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Experimental Investigation of a Model Jack-Up Unit on Clay

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ABSTRACT

Offshore jack-up units are primarily used in relatively shallow water depths as hydrocarbon exploration units. In recent times, the offshore industry has considered extending their use to deeper waters and for longer durations as production platforms. The severe conditions experienced by these units necessitate a comprehensive understanding of the overall jack-up behaviour, particularly soil–structure interaction and load sharing among the spudcan footings.

Previous experimental studies of soil–structure interaction have generally been performed with single spudcan footings This paper presents results from a series of 1-g experiments conducted on a scaled three-legged jack-up unit model, equipped with spudcan footings, on soft clay. The model rig is subjected to combined vertical and horizontal loads at the hull level, resulting in combined vertical, moment and horizontal loads at the footings. The physical tests explore the load redistribution among the spudcan footings, hull and footing displacements at failure, and ultimate system capacity. Experimental observation of rotational footing fixity is also emphasized.

KEY WORDS: Jack-up, spudcan, soil–structure interaction, model tests.

INTRODUCTION

Jack-up platforms have been utilised in the offshore hydrocarbon industry since the mid 1950s as exploratory and maintenance units. They are typically temporary structures used in water depths up to 120 metres. Constructed to be mobile and for ease of installation, today a typical jack-up consists of three independent latticework legs, a triangular hull and 'spudcan' footings as foundations. Spudcans are usually roughly circular in plan, with a shallow conical underside and often a sharp protruding spigot.

The platform is transported to site floating on its hull with its legs elevated out of the water. On site the jack-up is positioned by lowering the legs onto the seabed and then slowly jacking the hull off the water surface. The spudcans penetrate under the self-weight of the jack-up unit until equilibrium with the soil is reached. By pumping seawater into ballast tanks located within the hull section further penetration is achieved, increasing the bearing resistance. This preloading attempts to expose the soil to higher levels of vertical stress than those that would be expected during an extreme storm event. The water is removed once the maximum preload is achieved, and the platform ascends the trussed legs to its operational height. The preload applied to the foundations is usually around twice the operational weight (this ratio will be used in the physical experiments described in this paper).

In a perfectly calm sea, vertical self-weight is the only loading on the spudcans. During a storm, however, environmental wind and wave forces impose additional horizontal (H) and moment loads (M) on the foundations of the jack-up, as well as altering the vertical loads (V). An understanding of spudcan performance under these combined load (V, M, and H) conditions is essential to the analysis of jack-up response. However, the modelling of jack-ups (whether physical or numerical) is challenging due to the interaction between complex systems of soil, structure and loading. Adequate modelling requires not only an understanding of individual components, such as the interaction of spudcan footings with soil, but an understanding of the complete system. This paper aims to add to that understanding.

Most of the research conducted on the behaviour of spudcans has been performed using single model footings. Santa Maria (1988) and Martin (1994) have carried out combined loading tests on single spudcans on clay, whilst Shi (1988), Tan (1990) and Gottardi *et al.* (1999) have performed similar experiments on sand. There has, however, been some research into the overall behaviour of complete three-legged jack-up units on sand, including Tsukamoto (1994), Dean *et al.* (1997) and Murff *et al.* (1991). The experiments to be conducted using the model jack-up described in this paper will concentrate on jack-up behaviour on soft clay.

This paper presents results from a preliminary series of unit gravity experiments. A diagram of the experimental set-up is shown in Figure 1, with a more detail description given in a section below.

EXPERIMENTAL AIMS

The aim of the experiments is to investigate the overall behaviour of the rig, but specifically the load sharing between the three independent legs. By using both weights and a horizontal actuator, the model rig is subjected to a combination of vertical and horizontal loads at the hull level (simulating an environmental loading situation). The resulting vertical, moment and horizontal loads on the measured The data obtained through these tests will give some indication of the amount of rotational foundation fixity that spudcan footings on clay can provide. This issue has been the subject of much interest in recent years. This is because if some foundation fixity is taken into account, member stresses at the leg–hull connection and other response values critical to the structural integrity of the jack-up are reduced (Chiba *et al.*, 1986).

The long-term aim is to use the scaled rig described in this paper to refine existing work-hardening plasticity models that describe the combined load–displacement behaviour of spudcans on various soils. This will allow direct numerical simulation of the present model tests and evaluation of a suitable plasticity-based spudcan footing model. While this is beyond the scope of this paper, some of the experimental results will be examined within the framework of work-hardening plasticity.

EXPERIMENTAL APPARATUS

Three-legged Model Jack-up Unit

A scale model jack-up unit for testing at unit gravity has been designed and assembled at the University of Western Australia. The dimensions of the scaled model were based on information from the Friede & Goldman (1998) web site, as summarised in Prior (1999). Various sizes were considered, however, due to physical constraints a 1:250 scaled version has been built. Table 1 shows the chosen prototype and model jack-up dimensions. The legs have been constructed from stainless steel with a Young's modulus E of 193000 MPa and a shear modulus G of 80000 MPa.

