Numerical modelling of three-leg jackup behaviour subject to horizontal load

E.T.R.Dean[1], R.G.James[2,3], A.N.Schofield[2,3],
and Y.Tsu kamoto[4]

[1]   Soil Models Limited

[2]   Cambridge University Engineering Department

[3]   Andrew N Schofield & Associates Limited

[4]   Science University of Tokyo

Synopsis

This paper examines a method of numerical simulation of 3-leg jackup response to horizontal load. The method assumes variable rotational (moment) fixity, variable horizontal fixity, and complete vertical fixity. Numerical results are compared with centrifuge model test data. Consistently with Wong et al (1993), it is shown that moment fixity increases with increasing spudcan rotational stiffness, increasing leg length, and decreasing leg flexural rigidity. It is further shown that fixity degrades with increasing horizontal load. Fixity with a longer leg under high horizontal load may become smaller than fixity with a shorter leg length under low horizontal load.

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Appendix 1. Notation

1. Introduction

Figure 1 shows features of an independent-leg offshore jackup platform. Typical operations and geotechnical considerations are described by McClelland et al (1982), Young et al (1984), Boswell (1986), Reardon (1986), Poulos (1988), Ahrendsen et al (1989), Chaney and Demars (1991), Senner (1992), Boswell and D'Mello (1993, 1995), SNAME (1994). The unit is typically moved to location with its legs elevated. The legs are then jacked onto the seabed and the jacking systems are used to lift the hull out of the water. Water ballast may be taken on board to "preload" the foundation. The ballast is then discharged and the hull is raised further to provide adequate air-gap during subsequent operations.

Environmental loads include wind load (typically 25-35% of the total extreme lateral load), wave (typically 55-65%), and current (10%; Poulos, 1988, p.255). Earthquake effects can be significant in seismic regions, but are not considered here. Control of net buoyant weight and of the position of its centroid is important. In this paper, considerations are restricted to loading in the plane of Figure 1. Soil reactions at the i-th spudcan are vertical load V_i, horizontal load H_i, and moment M_i. The moments are important in serviceability and ultimate limit state calculations, and for fatigue, particularly at the spudcan-leg connections and for the jacking mechanisms (Santa Maria, 1988; Tan, 1990; Murff et al, 1991; Houlsby and Martin, 1992).

Field data and analyses of cyclic loading are reported by Hattori et al (1982), Brekke et al (1989, 1990), Stewart et al (1989, 1991), Hambly et al (1990), Hambly and Nicholson (1991), Liu et al (1991), Hambly (1992), McCarron and Broussard (1992), Spidsøe and Karunakaran (1993), Springett el al (1993), Weaver and Brinkmann (1995), and others. Centrifuge model test data and analyses of spudcan and 3-leg jackup models on sand are reported by Silva Perez (1982), Tanaka (1984), Lau (1988), James and Shi (1988), Shi (1988), Tan (1990), Osborne et al (1991), Murff et al (1991, 1992), Dean et al (1992a-d; 1995a,b), Wong et al (1993), Tsukamoto (1994), Hsu (1995), and others.

This paper describes and discusses a numerical simulation of the behaviour of a 3-leg jackup subject to horizontal load. The simulation incorporates variable horizontal fixity, as well as variable moment fixity. Results are compared to centrifuge data of drained loading reported in Dean et al (1992b) and Tsukamoto (1994). A limitation of the work reported here is that, for field loading conditions, the soil may be only

partially drained over the typical period of a single extreme design wave. Work on partially drained responses is reported by Dean et al (1995a,b) and Hsu (1995).

2. A numerical simulation of 3–leg jackup behaviour

Schotman (1989) showed that displacements are important in numerical modelling of spudcan response to loads. Murff et al (1991, 1992), Dean et al (1992c, 1995a), and Wong et al (1993) considered idealisations with complete vertical and horizontal fixity at each spudcan, and with variable moment fixity. In the following formulation, both moment and horizontal fixity are assumed to be variable. Complete vertical fixity is assumed, which means that the simulated jackup will not rotate with respect to the seabed during horizontal loading.

