the caisson and structure. The installation is completed by reducing the water pressure inside the caisson, thus forcing the skirts into the seafloor. In clay the net downward force caused by the pressure differential inside and outside the caisson drives the bucket into the ground. In sand, the hydraulic gradients set up in the soil around the bucket skirt also contribute to the process, as they reduce the soil resistance at the skirt tip, and within the caisson, to almost zero, allowing the bucket to penetrate easily into even very dense sand (Erbrich and Tjelta 1999). Typically, a caisson in sand is designed with a skirt depth (L) less than the diameter (D), while in clay the ratio L/D might be as large as 5. The suction caisson concept has found numerous applications in shallow or deep water, in many types of soils, and for either fixed or floating structures. This paper will present results that are applicable to low aspect ratio (L/D) caisson foundations that might be used for fixed structures on sand.

The in-service performance, particularly when combined vertical (V), moment (M), and horizontal (H) loads are applied, must be addressed so that a safe design can be achieved. In assessing the in-service performance two issues are relevant: performance during extreme events, and ''fatigue'' performance under the application of many cycles of low amplitude loads. This paper explores the application of extreme events, as well as multiple load cycles and the resulting load–displacement response of the foundation. The objective is to provide information for development of theoretical models capable of modeling the response to cyclic loading. The method used here is to carry out small-scale model tests. The results described below are general in the sense that they might apply to other types of shallow foundations, such as, for example, the spudcans used for mobile drilling units. This work is, therefore, relevant to a variety of offshore applications including the design of minimal facility structures, mobile drilling units and offshore wind farms.

Offshore Wind Application

The application to offshore wind turbines is of particular current interest (Houlsby and Byrne 2000; Byrne and Houlsby 2002b; Byrne et al. 2002b). Two different structural configurations have so far received the most attention: (1) a jacket structure such as tripod or quadruped and (2) a monopod structure. If a jacket structure is adopted, then the loading will be comprised of both horizontal and vertical loads. The magnitude of the horizontal load will depend principally on the water depth, though, perhaps more damaging, is that the vertical load will be comprised of both compressive and tensile loading. As the structural dead weight is, typically, low, it is likely that the wave and wind loading will cause uplift or tensile loading on the windward footing; the un-

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derstanding of this type of loading on suction caissons is discussed in detail by Byrne and Houlsby (2002a). One of the main conclusions from their study is that a softened response occurs immediately upon the application of tension to the footing. On applying larger uplift movements to the footing the response becomes stiffer and is ultimately governed by cavitation of the pore fluid. This indicates that serviceability requirements rather than ultimate conditions dictate the design, in tension, at least.

In the case of a monopod structure supporting the wind turbine there will be significant horizontal loads and moments, but relatively low vertical loads, applied to the foundation. The magnitudes of these loads are very different from those experienced by oil and gas structures, and so therefore there is little guidance to be gained from the established database. Furthermore, the wind and wave directions may not be coincident, so the base shear and moment may not be in the same direction. As an example, the main moment loading is derived from the wind force on the turbine blades, which for a 3.5 MW turbine might be about 100 m in diameter, with the hub located some 90 m or more from the sea surface. The resolved horizontal load from the wind on the blades of such a turbine is about 1 MN acting at the hub height. The loads from the waves act at a much lower level, as typical water depths may be about 10 m, and the resolved horizontal load might be about 3 MN. The net horizontal load is therefore about 4 MN, acting effectively at about 30 m above the seafloor with a vertical dead load of the order of 6 MN. As many structures may be installed at a given site, a simple and economic design is necessary for this concept to be viable. A design that may enable cost savings to be achieved is to use suction caisson foundations as opposed to piling. Of the two design approaches mentioned above the single monopod foundation could be the cheapest, and so the combined cyclic loading problem is of interest.

Cyclic Combined Loading

Experimental Evidence

There are few studies, in the public domain, on cyclic loading of shallow foundations on sand, and even fewer considering combined cyclic loading. Most relevant research has been proprietary. For example, in the design of Statoil's Sleipner T structure, confidential work on the effects of cyclic loading was carried out at the Norwegian Geotechnical Institute (NGI) and at Oxford University. Only part of this work is in the public domain, for example, the overall design framework proposed by Bye et al. (1995). That paper was mainly concerned with vertical loading, and included no discussion on combined cyclic loading. The main design framework was based on the concept that, for any given applied static load, limits could be established for the magnitude of cyclic loading that could be sustained. The concept is illustrated in Fig. 1, in which it can be seen that the allowable loads might range from a modest tensile load to a substantial compression. Unfortunately, no scales are given in Fig. 1 because the data used by Bye et al. (1995) are confidential. Degradation of response would, however, occur once the boundaries shown in Fig. 1 were reached.

The results from Byrne and Houlsby (2002a) suggest that degradation occurs in dense sand if the loading is sufficient to cause dilation. This response, which was found to be rate dependent, only occurred on pulling the foundation to relatively large displacements, typically, greater than about 2% of the diameter. At displacements less than about $0.02D$, the response was largely rate independent. In a properly designed foundation only small

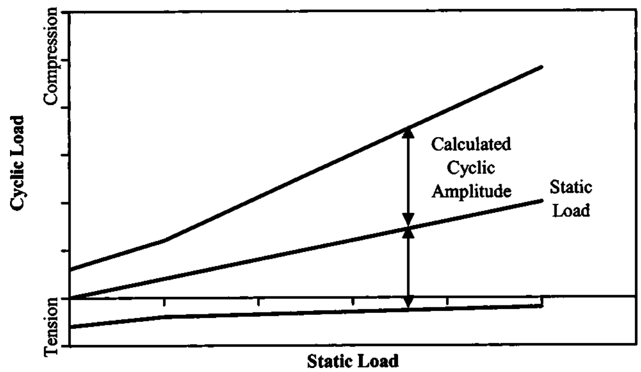

Fig. 1. Cyclic failure envelopes suggested by Bye et al. (1995)

displacements will occur, so the rate-dependent response may not be relevant, and the Bye et al. (1995) design framework may not be valid. It should be noted that consolidation of the soil matrix during long sequences of combined loading is an entirely different issue, discussed later in this paper.

Theoretical Understanding

The application of moment (M) and horizontal (H) loads in conjunction with vertical (V) loads has been an area of study for many years. Initial research concentrated on ultimate capacity under these load conditions, while more recent work has focused on establishing the subfailure response as well. This is achieved by considering the foundation response within the context of work hardening plasticity theory, as originally suggested by Roscoe and Schofield (1957). The postulate is that when the footing penetrates into the soil work hardening occurs and the footing yield surface in $(V,M/2R,H)$ space expands. Such a yield surface is shown for a flat footing on sand in Fig. 2. Any load combinations within the yield surface result in the footing undergoing elastic deformations, while load combinations that reach the yield surface result in elastoplastic deformations.

To develop such a model it is necessary to determine: (1) the shape of the yield surface; (2) the elastic response inside the yield surface; (3) the flow rule, which determines the direction of plastic deformation vectors; and (4) the hardening law, which defines how the yield surface changes with plastic deformation. Such models have been determined in reasonable detail for foundations on clay (Martin and Houlsby 2000; Martin and Houlsby 2001),

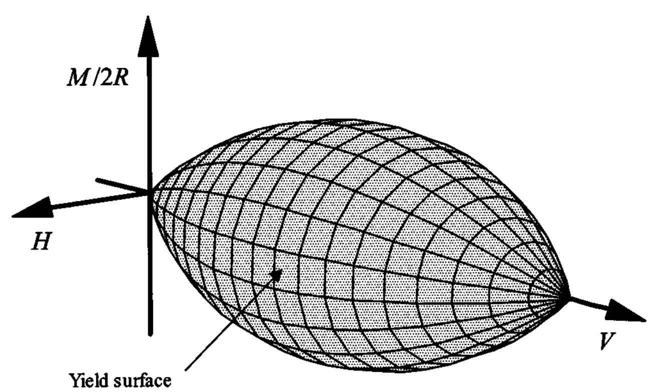

Fig. 2. Typical $(V,M/2R,H)$ yield surface for footings under combined loads

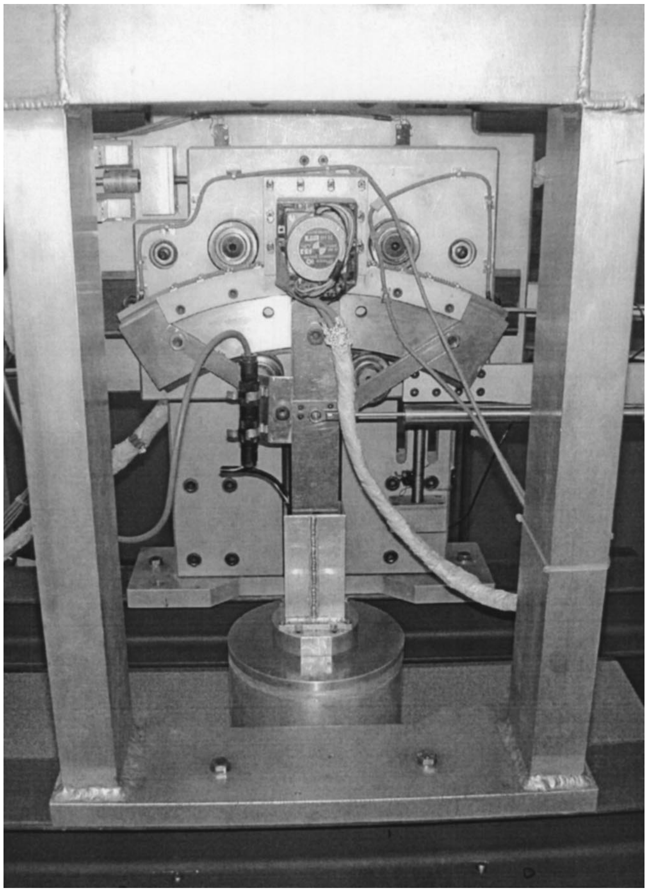

Fig. 3. Loading apparatus at Oxford University

dense and medium sand (Butterfield and Ticof 1979; Nova and Montrasio 1991; Gottardi and Butterfield 1993; Gottardi et al. 1999; Byrne and Houlsby 1999; Houlsby and Cassidy 2002), and loose carbonate sand (Byrne and Houlsby 2001; Cassidy et al. 2002).