Table 1 – Jack-Up Model Dimensions (after Prior, 1999)

MODEL CHARACTERISTICS	PROTOTYPE	1:250 SCALED MODEL	BUILT MODEL
Leg Length, Full and Partial	150, 50 m	600, 200 mm	600, 200 mm
Spudcan Diameter	18 m	72 mm	72 mm
Centre to Centre of Aft Leg Separation (measured from centre of legs)	51 m	204 mm	216 mm
Aft and Forward Leg Separation (measured from centreline of legs)	45 m	180 mm	187 mm
Depth of Hull	10 m	40 mm	40 mm
Breadth of Hull	78 m	312 mm	324 mm
Length of Hull	70 m	280 mm	280 mm
Second Moment of Area of Leg	7.2 m^4	1843.2 mm^4	1892 mm
Cross-sectional Area of Leg	1 m^2	16 mm^2	73.8 mm

Other characteristics of the model rig include:

- Two sets of tubular legs have been built. They have identical properties except for their lengths, with one set 600 mm long and the other 200 mm long. The results presented in this paper were obtained using the longer legs.
- The second moment of area of the legs is similar to that of the scaled prototype, however, the cross-sectional area has been distorted. This is one of the limitations of testing small scale models, where accuracy of one property often means forfeit of another. As flexural bending of the legs is more significant than the secondary shear effect (Skoglund, 1967; Dean *et al.*, 1997), the decision to scale the second moment of area is believed to be justified.
- The legs are bolted to the underside of the hull, creating a rigid connection. Although the non-linearities caused by the jack-house are recognised as significant (Grundlehner, 1989) they have not been modelled.
- As the hull is constructed from a solid aluminium block, the hollow ballast tanks of a real jack-up have also not been modelled.

The three independent legs have been instrumented at two locations: 40 mm below the leg–hull connection, and 40 mm above the spudcan footings. The upper gauges register only bending while the lower gauges measure both bending and axial loads. From these readings, the vertical, moment and shear stress resultants at any position in a leg can be deduced using simple beam theory. This includes the critical bending moments at the leg–hull connection and also all the spudcan reactions.

The vertical and horizontal displacements and the rotation of each spudcan footing are recorded, in addition to the hull displacement and rotation measurements. Two linear potentiometers (one vertical and one horizontal) and one tilt sensor are located at each spudcan footing and another set is attached to the hull. Direct attachment of the displacement sensors to the spudcans is impractical, considering the large embedment of the footing. Therefore, a 'sensor holder' connects the spudcan footing to the potentiometers and tilt sensors as shown in Figure 1.

The loads applied to the spudcan footings (V, M and H) and the corresponding displacements (w, θ, and u) are calculated as those at the Load Reference Point (L.R.P.), as shown in Figure 2. The sign convention adopted is that recommended by Butterfield *et al.* (1999), and this is also depicted in Figure 2.

The overall size of the three-legged jack-up model restricts testing to one site per clay sample. The vessel walls are at least 2 spudcan diameters away from the edge of any footing, and the base is approximately 2.5 diameters below the spudcan tips during a test.[1] This minimises possible interference from the boundaries, as well as allowing the soil characterisation tests to be performed in undisturbed areas of the sample (see the site plan shown in Figure 1).

Sample Preparation

As only one jack-up test can be performed in each sample, a method has been developed to prepare a consistent sample with an undrained shear strength (s_u) of 10 kPa at a depth of one spudcan diameter. Key properties of the kaolin clay used are shown in Table 2, and the method employed is as follows:

Table 2 – Kaolin Clay Properties (after Stewart, 1991)

PROPERTY	VALUE
Liquid Limit, LL	61 %
Plastic Limit, PL	27 %
Plasticity Index, I_p	34 %
Specific Gravity, G_s	2.60
Angle of Internal Friction, ϕ'	23°
Consolidation Coefficient (mean), c_v	2 m^2/year
Submerged Unit Weight of Soil, γ'	6.82 kN/m^3

Step 1 – Mixing: Kaolin powder is mixed with water to a slurry of 120% moisture content, approximately twice the liquid limit, and placed in a conventional barrel mixer (de-aired under a 100 kPa vacuum) for 4 hours.

[1] Other researchers have had narrower tolerances on their footing-to-wall space ratio (Santa Maria, 1988; Martin, 1994; Tsukamoto, 1994).

Step 2 – Consolidation: The slurry is then pumped into duraluminium consolidation tanks of 600 mm internal diameter. To ensure that no air is entrapped during this placement, the slurry is pumped under a water layer of 100 mm.

The consolidation pressure is applied in steps, from 25 to 75 and then to a maximum of 110 kPa. The increments are applied once the rate of consolidation falls below 1 mm/h. During the final pressure increment, primary consolidation is considered to have been achieved when the rate drops to 0.1 mm/h. The sample is then unloaded to 75 and 25 kPa, and finally to atmospheric pressure. An initial slurry height of 500 mm is required to achieve the desired sample depth of between 270 and 280 mm. The total time required for this consolidation is two and a half weeks. Geo-fabric drainage mats are used at the top and bottom of the specimen to allow two-way drainage at all times.

Step 3 – Swelling: The sample is then left to swell for 2 days before testing commences. This is to ensure that the required undrained shear strength of 10 kPa at one diameter depth is achieved[2], and to ensure that the strength remains reasonably constant over the course of a test. As typical tests last 2-3 hours, this latter requirement is seen as important. A 5 mm layer of water covers the sample during swelling (and testing). Clearly this method produces heavily overconsolidated samples of soft clay, whereas offshore deposits are more often normally consolidated.