It is assumed here that the jackup has a rigid hull and elastic legs, as shown in the idealisation in Figure 2. In the absence of environmental loads, the gravity load W is taken to be equally distributed to the three spudcans. Net horizontal environmental load H_T is assumed to act on a fixed point on the hull at height $L^*=L+S+Y$ above the spudcan load reference points (LRP's), which are the points on the spudcans at which spudcan loads are evaluated, where L is the leg length (hull-leg connection HLC to spudcan-leg connection SLC), S is the height of the rigid spudcans (SLC to LRP), and Y is the height of the line of action of H_T above the hull-leg connections. The total vertical load W is assumed constant. In plan view, the three legs typically form an equilateral triangle. Legs 2 and 3 are at symmetrical positions, and are assumed here to experience equal loads and displacements. Quantities for these legs are denoted either using the separate suffices "2" and "3", or using suffix "23". For example, V_2 and V_3 are the vertical loads on the spudcans on legs 2 and 3 respectively. V_{23} is the average vertical load on these two legs, and $V_{23}=V_2=V_3$.

If there is complete vertical fixity at the spudcans, and if the legs deform in bending only, then the idealised jackup hull moves horizontally, parallel to the seabed, when net horizontal load H_T is applied. Horizontal displacements of the hull are here denoted as h_{HULL} (Figure 3). Horizontal displacements of the top of the legs relative to the spudcan load reference points are denoted as δ_1 and $\delta_{23}=\delta_2=\delta_3$. Spudcan rotations are denoted by θ_1 and $\theta_{23}=\theta_2=\theta_3$. Spudcan horizontal deflections relative to a fixed datum are h_1 and $h_{23}=h_2=h_3$, assessed at the load reference points. Since the hull is rigid:

$$h_{HULL} = h_1 + \delta_1 = h_{23} + \delta_{23} \quad\text{..(1)}$$

In the absence of dynamic acceleration effects, horizontal and vertical equilibrium of forces on the idealised jackup in Figures 2 and 3 implies that:

$$H_T = H_1 + 2H_{23} \quad\text{...(2)}$$

$$W = V_1 + 2V_{23} \quad\text{..   ....(3)....}$$

where $H_{23}=H_2=H_3$ and $V_{23}=V_2=V_3$. By taking moments about appropriate points on the spudcans, Dean et al (1992c) derived equations for spudcan vertical loads which, in the notation and with the sign conventions used in this paper, and noting that δ_1 and δ_{23} may be different, may be written as:

$$V_1 = \frac{W.\left((D/3) + \delta_{23} - e_{23} \right) + H_T.L^*}{D + (e_1 - e_{23}) - (\delta_1 - \delta_{23})} \quad\text{..(4)}$$

$$V_{23} = \frac{W.\left((D/3) - (\delta_1/2) + (e_1/2) \right) - (H_T.L^*/2)}{D + (e_1 - e_{23}) - (\delta_1 - \delta_{23})} \quad\text{.......................................(5)}$$

where D is the horizontal distance in elevation between leg 1 and legs 2 and 3, $e_1=M_1/V_1$ is the load eccentricity at the spudcan on leg 1, and $e_{23}=M_{23}/V_{23}$ is the load eccentricity at the spudcans on legs 2 and 3.

Figure 4 shows the i-th leg and spudcan. It is assumed here that the rotation θ_i of a spudcan is related to the moment M_i at the spudcan by a secant rotational stiffness $K_{RS,i}$ as follows:

$$M_i = K_{RS,i}.\theta_i \quad\text{...(6)}$$

Assuming that the leg deflects in bending only, and taking (x,y) coordinates as shown in Figure 4, with x=0 at the hull-leg connection, the leg deflection y relative to the hull-leg connection satisfies the following elastic bending equation:

$$EI\, d^2y/dx^2 = H_i.(L+S-x) - M_i \quad\text{...(7)}$$

where EI is the leg flexural rigidity. By integrating this expression once with respect to x, by evaluating the rotation dy/dx at x=L, then by substituting for the moment using equation 6 and re-arranging the result, it is found that:

$$\theta_i \; = \; \frac{H_i.L^2}{2EI}.\left(\frac{EI}{EI+K_{RS,i}L} \right).(1+2.(S/L)) \dotfill (8)$$