A drawback of the above models is that only monotonic loading is modeled well. In reality, even at small displacements, the response of the foundation on the soil is not elastic. More complex models involving either multiple yield surfaces or a bounding surface approach could be used to achieve a more realistic elastoplastic response on unloading. An approach called continuous hyperplasticity (Puzrin and Houlsby 2001a,b), a development of the multiple yield surface method, has been developed, which is able to describe cyclic loading behavior in a rigorous yet simple manner. To develop such models an understanding of the foundation response under combined cyclic loading is needed, so that realistic behavior can be incorporated. The experiments described here are specifically directed towards development of these models. A preliminary version of a continuous hyperplasticity model is described, and shown to provide a very good approximation to the cyclic behavior.

Experimental Equipment and Program

This research was carried out using a three degree-of-freedom loading rig on the laboratory floor as shown in Fig. 3. This apparatus was designed specifically for carrying out combined loading experiments (Martin 1994; Mangal 1999; Byrne 2000) necessary to develop plasticity models for foundations. Footing displacements and loads are measured using a system of linear variable differential transformers (LVDTs) and a "Cambridge" style load cell (Bransby 1973). The footing used in most of the tests was 150 mm diam, 50 mm skirt length, and 0.45 mm wall thickness. The sand used during the investigation was "Baskarp cyclone sand" with the properties given by Byrne and Houlsby (2002a). Four key characteristics are $d_{10} = 17.8\ \mu\text{m}$, minimum dry density of 12.72 kN/m^3, maximum dry density of 16.85 kN/m^3, and a critical state friction angle of 32.5°. The sand was saturated with 100 centistoke silicon oil so that partial drainage rates comparable to the field situation could be obtained in the laboratory within the constraints of the loading device. The experiments were carried out on saturated samples prepared to densities of 76 and 92%.

In carrying out laboratory floor experiments involving sands it is important to understand the implications of scale, and therefore stress level, on the results. The stress–strain behavior does not scale linearly with stress level; such effects are reported in detail by Bolton (1986). The sand will dilate more at low stress levels, as in laboratory floor experiments, when compared to the higher stress levels in the prototype. For experiments on footings this issue is discussed by Lau (1988). Differences in stress level can to a certain extent be compensated by employing lower relative densities for laboratory scale tests. In general, the behavior will be sufficiently similar so that phenomenological models based on laboratory results will be valid at field scale, albeit with a change of parameter values. Engineering judgment will be required to apply the models to field problems.

To obtain the correct drainage characteristics for the foundation–soil system the mean particle size was reduced and the viscosity of the pore fluid increased. Byrne (2000) gives a description of the relative performance of oil- and water-saturated sand in both drained and undrained triaxial compression tests (data as reported by NGI 1994). The main observation is that the oil-saturated sample gave a peak friction angle about 3° lower than the water-saturated sample. The peak dilation rate is also reduced to about half that of the water-saturated sample. Undrained triaxial tests (NGI 1994) also show that the oil tends to reduce the stiffness of the soil. All these effects mean that the oil-saturated sand behaves rather like a water-saturated sand at a higher stress level, thus partially offsetting the disadvantage of small-scale model tests.

Consolidation tests were carried out to determine the appropriate time scale for the cyclic loading tests, to be consistent with field applications. Typical t_{50} values for pore pressure dissipation ranged from 300 s at the beginning of a test to 30 s towards the end of a test, with the shorter times being due to increased stiffness after consolidation. The test tank was large enough so that eight separate experimental sites were available. Pore fluid pressures were measured directly under the caisson base at three locations along the line of loading. The experiments are computer controlled, with feedback, to control any combination of load $(V, M/2R, H)$ or displacement $(w, 2R\theta, u)$, thus enabling quite complex experiments to be performed. The sign convention and notation, shown in Fig. 4, follow that of Butterfield et al. (1997) with the load reference point at the center of the caisson base plate (i.e., mudline). Further details of the experimental setup may be found in Martin (1994), Mangal (1999), Byrne (2000), and Byrne and Houlsby (2002a).

Experimental Results

Typical tests, described further below, were monotonic tests and combined cyclic loading tests (moment, horizontal, or both) under constant vertical load. Selected test results will be presented to

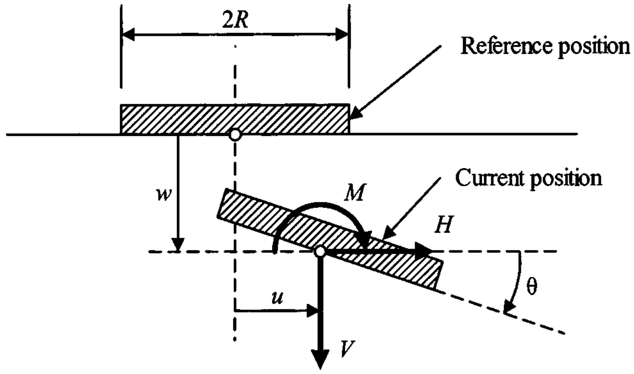

Fig. 4. Sign convention and notation after Butterfield et al. (1997)

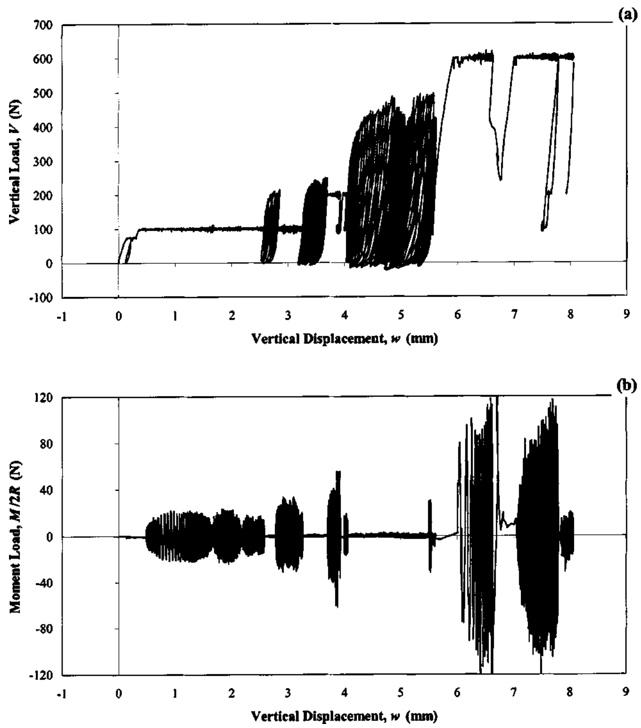

Fig. 5. Typical test sequence, which includes (a) vertical cyclic loading, and, (b) moment cyclic loading, both plotted against vertical displacement

illustrate the behavior of suction caissons under cyclic combined loading. A typical test is shown in Fig. 5, where both vertical and moment loads are plotted against the vertical displacement. This test included phases of vertical cyclic loading on the foundation, as well as combined cyclic loading. Significant vertical displacements occur when the moment loading is applied to the caisson under a constant vertical load, particularly at the beginning of the test.

Cyclic Loading

Early in the research it was believed that extreme events were of prime importance, as indicated in the framework of response set out by Bye et al. (1995). That paper gave selected results from the confidential program of research undertaken during the development of Statoil's Sleipner T jacket and foundation system. Bye et al. (1995) suggested that for vertical loading certain amplitudes of cyclic loading could be sustained, but once these limits were crossed there would be rapid degradation of performance. When the original testing program was conceived this framework was also expected to apply to horizontal and moment loading, and the experiments were designed accordingly.

The "constrained new wave" method (Taylor et al. 1995) was developed by Byrne (2000) to define load histories, such as that shown for moment loading in Fig. 6(a), to study extreme loading events. This technique allows extreme events to be embedded within a pseudo random background loading, so that they are statistically indistinguishable from a random occurrence of that event. A typical response to such a load history is shown in Fig. 6(b) and the load–displacement response is shown in Fig. 6(c). Many other load histories were used to examine the effects of load repetition, loading rate, and loading history. Tests were also performed to aid the development of a new theoretical model for cyclic loading. During the application of the combined cyclic loading it was necessary to use feedback to keep the vertical load constant.