EXPERIMENTAL METHODOLOGY

Each test is separated into two distinct stages (refer to Figure 1):

Stage 1 – Installation: A mild steel reaction frame is securely bolted onto the sample tank. A vertical actuator is placed on top of the reaction frame, which holds the jack-up model above the soil surface (with the spigots just touching the surface). All strain gauges are then zeroed and the logging program commences. The jack-up unit is lowered at a constant rate of 1.5 mm/s. This speed ensures undrained conditions according to the expression recommended by Finnie (1993):

$$\frac{vD}{c_v} > 30 \quad \text{(for undrained conditions)} \qquad \text{(Eqn 1)}$$

where v is the velocity, D the diameter of the footing and c_v the consolidation coefficient.

When a penetration of one diameter is reached the unit is then unloaded (at a slower speed of 0.5 mm/s) to approximately 20% of the maximum load achieved during penetration. The vertical actuator is removed and weights are then placed onto the jack-up, re-loading the unit to the target preload level ($V/V_{preload} \approx 0.5$).[3]

During installation the legs are prevented from splaying by the use of a central column that connects to the legs at 75% of their length from the hull. Once the installation is completed the central column is removed. Following the preload the displacement sensors are connected to each footing. The actuator is moved to a horizontal position, ready to apply the monotonic pushover load to the side of the hull *via* a loading arm that is pinned at both ends, with a load cell at its midpoint. This arrangement of equipment between the two stages occupies the majority of the testing time.

Stage 2 – Pushover: Horizontal displacement is applied at a constant rate of 0.75 mm/s. The pushover test is terminated when the applied horizontal load has clearly reached an ultimate value, or when one of the displacement sensors has run out of length.

Once the pushover has finished, to assess behaviour in remoulded clay, several additional pushovers are performed back and forth, though these results are not discussed in this paper. Only then is the jack-up pulled out of the clay and all zeroes checked.

EXPERIMENTAL RESULTS

The results presented in this paper are for two different loading configurations, which were tested on two different samples. The first results were obtained for a jack-up orientation of two legs to windward and one leg to leeward; this test was called *JUP-3*. A second configuration with one leg to windward and two legs to leeward was tested to allow comparison between the two different environmental loading directions; this test was named *JUP-4*. Figure 1 shows the site plan and pushover directions.

Soil Profile

Soil characterisation tests were undertaken using a T-bar penetrometer[4] of projected area 100 mm^2, both before installation of the jack-up unit and immediately after completion of the pushover test. Assuming a bearing capacity factor of $N_{tbar} = 10.5$, Figure 3(a) shows the interpreted strength profile for test *JUP-3*.[5] Due to the separation in time between the T-bar tests, a clear gap is visible between the profiles as a result of the additional swelling. For instance, at a depth of 70 mm a 10.5% loss in strength was recorded. The undrained shear strength profiles for the second experiment, *JUP-4*, are shown in Figure 3(b) with the corresponding loss for this sample at a depth of 70 mm being 3.2%.

The average undrained soil profile for each sample was obtained by using the semi-empirical expression (Ladd *et al.* 1977, Wroth 1984):

$$\frac{s_u}{\sigma'_v} = A(OCR)^B \qquad \text{(Eqn 2)}$$

Theoretically the parameters A and B represent the undrained strength ratio for a normally consolidated soil and the plastic volumetric strain ratio in the Cam-Clay constitutive model. Here, however, they are simply used to fit the experimental T-bar results. The best fit for *JUP-3* was obtained when $A = 0.331$ and $B = 0.741$, and for *JUP-4* when $A = 0.337$ and $B = 0.747$, as shown in Figures 3(a) and 3(b).

Installation Test JUP-3 (Stage 1)

During installation the vertical load–displacement relationship for each spudcan was obtained, as shown in Figure 4. Since the vertical displacement is defined as zero when the L.R.P. is at the undisturbed soil surface level (see Figure 2), until this point is reached a negative vertical displacement is recorded and the contact area is less than that for a fully penetrated spudcan. Figure 4 shows each footing reaction increasing rapidly once the spigot is fully embedded and a larger spudcan area is in contact with the soil. Once the spudcan's L.R.P. arrives at the level of the undisturbed surface (and the maximum contact area is reached) the load increases at a lesser rate, basically reflecting the increase of strength with depth. All three spudcan footings exhibit similar behaviour, indicative of a spatially consistent sample and an equal distribution of the applied vertical load to the legs and footings.

[2] The 2-day swelling period was determined after a series of strength profile tests were conducted on 6 samples, from load removal to 4 or 5 days later.

[3] As shown in Figure 1, the weights are placed on top of the hull applying a load through the jack-up's centre of mass.

[4] The T-bar device has been widely accepted as an accurate means of deducing shear strength profiles for soft cohesive soils (Stewart & Randolph, 1991; Randolph *et al.*, 1998; Watson, 1999).

[5] This N_{tbar} value has had extensive experimental validation (Stewart & Randolph, 1991; Watson, 1999).

As a comparison, the vertical load Q obtained by using Skempton's bearing capacity factor:

$$Q = N_c s_{u(aver)} * \frac{\pi D^2}{4} \qquad \text{(Eqn 3)}$$

has also been shown in Figure 4 for $w \geq 0$. The bearing capacity factor N_c is defined as:

$$N_c = 6 + 1.2 * \left(\frac{w}{D}\right) \leq 9 \qquad \text{(Eqn 4)}$$

where w is the vertical penetration of the widest cross-section, D is the diameter of the spudcan at the widest cross-section and $s_{u(aver)}$ the average undrained shear strength over half a diameter below the widest cross-section, as recommended by Young *et al.* (1984).

Skempton's bearing capacity equation is widely used in the offshore industry and is recommended in SNAME (1994). For most of the penetration Skempton's equation underpredicts the strength profile, however, it accurately predicts the spudcan pressure after one diameter penetration (w = 72 mm), when the strength profile becomes more uniform with depth.