Analysis of the Data

The large amount of data that are accumulated during a cyclic testing program is unwieldy in its raw form. The method used for reducing vertical cyclic loading data was also used for combined cyclic loading as depicted in Fig. 7. The peak load ($M/2R_{\mathrm{peak}}$ or H_{peak}), temporary displacements (δ_{temp}), and permanent displace-

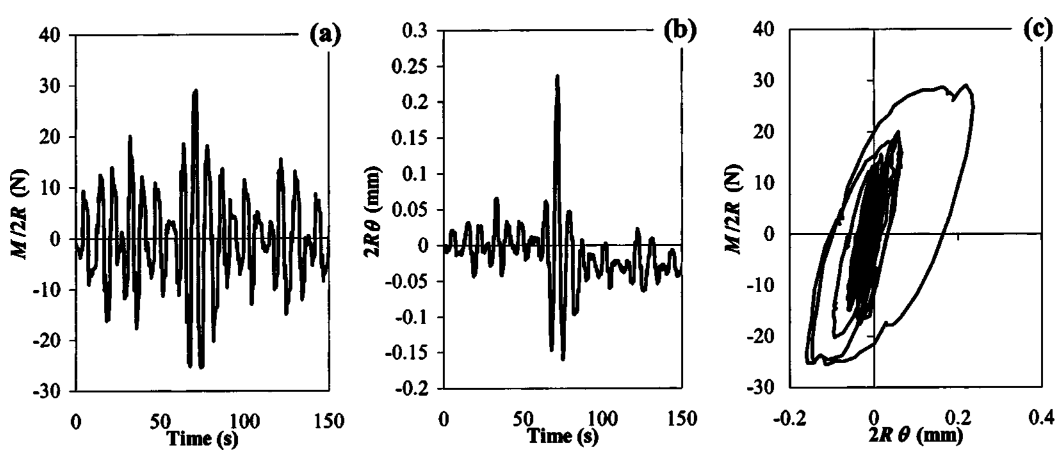

Fig. 6. Typical pseudorandom (a) loading time history, (b) corresponding displacement response, and (c) the load displacement behavior showing increasing hysteresis for large cycles

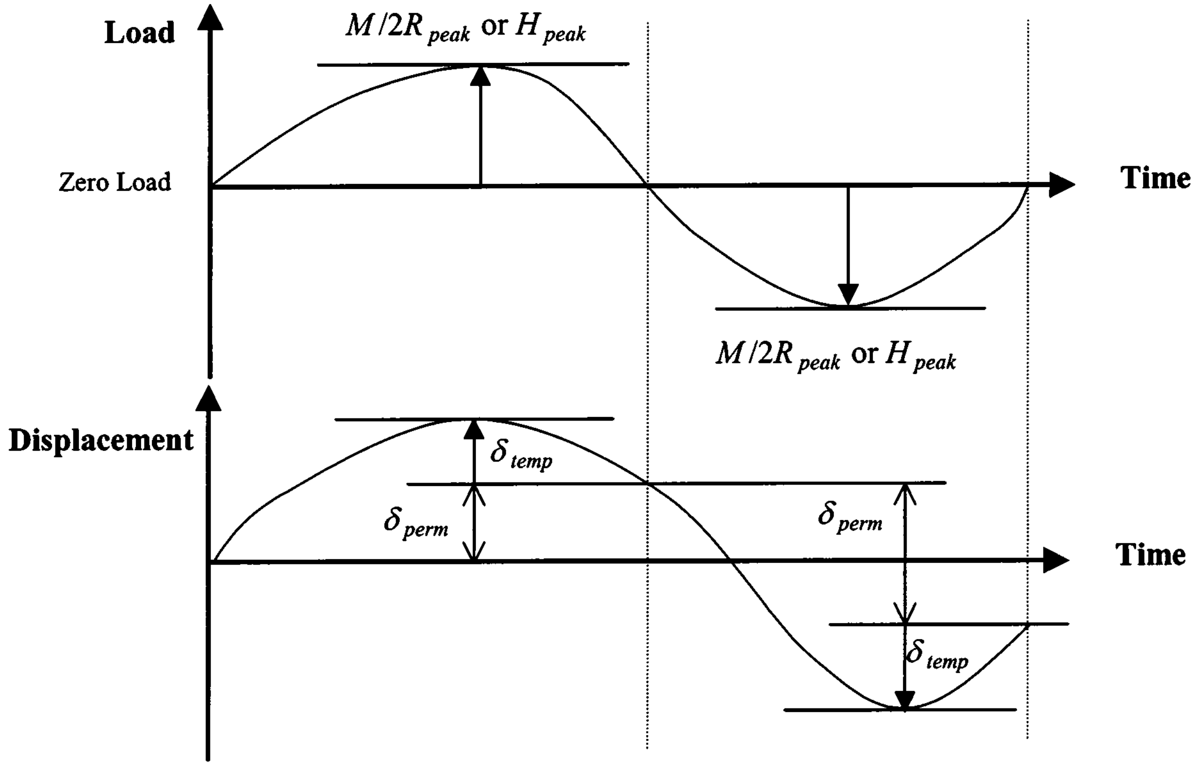

Fig. 7. Methodology used for reduction of cyclic data

ments (δ_{perm}) are determined between zero load crossings. This process is straightforward and can be automated in a spreadsheet program. A set of these reduced results is given in Figs. 8(a–c), which shows results from two different cyclic moment loading tests under the same constant vertical load. Test SM1-4 shows results from a cyclic test on a normally consolidated foundation, prior to any other combined loading. The permanent displacements show a soft response, due to plasticity occurring as the yield surface expands. The "SM1-4 after cycling" results show a test completed after the yield surface had been expanded significantly by repeated cycling. The foundation exhibits a much stiffer response. The initial stiffness of both tests is approximately similar. The larger strain stiffness is much lower for the test in which many previous cycles have not yet occurred. The same observations also apply for the temporary displacements.

Response to Initial Cyclic Loading

The first storm loading of the structure is a critical period in the life of the foundation, as more plastic deformation is likely to occur than at any other time during its service. Typically, the foundation would not have experienced higher vertical loads ear-

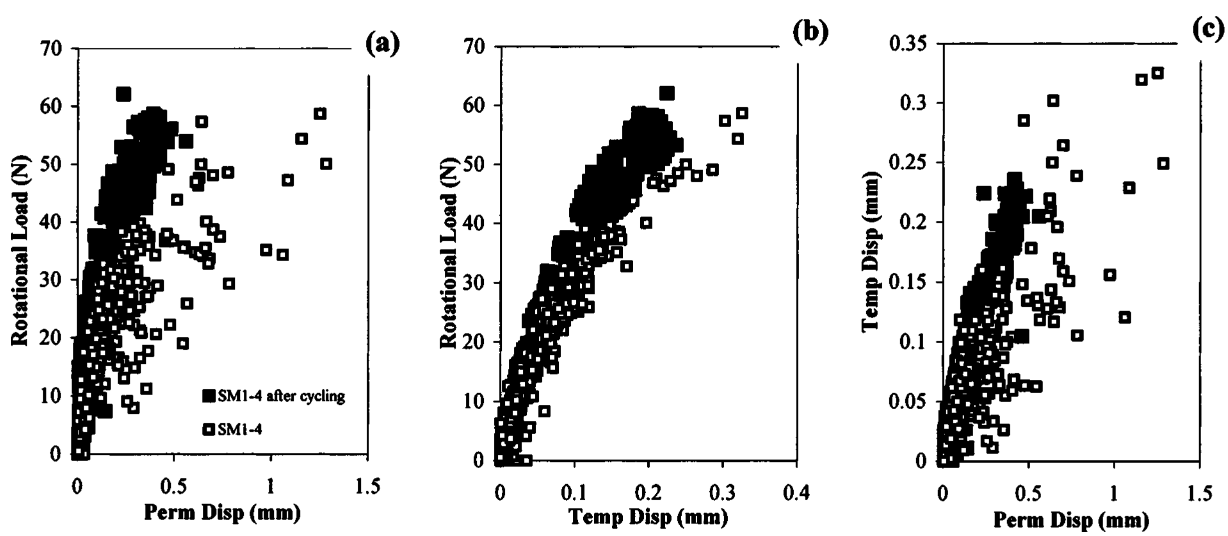

Fig. 8. Reduced data from several cyclic loading tests showing (a) permanent displacements, (b) temporary displacements, and (c) displacement relationship

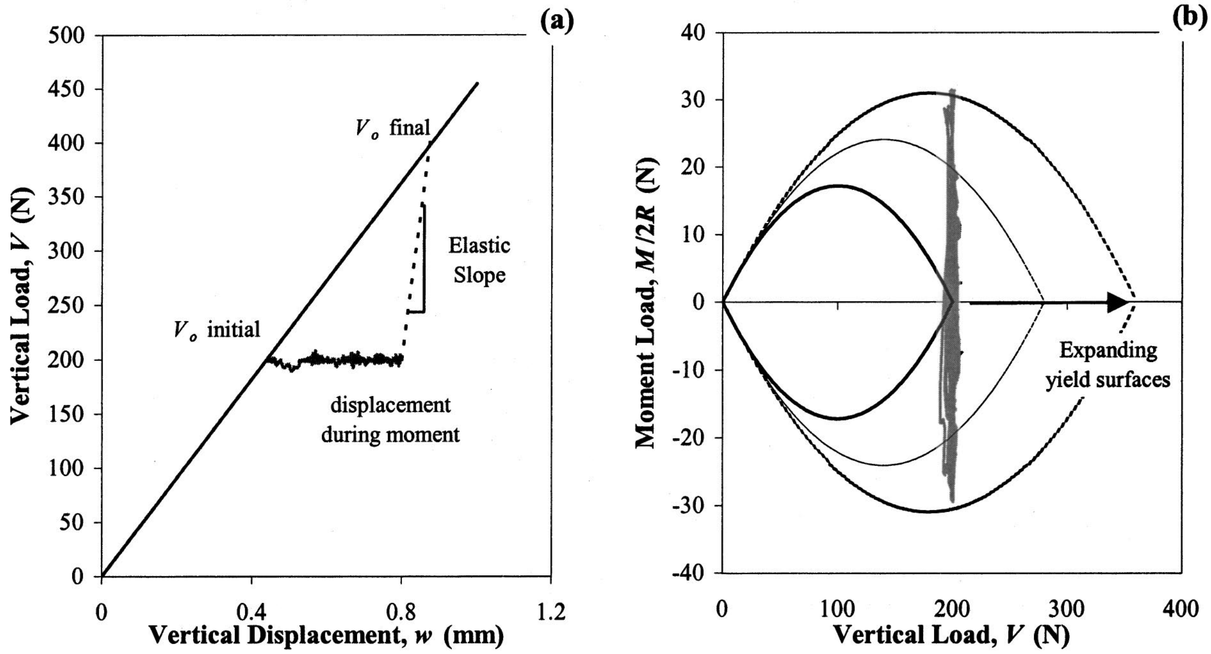

Fig. 9. Initial moment loading showing (a) vertical displacement during test, and (b) interpretation of behavior with yield surface framework

lier. It might be possible to apply a preload to the caisson, either through applying a greater suction than that required initially to install the caisson, or by adding temporary ballast. Fig. 9(b) shows the shape of the yield surface before, during, and after an initial storm loading in which there is significant moment loading. Initially, the load state is at the vertical load apex of the yield surface. As the moment load is applied the yield surface expands, and vertical displacements occur, depending in detail on the shape of the plastic potential. It is probable that the plastic potential at the initial stages of yield will be steeper in this vicinity than the yield surface, so that the ratio of vertical to rotational displacements will be high. As a significant amount of volumetric change occurs due to the large vertical displacements [shown in Fig. 9(a)], expansion of the yield surface occurs. This will lead to a reduction of effective stress, as the vertical load is partially transferred to the pore fluid, since only limited drainage occurs within the time scale of the loading event.

It is possible that significant reductions of effective stress might occur, perhaps even causing liquefaction, particularly during extreme events associated with large amounts of plasticity. This is shown in Figs. 10(a–f) where the foundation is subjected to moment cycling after being first loaded to a vertical load of 200 N ($V/A = 11.3$ kPa). There are large increases in the pore fluid pressure on the application of the moment loads, and a limited amount of drainage occurs during the passage of the loads. When the initial extreme event is applied there is a large vertical displacement (~0.1 mm). Subsequent applications of similar loads do not lead to the same magnitude of displacement, or reduction in effective vertical stress, since the load point will now be within the expanded yield surface. However, if the foundation experiences loads larger than any previously applied, yield surface expansion, and hence, volumetric change, will occur.

Clearly, during the early life of the foundation, either preload must be applied, or drainage provided, so that yield surface expansion can occur with minimal consequential reduction in effective stress. The most opportune time to carry out this operation, in a controlled manner, would be during installation. This could be either by applying an enhanced suction for a period (although the effectiveness of such a technique has yet to be proven) or by adding some ballast. If the foundation is installed in the summer it is likely that immediate large loads can be avoided and, therefore, a gradual bedding in of the foundation may be possible. During service further small yield surface expansions may occur due to the loadings applied, but the displacement and effective stress consequences should be minimal.

Cyclic Loading at Different Constant Vertical Loads

Cyclic load tests were performed after a wide variety of loading histories. Tests were carried out to investigate the initial behavior such as described above. Tests were also performed after various preloading histories so that working load behavior could be examined. Typically, the working state of an offshore foundation is such that the behavior is mostly within the yield surface, and thus the stiffer "elastic" response is appropriate. It is only during extreme events that yield surface expansion, and hence significant plasticity, may occur. The results from the combined loading on preloaded foundations suggest that the elastic foundation stiffness is dependent on the magnitude of the mean vertical load applied to the foundation. Fig. 11 shows results of cyclic tests conducted on the same foundation at different values of constant vertical load. In each case the footing was vertically preloaded to 1400 N ($V/A = 79.2$ kPa) before being unloaded to the prescribed vertical load. As the vertical load level increases the stiffness of the response increases. This dependency is important for the tripod structural configuration (or for jack-up platforms) as the mean vertical loads on the foundations differ for windward and leeward foundations.

Comparison of Monotonic Tests and Cyclic Loading Results (Masing Behavior)

Cyclic loading was applied at different rates, including periods of 3, 6, 10, and 12 s, to investigate the effects of partial drainage and

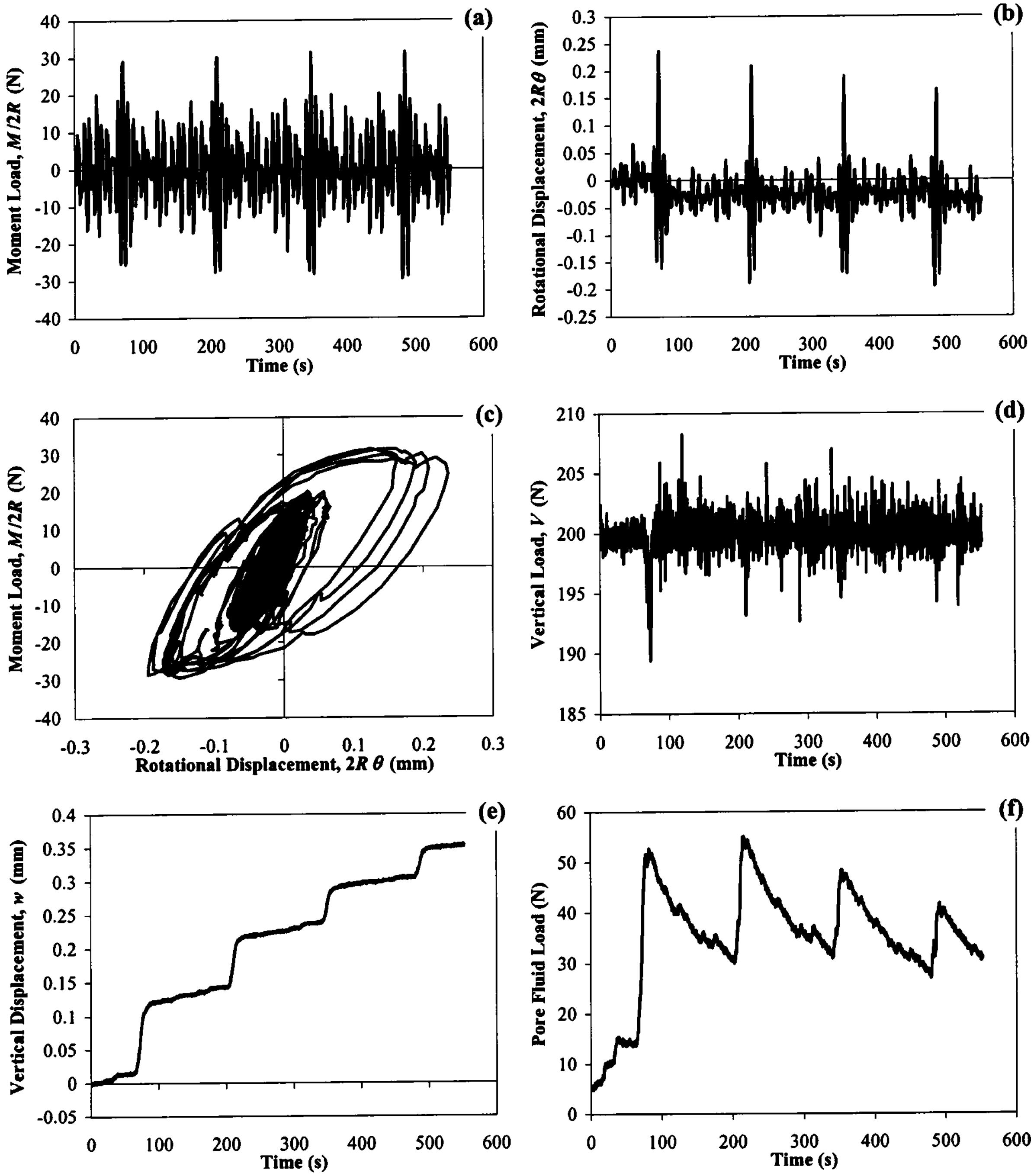

Fig. 10. Initial moment loading showing (a) moments applied to foundation, (b) resulting displacement path, (c) the load displacement response, (d) the applied "constant" vertical load, (e) resulting vertical displacement, and (f) pore fluid load

the transient response. The periods were chosen with reference to the t_{50} times found in the consolidation tests. It became evident that on the samples tested there were no significant differences between the tests conducted at different rates. This was also the case for vertical cyclic loading tests. The same observation was made by Tan (1990) for horizontal cycling within the yield surface, during a centrifuge investigation of the response of spudcan footings on medium dense saturated silica sand.

For further confirmation of the lack of effect of rate it is necessary to examine the relationship between slow monotonic tests and rapid cyclic loading tests. The simplest form of relationship is implied by pure kinematic hardening, which has been observed to be applicable to soil response in cyclic element testing (Prevost 1977; Pyke 1979; Vucetic and Dobry 1988; Vucetic 1990). Masing (1926) suggested that a pure kinematic hardening material would behave according to the following rules:

1. The tangent modulus at the start of each loading reversal assumes a value equal to the initial tangent modulus for the initial loading curve.
2. The shape of the unloading or reloading curves is the same as that of the initial loading curve, except that the scales of both load and displacement axes are enlarged by a factor of 2.