In Equation 3 the additional contribution of overburden pressure to the vertical load capacity of an embedded spudcan has been neglected, since the weight of soil is insignificant in a 1-g model test. Furthermore, no back-flow occurs during the lab floor model testing. This is a phenomenon often encountered in soft soils at field scale, and its effect is to reduce the net vertical bearing capacity of the spudcans (Martin & Houlsby, 2000).

Pushover Test JUP-3: Two Legs Windward – One Leg Leeward (Stage 2)

As previously discussed, the vertical load for the beginning of the pushover was targeted to be half of the preload. Table 3 shows, for each spudcan, the maximum vertical load experienced during installation, the vertical load at the start of the pushover, and their ratio.

Table 3 – Vertical Load Levels for *JUP-3* Spudcans

SPUDCAN	$V_{preload}$ (N)	V (N)	$V/V_{preload}$
Windward Leg1	356	178	0.50
Windward Leg2	344	186	0.54
Leeward Leg3	359	187	0.52

Load Sharing Between Footings During Pushover

In the pushover stage, a monotonic horizontal load is applied at the hull level of the jack-up model. The combined load variation experienced by the footings during the pushover is shown in Figure 5. As the applied horizontal load is increased each windward footing experiences a loss of vertical load, and the leeward footing gains vertical load at twice the rate (to maintain vertical equilibrium). However, the opposite occurs with the horizontal and moment loads, where the leeward footing gradually sheds load to the windward spudcans.

Initially, all of the spudcan footings develop similar moment reactions under the applied loading. This is best seen in the moment paths of Figure 5 when the applied load is less than about 10 N. If thought of within the context of plasticity theory, these loading increments would be modelled as elastic (or entirely within a theoretical yield surface in V, M and H space). However, as the load paths are different (for roughly the same M and H, the leeward footing has increasing V whereas the windward footings have decreasing V) the behaviour is not the same once 'yield' has occurred. After about 10 N, Figure 5 indicates a quick loss of moment capacity at the leeward footing (though the vertical load continues to increase). At the same time, the horizontal load-carrying capacity of the leeward footing also decreases, an effect which accelerates as the test proceeds. Interestingly, while the windward footings indicate some softening in the moment response, no definite peak is detectable. Instead, the moment loads on the windward footings continue to increase, along with a steady increase in horizontal capacity throughout the pushover. This was also observed in a similar test by Prior (1999).

Displacement Paths Followed by Spudcan Footing

The vertical and horizontal displacements and the rotations of the spudcans are shown in Figure 6.[6] The leeward footing penetrates further into the soil as a result of the vertical load transfer during the pushover, whereas the windward footings show a small amount of heave. Figure 6 indicates minimal horizontal movement in the windward footings, and, after around 60 N of applied horizontal load, movement backwards is even recorded. This coincides with an acceleration in the windward moment curves shown in Figure 5, and could imply splaying of the legs. Lateral sliding of the single leeward spudcan also starts becoming noticeable from around 60 N onwards. Figure 6 shows similar spudcan rotations for both leeward and windward footings during the pushover, however, the moment–rotation responses are very different.

A clearer indication of the moment–rotation response can be seen in Figure 7. A stiff initial elastic response is visible for both footings up to around M/D = 9 N, with the leeward footing peaking at M/D = 11.8 N. The corresponding rotation (θ) at this peak is 0.11°. However, the windward footings do not show a distinct maximum value, but rather exhibit a gradual softening. A moment load M/D of 18.8 N is reached at θ = 0.11°, approximately 40% greater than the corresponding leeward footing moment. It is interesting to note that once the peak moment is reached in the leeward footing, complete loss of resistance to rotation eventually occurs and the footing acts like a pinned connection (at least as far as the rotational degree of freedom is concerned).

The reduction of rotational fixity provided by the footings during the pushover is shown in Figure 8, where the degree of fixity is measured by the ratio

$$\frac{M_{Leg-Hull}}{H_{L.R.P.} \times L} \qquad \text{(Eqn 5)}$$

$M_{Leg\text{–}Hull}$ is the moment at the leg–hull connection (or top of the leg), $H_{L.R.P.}$ the horizontal reaction at the L.R.P. of the spudcan and L the leg length. Using this definition, a value of 1 indicates pinned footings (no rotational restraint) and a value of 0.5 represents fully fixed footings (infinite rotational restraint). Figure 8 supports the argument that fixity of the windward footings is still present even at failure of the system, while the leeward footing approaches the pinned condition.

Recorded Hull Displacements

The displacements at the centre of the hull section during the horizontal pushover are depicted in Figure 9. The criteria for

[6] It should be noted that windward footing 1 displacements are omitted from Figures 6 and 7 due to tilt sensor problems. This causes errors in the calculation of not only the spudcan rotation but all of the displacements at the L.R.P. However, as the load paths and the degree of fixity were similar to windward footing 2 it could be expected that the displacement paths would be as well.

terminating the pushover can be more easily observed here, where eventually there is increasing horizontal hull displacement without any increase in applied horizontal load. This plateau at approximately 75.3 N indicates failure of the combined soil–structure system. At the outset of the load application, the unit resists any rotation and vertical settlement, however, the vertical displacement of the leeward footing finally causes the hull to settle and rotate.