These rules suggest that the initial loading curve, called the backbone curve, may be used to define the behavior during all subsequent load reversals. To show that pure kinematic hardening

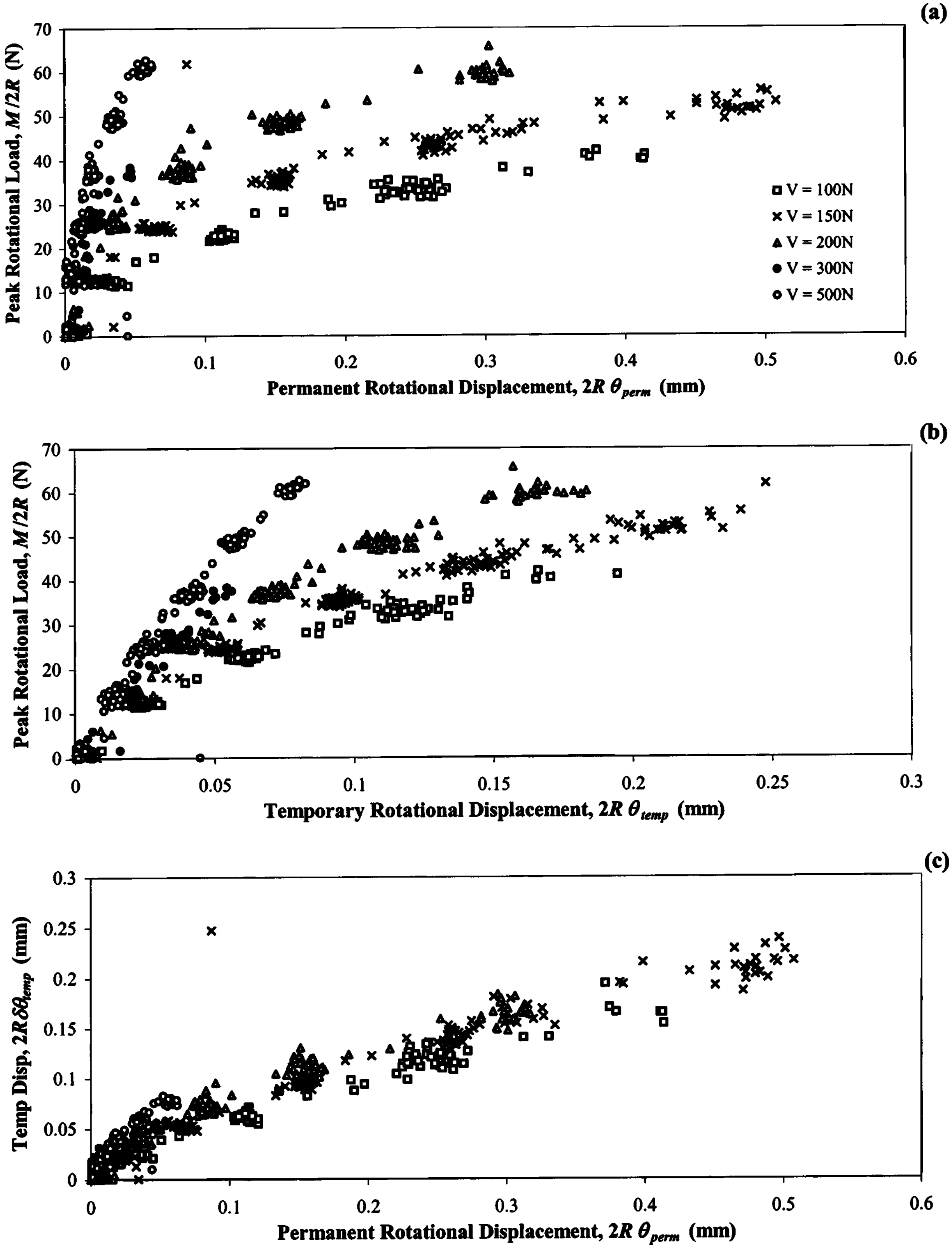

Fig. 11. Results from tests conducted at different values of overconsolidation ratio showing the effect of vertical load on rotational response, (a) permanent displacements, (b) temporary displacements, and (c) displacement relationship

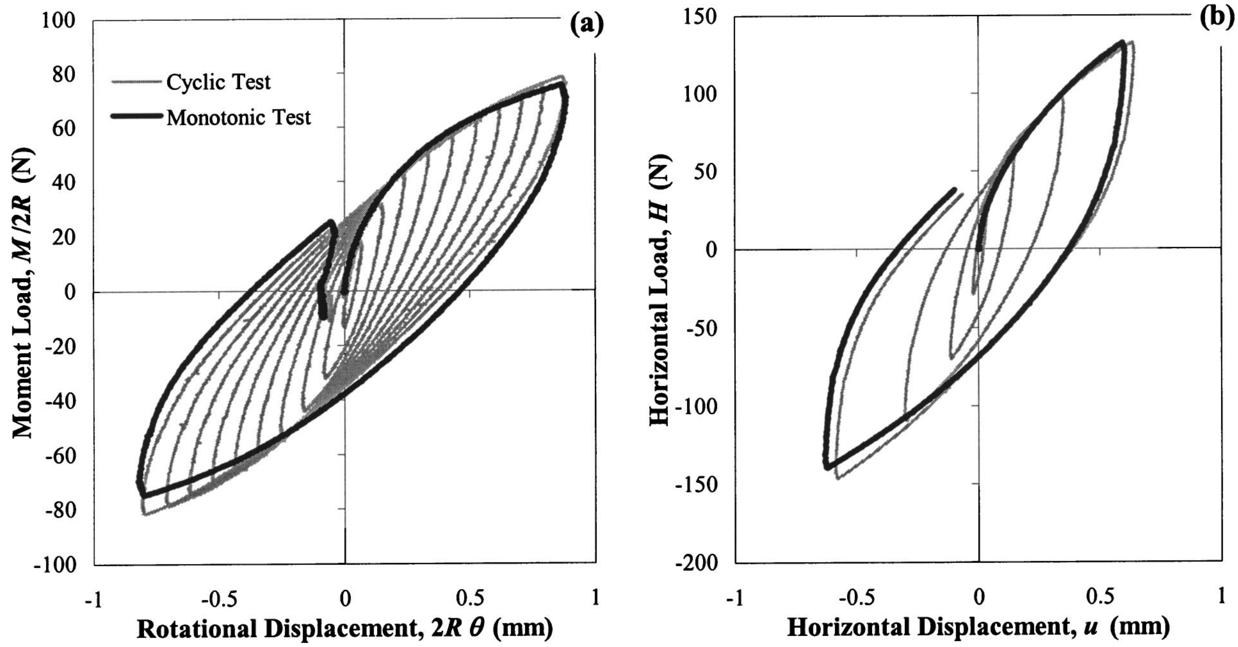

Fig. 12. Comparison of monotonic and cyclic tests for both (a) moment loading, and (b) horizontal loading

governs behavior for the test results obtained, it is only necessary to show that the second rule applies, as the first is in fact a consequence of it. It is also clear that these rules only apply to a nondegrading material. The response of clays (see, for example, Vucetic 1990) may degrade on the application of cyclic loading, so it is necessary to degrade the backbone curve in some way dependent on the history of loading.

To examine whether the above framework applied, slow monotonic tests were carried out, along with faster transient cyclic loading tests. These are shown in Figs. 12(a and b) for moment and horizontal loading, respectively. In both cases the cyclic test consists of cycles of increasing stress magnitude. Clearly, there is a reduction in secant stiffness as the deformation level increases. Furthermore, on passing the previous extreme load level, the unloading or reloading curve follows along the initial loading curve. This is shown by the monotonic test data that are also shown in Figs. 12(a and b). In both cases the monotonic tests pass through the extreme points of each cycle. While this behavior implies kinematic hardening under the Masing definitions, Pyke (1979), formally stated two additional rules (entitled the extended Masing rules) specifying these characteristics:

3. The unloading and reloading curves should follow the initial loading curve (backbone curve) if the previous maximum shear strain is exceeded.
4. If the current loading or unloading curve intersects the curve described by a previous loading or unloading curve, the stress–strain relationship follows the previous curve.

It is clear that the results in Fig. 12, for both moment and horizontal loading, conform to these extended Masing rules, where the monotonic test clearly provides the backbone curve for the cyclic loading test. The second confirmation of Masing behavior is to check whether the shape of the reverse loading loop is a factor of 2 greater than the backbone curve [i.e., rule (2) above]. This confirmation is shown for different moment and horizontal load tests in Figs. 13(a and b). In Figs. 13(a and b) the reverse loading data (unload path) have been extracted, reversed, scaled down by a factor of 2, and replotted from the origin. For the cases shown the scaled unload path gives a close approximation to the original loading path.

Finally, evidence has been obtained that the cyclic loading behavior (Fig. 11) is dependent on the mean vertical load, and Fig. 14(a) shows monotonic tests carried out at different vertical loads, indicating similar behavior. If Masing behavior were applicable the peak data from each cycle of the tests shown in Fig. 11 would plot close to the relevant monotonic curve shown in Fig. 14(a). Indeed, Fig. 15 shows that there is an excellent correlation between monotonic and cyclic behavior in accordance with rule (iii). This also implies that the response of the foundation is essentially rate independent, as the monotonic tests were performed at a much slower rate than the cyclic tests. (Although there is, of course, also a rather unlikely possibility that the result arises from the coincidence of two canceling effects, one due to rate effects and the other due to a difference between cyclic and monotonic response).

Fig. 14(b) shows the vertical displacement response during the moment monotonic tests, where for low vertical loads there is a large amount of heave. As the vertical load level increases the amount of heave reduces, and eventually a load level is reached where there is settlement of the foundation. This gives important information about the nature of the plastic potential (or flow rule), which is an essential component of any plasticity theory that may be developed.

Normalization of Experimental Data

The results presented so far have indicated that the combined load response (1) conforms to Masing behavior, (2) appears to be rate independent, and (3) is dependent on the level of the vertical load. The experimental observation of points (1) and (2) simplifies the task of developing a theoretical model for cyclic loading, as rate independent Masing behavior has been observed in other experimental studies of material response. Point (3) requires careful consideration, so that the effect is described within any theoretical

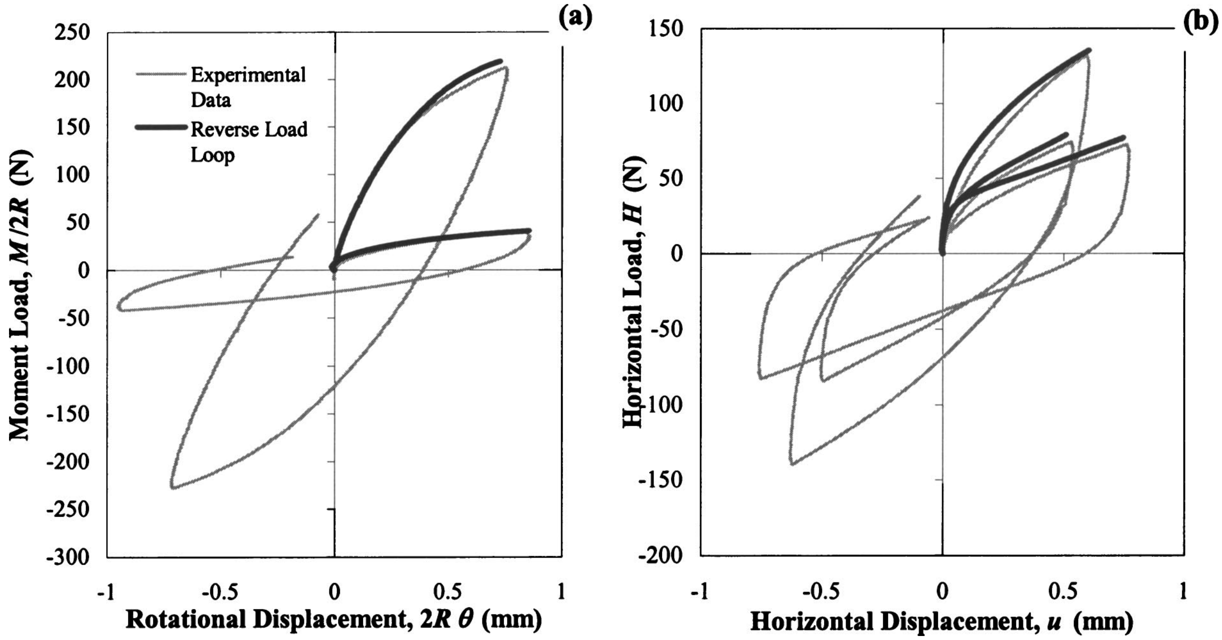

Fig. 13. Comparison of the reverse loading loop with the initial loading for (a) moment loading, and (b) horizontal loading, as a check for Masing behavior

framework developed. Byrne and Houlsby (2002a), using dimensional analysis, postulated the following relationship for vertical loading:

$$w\sqrt{\frac{p_a}{V_m}}=f\left(\frac{V_p}{V_m}\right) \tag{1}$$

where V_m = mean vertical load applied to the foundation; V_p = difference between the peak vertical load and mean vertical load; and w = vertical displacement. This normalization held true provided that the mean load is very small compared to the peak bearing capacity. The reference pressure p_a (conveniently taken as atmospheric pressure) is introduced for dimensional consistency. This relationship appeared to be successful for vertical loading, so it was reasonable to investigate a relationship of this form for combined loading. The most relevant dimensionless group for the load involves division by the ultimate combined load capacity (i.e., M/M_{ult} or H/H_{ult}). It is also useful to express $M_{\mathrm{ult}}/2R$ or H_{ult} as a factor (m_o or h_o) multiplied by the mean vertical load so that, for example, the ultimate moment load is $M_{\mathrm{ult}}=2Rm_oV_m$. Using a similar normalization to vertical loading gives a dimensionless relationship for moment loading (and for horizontal loading) of

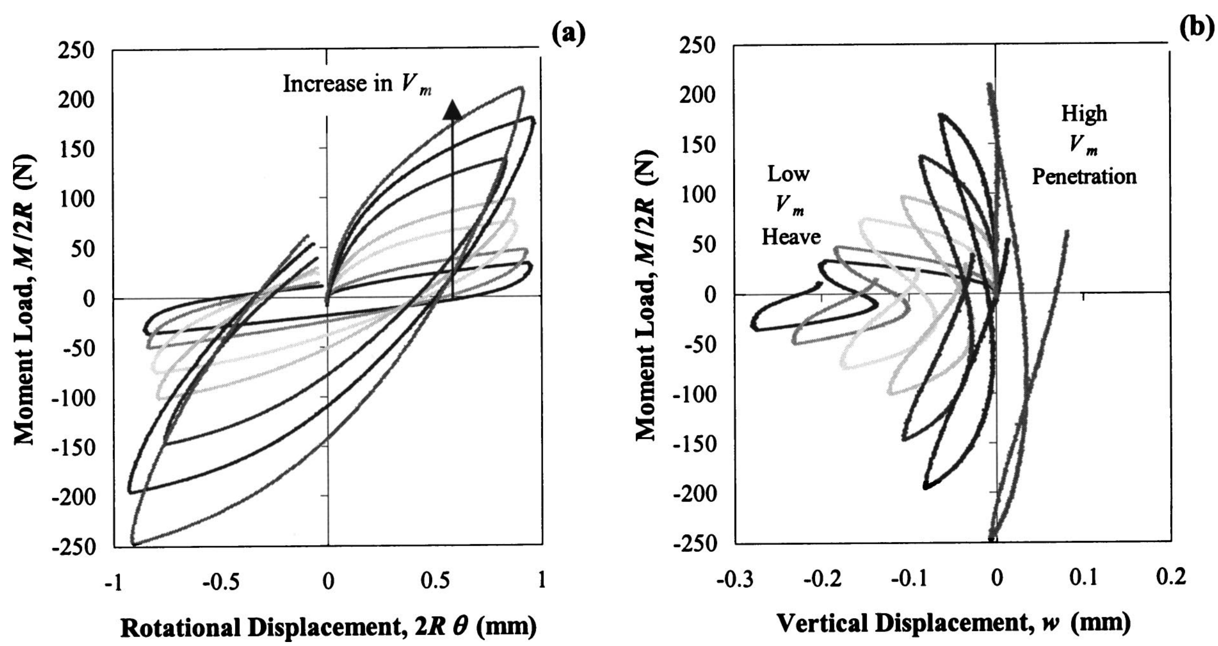

Fig. 14. Results from monotonic moment rotation tests under different constant vertical loads; as the vertical load level increases (a) the stiffness of response increases, and (b) the heave of the footing decreases

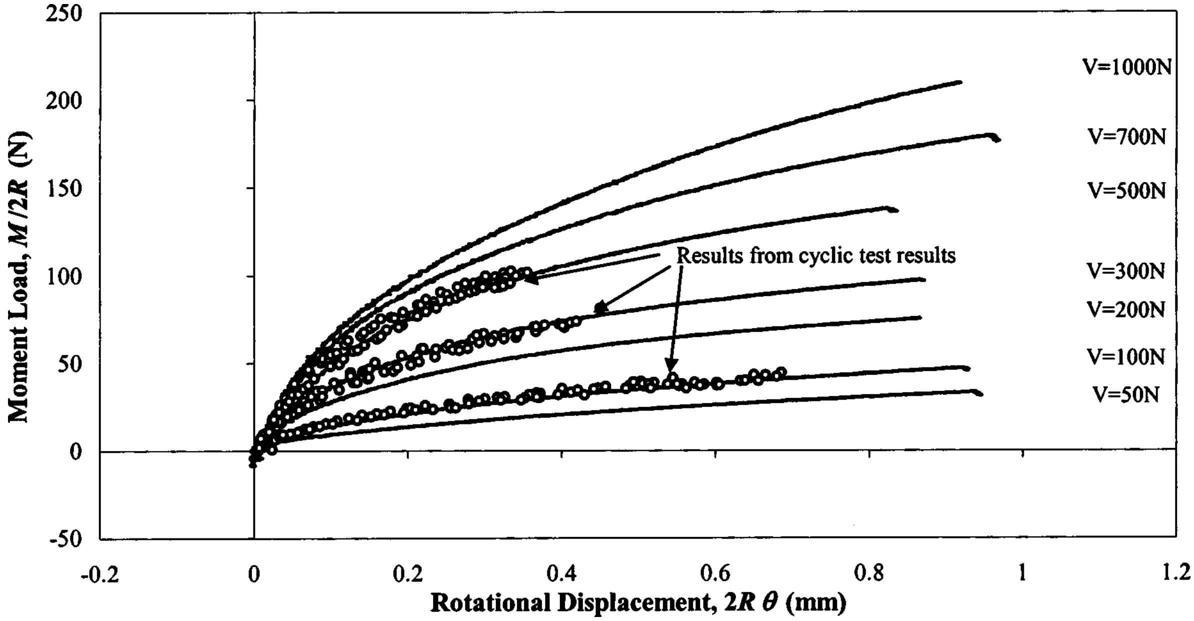

Fig. 15. Results from moment rotation tests at different constant vertical loads comparing to the results from cyclic tests

$$2R\theta\sqrt{\frac{p_a}{V_m}}=f\left(\frac{M}{2Rm_oV_m}\right) \tag{2}$$

$$u\sqrt{\frac{p_a}{V_m}}=f\left(\frac{H}{h_oV_m}\right) \tag{3}$$

The application of these normalizations brings together the results from tests at different stress levels. Fig. 16 shows the normalization applied to several of the monotonic tests shown in Fig. 14. The tests show an almost unique relationship in terms of the dimensionless quantities. A hyperbolic curve of the form:

$$2R\theta\sqrt{\frac{p_a}{V_m}}=\frac{\frac{M}{2Rm_oV_m}\left(1-\left(2-\frac{k_{\text{initial}}}{k_{50}}\right)\frac{M}{2Rm_oV_m}\right)}{k_{\text{initial}}\left(1-\frac{M}{2Rm_oV_m}\right)} \tag{4}$$

has been used to fit a backbone curve to the experimental moment loading data, where k_{initial} and k_{50} = initial stiffness and secant stiffness at 50% stress, respectively. Fig. 16 also shows these normalizations applied to the cyclic loading tests presented in Fig. 15. As for the cyclic vertical loading, the normalization works well and provides a useful basis for the development of a theoretical model for footing response. This understanding simplifies the next stage of experimental study, as it takes into account the effect of mean stress level on response. The scaling applies equally well to the horizontal loading case, as shown in Fig. 17, where a similar hyperbolic curve can be used to fit the data. The values of M_{ult} and H_{ult} for the cases described above are plotted against V_m in Fig. 18. It is clear that m_o and h_o are both close to 1.0 as M_{ult} and H_{ult} are approximately equal to V_m. A possible reason for this is that sections of the outer yield surface, which