Importance of Rig Orientation (Comparison of JUP-3 with JUP-4)

In order to highlight the directional effect of the environmental load on the jack-up unit, a second configuration, named *JUP-4*, was tested with one windward footing and two leeward footings. The comparison between tests *JUP-3* and *JUP-4* presented here concentrates on the spudcan load paths. As previously noted, *JUP-4* was conducted using a sample with a slightly different undrained shear strength profile (Figure 3(b)). Therefore, to allow direct comparisons between the tests all loads (*V*, *M/D* and *H*) have been normalised by the maximum preload value ($V_{preload}$) experienced by each footing during installation. Table 4 gives the vertical preload level and the vertical load at the start of pushover for all of the spudcans in test *JUP-4*.

Table 4 – Vertical Load Levels for *JUP-4* Spudcans

SPUDCAN	$V_{preload}$ (N)	V (N)	$V/V_{preload}$
Leeward Leg1	294	153	0.52
Leeward Leg2	319	131	0.41
Windward Leg3	290	174	0.60

The lower $V_{preload}$ levels of *JUP-4* can be attributed to stopping the penetration and unloading at 50 mm (as opposed to 72 mm in *JUP-3*). The uneven load distribution between the spudcans is the result of a slight initial tilting of the jack-up unit, and to a lesser extent the non-uniformity of the sample.

Despite its significantly smaller preload, the maximum pushover load *JUP-4* withstood was approximately 97.4 N, compared with *JUP-3*'s 75.3 N. The normalised horizontal–vertical and moment–vertical load planes will be used to highlight the experimental results. Furthermore, the degradation of rotational fixity during the pushover test will be discussed.

Horizontal and Vertical Load Paths

Figures 10(a) and 10(b) show the normalised horizontal–vertical load paths of the spudcan footings in *JUP-3* and *JUP-4* respectively. As expected, vertical load transfer from the windward to leeward footing(s) is seen in both tests. However, the footing(s) taking a larger share of horizontal load changes with orientation. It is shown in Figure 10 that in the single footing to leeward case (*JUP-3*), the horizontal load taken by the leeward footing drops off (also shown in Figure 5). In the single footing to windward case (*JUP-4*), the leeward footings are now the ones subjected to larger horizontal loads. Another interesting observation is that in *JUP-4* significant tensile capacity is mobilized at the windward footing. This effect could improve the ultimate design capacity of the jack-up, if proven to be reliable, although it would offer no benefit for the (more onerous) single leg to leeward orientation.

Moment and Vertical Load Paths

In the normalised moment–vertical load plane of Figures 11(a) and 11(b), for *JUP-3* and *JUP-4* respectively, there is a similar redistribution of load among the footings. Figure 11(a) shows that for the single leeward leg, the footing gradually yields as it gains vertical load and reduces its moment load. However, the moment-carrying capacity is sustained in the windward footings, even after initial yielding (as discussed previously with reference to Fig. 5).

All footings in Figure 11(b), however, exhibit distinct maximum values followed by post-yield softening. In this case the single windward spudcan loses the ability to resist moment load, which reduces to nearly zero (in the tensile vertical load range). Again, the leeward footings exhibit a reduction in moment-carrying capacity with increasing vertical load. However, at jack-up 'collapse' the two leeward footings both have larger moment reactions than the single windward footing.[7]

The curves in Figures 10 and 11 initially display a degree of linear elastic behaviour, followed by yielding. This is consistent with the hypothesis of an elastic core within a *V*, *M*, *H* yield surface. However, yielding takes place gradually and there is no clear indication as to where first yield occurs, particularly in Figure 10. Evidently a rather complex plasticity model, possibly with multiple yield surfaces, will be required to capture this behaviour in detail.

Rotational Fixity

All *JUP-4* footings suffer a loss of rotational fixity as the pushover proceeds. This is shown in Figure 12, again using the ratio $M_{Leg-Hull}/(H_{L.R.P} \times L)$, with all footings approaching the pinned condition (*i.e.* a ratio of 1.0). This is in contrast to Figure 8, where the windward footings in *JUP-3* still retain significant rotational stiffness at the conclusion of the pushover.

CONCLUSIONS

This paper has presented the results from preliminary experiments on a 1:250 scale model jack-up unit with spudcan footings on soft clay. The jack-up has been instrumented so that when loads are applied at the hull the moment, shear and axial forces in the legs, and hence the spudcan reactions, can be recorded. The displacement and rotation of the footings and the hull can also be measured.

Monotonic pushover tests allow the examination of complex soil–structure interaction processes, and specifically the degree of rotational fixity provided by the spudcans. In this paper, preliminary results have been presented for two different jack-up orientations. These show markedly different behaviour with regard to load redistribution between footings, and the loss of rotational restraint after initial yielding of the soil has occurred. In terms of the ultimate lateral capacity for a given preload ratio, the single leg to leeward orientation would appear to be more critical than single leg to windward. In the latter case, the development of a tensile vertical reaction at the windward footing plays a crucial role in providing the increased capacity. It is interesting to note, however, that most of the available numerical models and design guidelines (conservatively) disallow tensile vertical loading of a spudcan on clay.