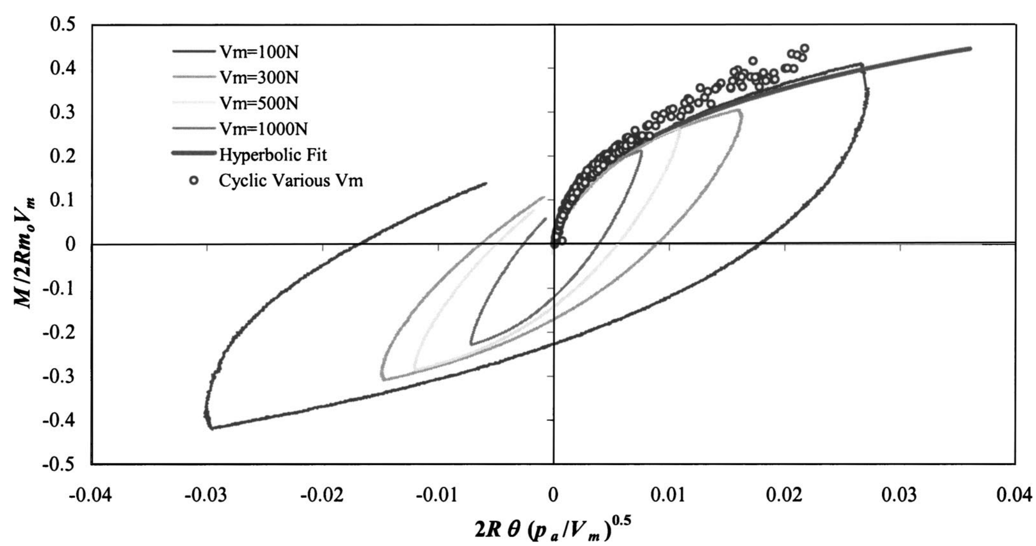

Fig. 16. Results from moment rotation tests at different constant vertical loads compared using an appropriate normalization. A hyperbolic is fitted through the common backbone curve

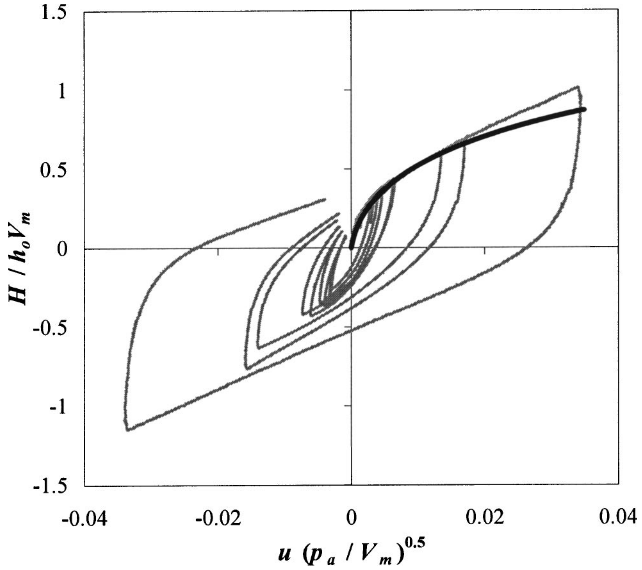

Fig. 17. Similar normalizations work for horizontal loading

bound the ultimate loads at these low vertical loads (compared to the peak bearing capacity), on the $(V,M/2R)$ and (V,H) planes have slopes close to 1.0 near the origin.

New Plasticity Theories

To be of general value 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 behavior of foundations has been found to be plasticity theory, as discussed above. The reasons for this choice are (a) theories can be constructed which reproduce the behavior of the foundations well, (b) they provide predictions for loading conditions which have not been explicitly tested, and (c) the resulting models can readily be included in a numerical analysis of a complete offshore structure.

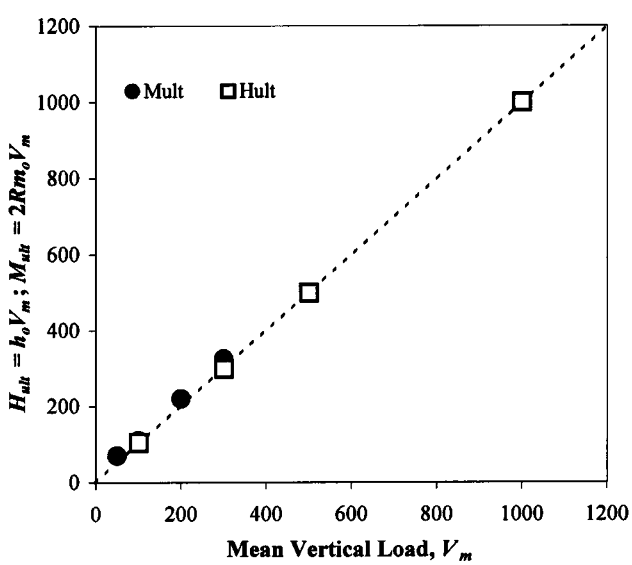

Fig. 18. Comparison of ultimate deviatoric loads to the mean load

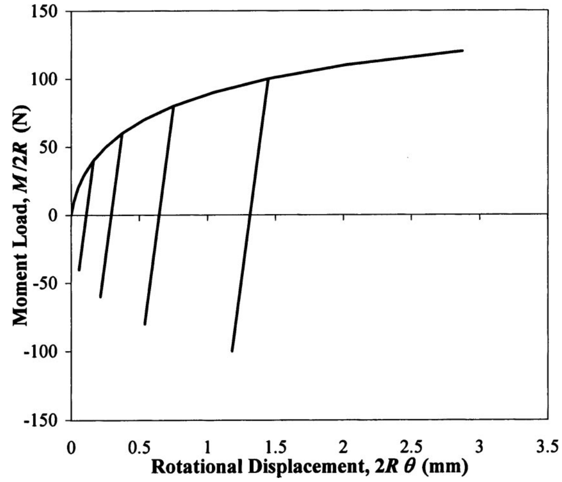

Fig. 19. Typical response from a typical plasticity theory for load reversals

Plasticity theories for slow monotonic loading of foundations have been established such as those given in Martin and Houlsby (2001) for clay or in Houlsby and Cassidy (2002) for sand. A weakness of these models is that they achieve only a poor modeling of cyclic loading tests such as that shown in Fig. 6. A remarkable feature of this experimental result (which is typical of any cyclic horizontal or moment load test on a foundation) is that smooth curves are obtained as the load is cycled. A conventional single-surface plasticity model could not model this type of behavior, but instead would result in well-defined yield points at which a sudden change of stiffness would occur, such as shown in Fig. 19. 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 modeling cyclic loading, but given its proven success for modeling monotonic loading this is excessively pessimistic. A number of approaches have been employed in constitutive modeling of soils to improve the modeling of cyclic loading. "Bounding-surface" methods (Dafalias and Herrman 1986) introduce plastic strains within a bounding surface. While this can provide realistic modeling of large amplitude cycles, these models can exhibit unrealistic behavior for small cycles, and are also unable to capture the detailed effects of recent stress history on the incremental stiffness. The principal alternative is multiple yield surface models (Prevost 1977), which can meet the above objections, and the development described below can be regarded as a development of this concept.

The framework used here to describe cyclic loading is termed "continuous hyperplasticity." A full 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 (2000) and Puzrin and Houlsby (2001a,b).

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. It is, thus, a development of the multiple yield surface concept. The theories are expressed within a manageable mathematical framework by deriving the behavior entirely from two potentials. For the case of the infinite field of plastic strains these potentials are functionals ("functions of functions") of the

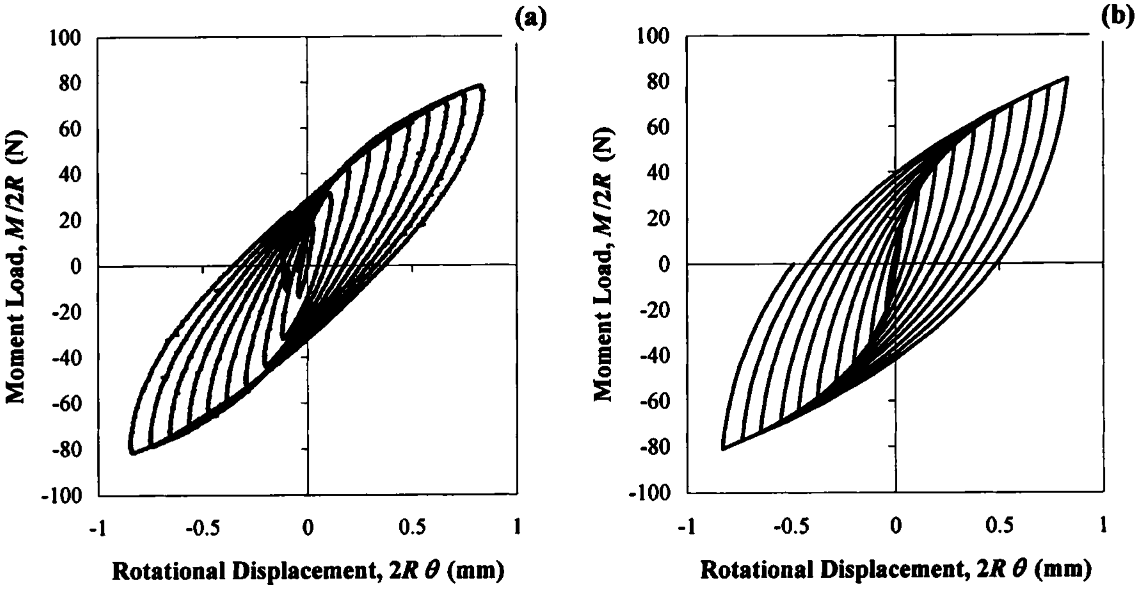

Fig. 20. (a) Experiment carried out where increasing cycles of stress have been applied to the foundation, and (b) the response of the theoretical model to the same cycles of stress

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 Fig. 6 can be modeled. The mathematical structure of the theories is relatively simple although slightly dissimilar from that used in conventional plasticity. For example, Fig. 20(a) 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). Fig. 20(b) shows the fitted response using the continuous hyperplastic model. The actual fitting of the data and mathematical development, within the context of combined loading, is described further by Byrne (2000) and Byrne et al. (2002a). While the fitting is not exact, the model captures the main features of the cyclic test. Only three parameters are required to define the behavior shown in Fig. 20(b), those required to define the hyperbolic backbone curve, m_o, k_{initial}, and k_{50}.

Concluding Comments

This paper has presented selected results from a laboratory testing program aimed at investigating the response of suction caisson foundations to combined loading. It is likely that new applications of this technology, particularly in the renewable energy sector, will seek structural forms where large combined loads are applied to the foundations. It is, therefore, necessary to be able to determine the response of the foundations under these loads so that design calculations can be carried out.

A novel method of developing load time histories was employed during the research to study the transient foundation response under the action of extreme events. It was found that the critical stage of the foundation's life is during the first loading, unless preload has been applied, so that the foundation is working within the elastic region of its yield surface. During this loading, as the yield surface expanded, there was the possibility of effective stress decreases, as volumetric change occurred, and the foundation experienced consolidation behavior. It is clear that during this period drainage should be allowed so that settlement can occur without risk of liquefaction.

A large amount of testing was focused on the response of the foundation at varying levels of working load, and it was found that the response was dependent on the applied vertical load. Dimensional analysis revealed a simple scaling relationship, which could lead to much reduced testing procedures in the future. It will be necessary to observe whether this scaling law is applicable to a larger range of vertical stresses and foundation sizes than were used within this investigation.

Finally, the paper described in outline a theoretical framework that captures the main features of the experimental cyclic tests—that of change in stiffness with strain level and the hysteresis observed on unloading. This model, termed continuous hyperplasticity, represents a significant improvement on conventional plasticity theory, which could not capture this behavior. The model was used to reproduce experimental results, and compared favorably. The combination of the observed scaling relationship and this state-of-the-art theoretical model may lead to a fully generalized footing model. Once fully extended to the three-dimensional load case this framework will enable a much closer representation of the physical reality when used within typical structural analyses programs.

Acknowledgments

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References

Bolton, M. D. (1986). ''The strength and dilatancy of sands.'' *Géotechnique,* 36(1), 65–78.

Bransby, P. L. (1973). ''Cambridge contact stress transducers.'' *Rep. No. CUED/C-SOILS/LN2*, Cambridge Univ. Eng. Dept.

Butterfield, R., and Ticof, J. (1979). ''Design parameters for granular soils.'' *Proc., 7th ECSMFE,* Brighton, 4, 259–261.

Butterfield, R., Houlsby, G. T., and Gottardi, G. (1997). ''Standardised sign conventions and notation for generally loaded foundations.''

Géotechnique, 47(4), 1051–1054; 48(1), 157.
Bye, A., Erbrich, C. T., Rognlien, B., and Tjelta, T. I. (1995). ''Geotechnical design of bucket foundations.'' *Proc., Offshore Technology Conf.*, Houston, Paper No. 7793.
Byrne, B. W. (2000). ''Investigations of suction caissons in dense sand.'' DPhil thesis, Oxford Univ.
Byrne, B. W., and Houlsby, G. T. (1999). ''Drained behaviour of suction caisson foundations in very dense sand.'' *Proc., Offshore Technology Conf.*, Houston, Paper No. 10994.
Byrne, B. W., and Houlsby, G. T. (2001). ''Observations of footing behaviour on loose carbonate sands.'' *Géotechnique,* 51(5), 463–466.
Byrne, B. W., and Houlsby, G. T. (2002a). ''Experimental investigations of the response of suction caisson to vertical transient loading.'' *J. Geotech. Geoenviron. Eng.*, 128(11), 926–939.
Byrne, B. W., and Houlsby, G. T. (2002b). ''Investigating novel foundations for offshore wind turbines.'' *Proc., 21st Int. Conf. on Offshore Mech. and Arctic Eng. (OMAE'02)*, Oslo, Norway, Paper No. OMAE2002-28423.
Byrne, B. W., Houlsby, G. T. and Martin, C. M. (2002a). ''Cyclic loading of shallow foundations on sand.'' *Proc., Int. Conf. on Physical Modeling in Geotech. (ICPMG)*, St John's, Newfoundland, Canada.
Byrne, B. W., Houlsby, G. T., Martin, C. M., and Fish, P. M. (2002b). ''Suction caisson foundations for offshore wind turbines.'' *Wind Eng.,* 26(3), 145–155.
Cassidy, M. J., Byrne, B. W., and Houlsby, G. T. (2002). ''Modelling the behaviour of a circular footing under combined loading on loose carbonate sand.'' *Géotechnique,* 52(10), 705–712.
Collins, I. F., and Houlsby, G. T. (1997). ''Application of thermomechanical principles to the modelling of geotechnical materials.'' *Proc. R. Soc. London, Ser. A,* 453, 1975–2001.
Dafalias, Y. F., and Herrmann, L. R. (1986). ''Bounding surface plasticity. II: Application to isotropic cohesive soils.'' *J. Eng. Mech.*, 112(12), 1263–1291.
Erbrich, C. T., and Tjelta, T. I. (1999). ''Installation of bucket foundations and suction caissons in sand: Geotechnical performance.'' *Proc., Offshore Technol. Conf.,* Houston, Paper No. 10990.
Gottardi, G., and Butterfield, R. (1993). ''On the bearing capacity of surface footings on sand under general planar loads.'' *Soils Found.,* 33(3), 68–79.
Gottardi, G., Houlsby, G. T., and Butterfield, R. (1999). ''The plastic response of circular footings under general planar loading.'' *Géotechnique,* 49(4), 453–470.
Houlsby, G. T., and Byrne, B. W. (2000). ''Suction caisson foundations for offshore wind turbines and anemometer masts.'' *Wind Eng.,* 24(4), 249–255.
Houlsby, G. T., and Cassidy, M. J. (2002). ''A plasticity model for the behaviour of footings on sand under combined loading.'' *Géotechnique,* 52(2), 117–129.
Houlsby, G. T., and Puzrin, A. M. (2000). ''A thermomechanical framework for constitutive models for rate-independent dissipative materials.'' *Int. J. Plast.*, 16(9), 1017–1047.
Lau, C. K. (1988). ''Scale effect in tests on footings.'' PhD thesis, Univ. of Cambridge.
Mangal, J. K. (1999). ''Partially drained loading of shallow foundations on sand.'' DPhil thesis, Oxford Univ.
Martin, C. M. (1994). ''Physical and numerical modelling of offshore foundations under combined load.'' DPhil thesis. Oxford Univ.
Martin, C. M., and Houlsby, G. T. (2000). ''Combined loading of spudcan foundations on clay: Laboratory tests.'' *Géotechnique,* 50(4), 325–338.
Martin, C. M., and Houlsby, G. T. (2001). ''Combined loading of spudcan foundations on clay: Numerical modelling.'' *Géotechnique,* 51(8), 687–700.
Masing, G. (1926). ''Eiganspannungen und Verfestigung beim Messing.'' *Proc., 2nd Int. Congress of Appl. Mech.*, 332–335.
Norwegian Geotechnical Institute (1994). ''Sleipner T—Special laboratory testing.'' *Rep. No. 932514-1*, Norwegian Geotechnical Institute, Oslo, Norway.
Nova, R., and Montrasio, L. (1991). ''Settlements of shallow foundations on sand.'' *Géotechnique,* 41(2), 243–256.
Prevost, J. H. (1977). ''Mathematical modelling of monotonic and cyclic undrained clay behavior.'' *Int. J. Numer. Analyt. Meth. Geomech.*, 1, 195–216.
Puzrin, A. M., and Houlsby, G. T. (2001a). ''A thermomechanical framework for rate-independent dissipative materials with internal functions.'' *Int. J. Plast.,* 17, 1147–1165.
Puzrin, A. M., and Houlsby, G. T. (2001b). ''Fundamentals of kinematic hardening hyperplasticity.'' *Int. J. Solids Struct.,* 38(21), 3771–3794.
Pyke, R. (1979). ''Nonlinear soil models for irregular cyclic loadings.'' *J. Geotech. Eng. Div., Am. Soc. Civ. Eng.,* 105(6), 715–726.
Roscoe, K. H., and Schofield, A. N. (1957). ''The stability of short pier foundations on sand: Discussion'' *Br. Weld. J.*, January, 12–18.
Tan, F. S. C. (1990). ''Centrifuge and numerical modeling of conical footings on sand.'' PhD thesis, Cambridge Univ.
Taylor, P. H., Jonathan, P., and Harland, L. A. (1995). ''Time domain simulation of jack-up dynamics with the extremes of a Gaussian process.'' *Proc., Conf. on Offshore Mech. and Arctic Eng.*, 1A, 313–319.
Vucetic, M. (1990). ''Normalized behavior of clay under irregular cyclic loading.'' *Can. Geotech. J.,* 27, 29–46.
Vucetic, M., and Dobry, R. (1988). ''Degradation of marine clays under cyclic loading.'' *J. Geotech. Eng.,* 114(2), 133–149.