The main series of monotonic pushover tests to be performed with the model jack-up unit will examine factors such as different preload levels, skewed loading (not along an axis of symmetry), and different foundation types. A series of cyclic loading tests is also under preparation. Numerical simulations of the experimental work will be conducted using an existing work-hardening plasticity model of

[7] The values for the leeward footing 2 of *JUP-4* are spurious in the late stages of the test (last 30 points). One of the displacement sensors indicated 'sharp' movements, possibly because the potentiometer was touching (and possibly stuck) against its support. However, the displacement sensors on leeward footing 1 did not indicate such a problem and therefore can be assumed to be behaving normally.

spudcan behaviour, which has been incorporated as a user element into the finite element program ABAQUS. The aims of the numerical work are (i) to investigate the suitability of such models for predicting jack-up capacity and behaviour; (ii) to enhance existing models to account for cyclic loading conditions.

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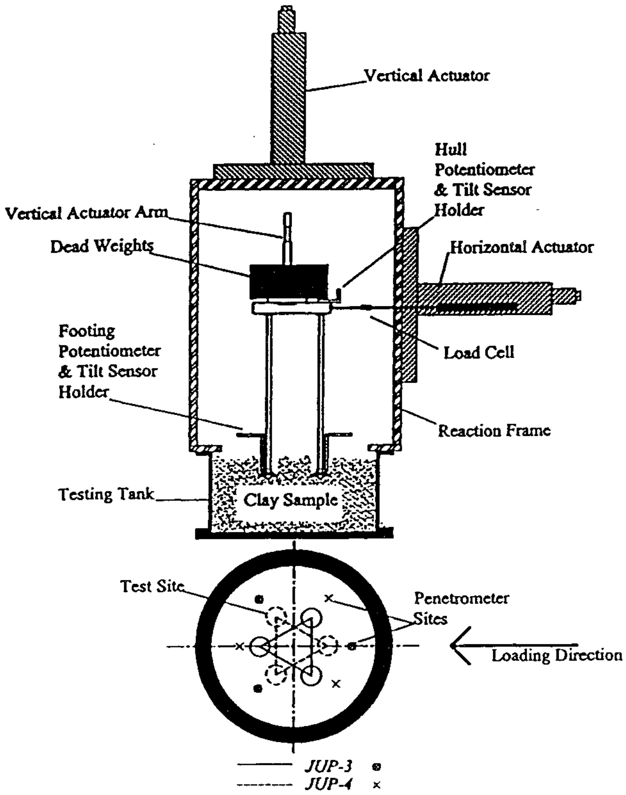

Figure 1 - Test Configuration and Site Plan

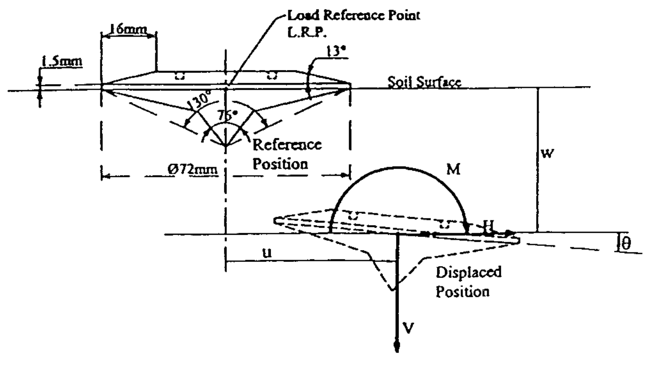

Figure 2 - Spudcan Profile and Sign Convention for Spudcan Loads and Displacements

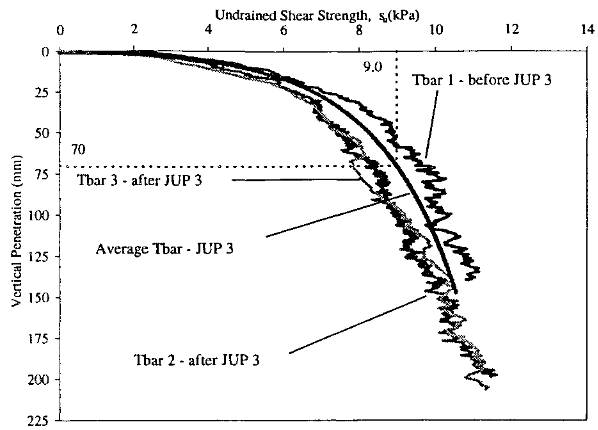

Figure 3(a) - Soil Profile for *JUP-3*

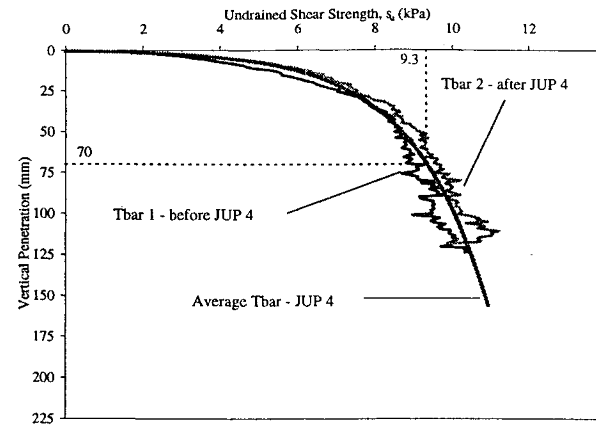

Figure 3(b) - Soil Profile for *JUP-4*

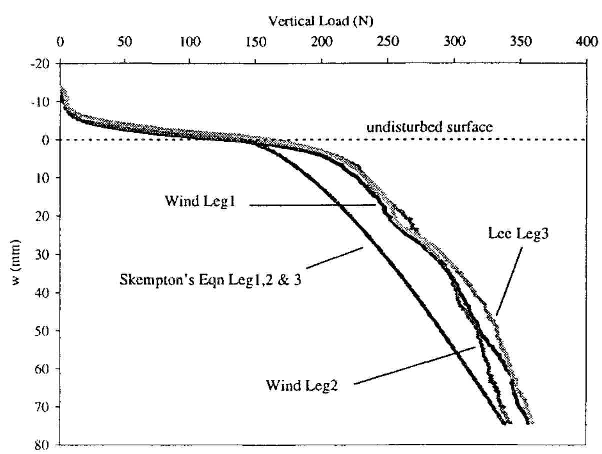

Figure 4 - Installation Load of Spudcan Footings (*JUP-3*)

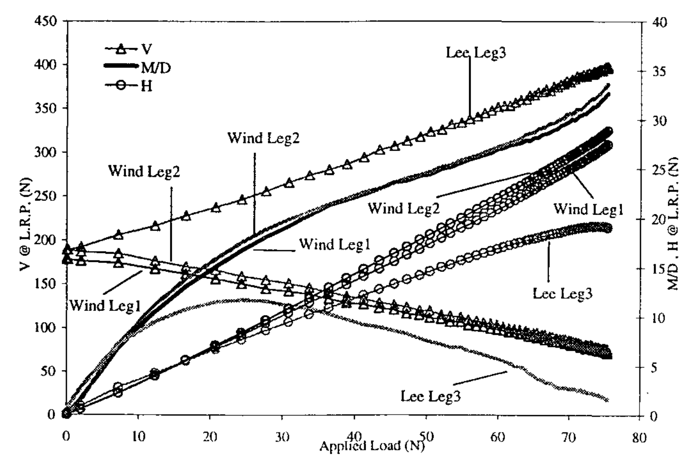

Figure 5 - Load Sharing Among Spudcans during Pushover (*JUP-3*)

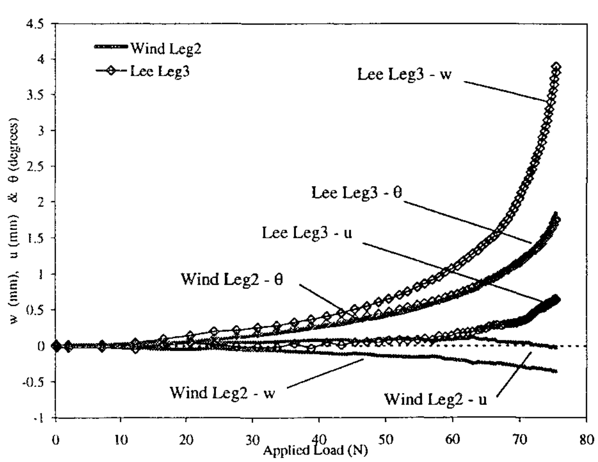

Figure 6 - Spudcan Displacements during Experiment *JUP-3*

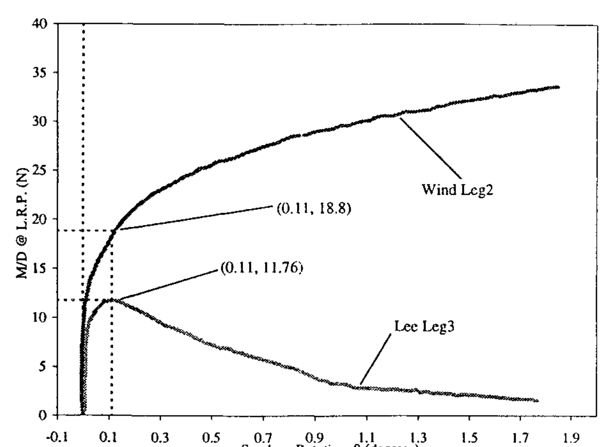

Figure 7 - Moment - Rotation Response of Spudcan Footings for *JUP-3*

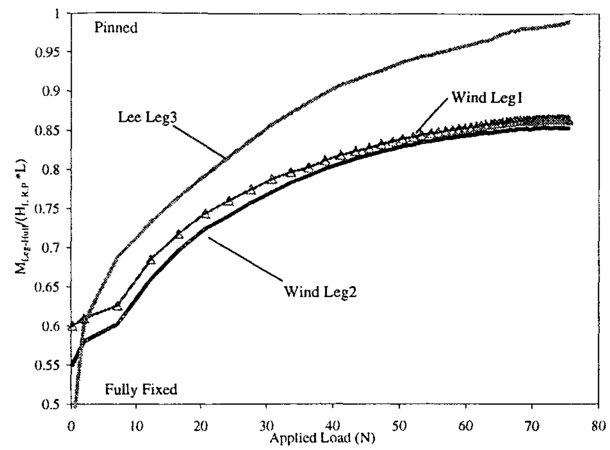

Figure 8 - Rotational Fixity of Spudcans during Experiment *JUP-3*

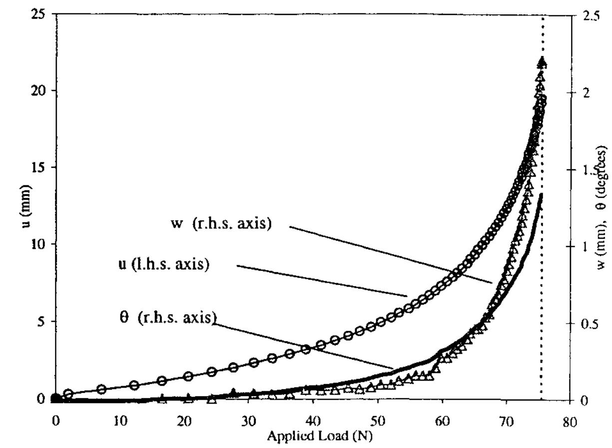

Figure 9 - Hull Displacements during Experiment *JUP-3*

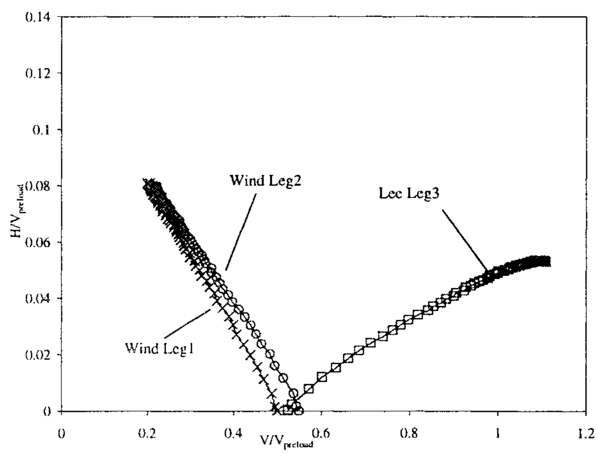

Figure 10(a) - Horizontal and Vertical Loadpaths (normalised by the individual spudcan preload) during *JUP-3*

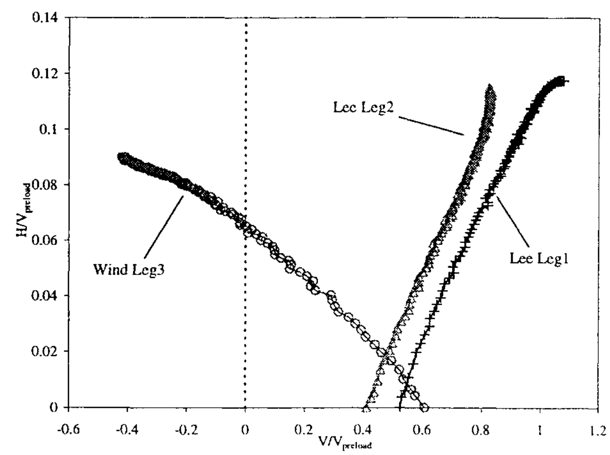

Figure 10(b) - Horizontal and Vertical Loadpaths (normalised by the individual spudcan preload) during *JUP-4*

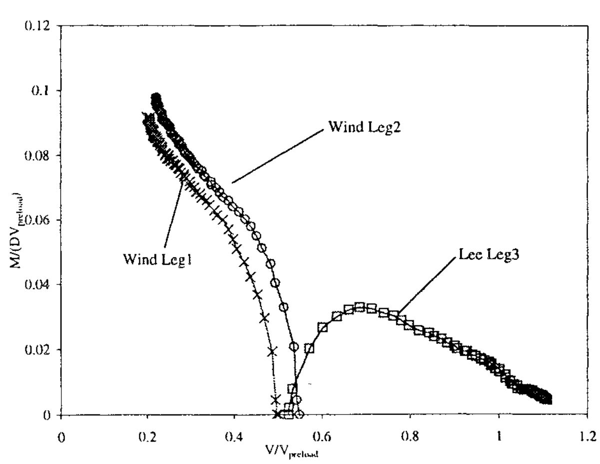

Figure 11(a) - Moment and Vertical Loadpaths (normalised by the individual spudcan preload) during *JUP-3*

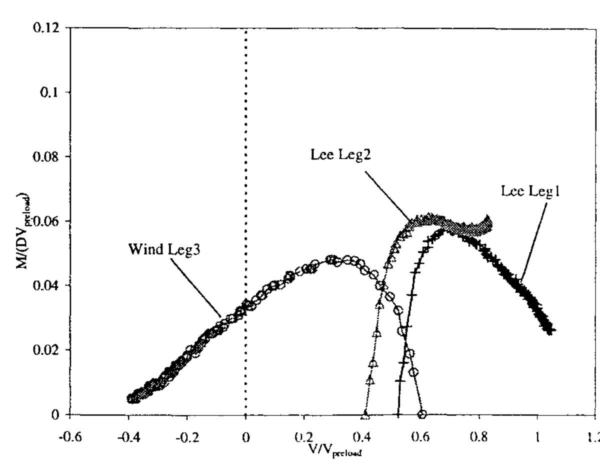

Figure 11(b) - Moment and Vertical Loadpaths (normalised by the individual spudcan preload) during *JUP-4*

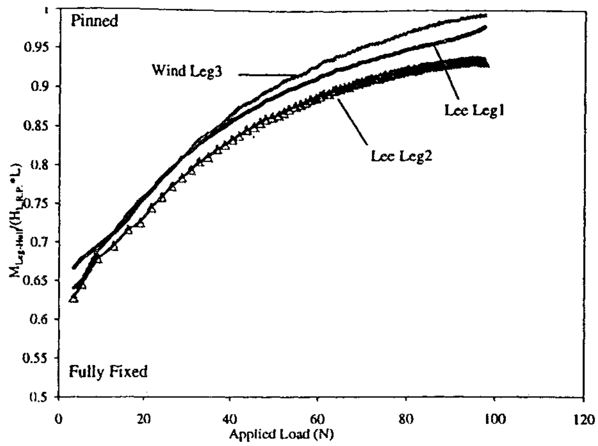

Figure12 - Rotational Fixity of Spudcans during Experiment *JUP-4*