By integrating equation 7 twice, evaluating the relative deflection at x=L, and adding the relative deflection $\theta_i.S$ due to the rotation of the spudcan about the load reference point, substituting for the moment using equation 6, and substituting for the rotation using equation 8, it is found that:

$$\delta_i \; = \; \frac{H_i.L^3}{12EI}.\left[1 \; + \; 3.\left(\frac{EI}{EI+K_{RS,i}L} \right).(1+2.(S/L))^2 \right] \dotfill (9)$$

A number of authors have proposed various kinds of yield locus or limiting locus or envelope for combined loads of circular or strip footings, including Roscoe and Schofield (1956, 1957), James (1987), Georgiadis and Butterfield (1988), Schotman (1989), Nova and Montrasio (1991), Murff et al (1991,1992), Dean et al (1992c), Gottardi and Butterfield (1993), Butterfield and Gottardi (1994). For the numerical simulation described in this paper, the following locus for the i-th spudcan is used. This locus is believed to be a modification of an earlier proposal by James (1987). It is described by Dean et al (1992c), except that they do not use the suffices "i":

$$\left[\left(\frac{M_i}{BV_{Mi}} \right)^2 \; + \; \beta^2.\left(\frac{H_i}{V_{Mi}} \right)^2 \right]^{1/2} \; = \; \alpha.\frac{V_i}{V_{Mi}}.\left(1 \; - \; \frac{V_i}{V_{Mi}} \right) \dotfill (10)$$

where B is the diameter of a circular spudcan, V_{Mi} is the current vertical bearing capacity of the footing, and a and β are dimensionless constants which depend on the geometry and roughness of the footing, and might also conceivably depend on vertical penetration depth, shear strength parameters of the soil, and other factors. The assumption of complete vertical fixity used in the present simulation is taken to imply that V_{Mi} is a constant. Dean et al (1992c, p.250) considered the values $\alpha=0.35$ and $\beta=0.625$. These values are used here. SNAME (1994, Section 6.3.4.1) use a similar formula, except for notation, but with $\alpha=0.3$ and $\beta=0.625$.

The following expression, developed by Tsukamoto (1994) from an expression in Dean et al (1992d), is assumed here for the relation between spudcan moment M_i and spudcan rotation θ_i at constant vertical spudcan load V_i:

$$M_i = M_{ULT,i} \left\{ 1 - \exp\left(\frac{-K_{RE,i} \cdot \theta_i}{M_{ULT,i}/B} \right) \right\} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(11)$$

where $M_{ULT,i}$ is obtained by re-arranging equation 10 and re-naming the moment, as follows:

$$M_{ULT,i}/B = \alpha \frac{V_i}{V_{Mi}} \left(1 - \frac{V_i}{V_{Mi}} \right) \bigg/ \sqrt{1 + \left(\frac{\beta}{\zeta} \right)^2} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots(12)$$

where $\zeta = (M_i/B)/H_i$, and where the value $K_{RE,i}$ is assumed to depend on the current vertical load V_i on the spudcan via a coefficient R_{RE} :

$$K_{RE,i} = R_{RE} \cdot \sqrt{V_i} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(13)\dots$$

where $K_{RE,i}$ is in kN/degree when V_i is in kN. Because the vertical loads V_i on the spudcans change as horizontal load H_T is applied to the jackup, the stiffness $K_{RE,i}$ and the ultimate moment $M_{ULT,i}$ also change. In this simulation, this is taken to imply that the curve on which the current moment-rotation values lie would shift as the vertical load changes, as indicated in Figure 5.

To evaluate the horizontal displacement h_i of the i-th spudcan, it is assumed in the numerical simulation that the normality rule of plasticity holds for incremental horizontal displacement and rotation. Consideration of equation 10 for a fixed value of vertical load V_i and a given V_{Mi} then implies that:

$$\Delta(B\theta_i) / \Delta(h_i/\beta) = (M_i/B) / (\beta H_i) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(14)$$

as illustrated in Figure 5. In applying this rule, for simplicity, the total incremental displacements and rotations were used in the simulation. The incremental displacements and rotations were not split into elastic and plastic components.

3. Comparisons with centrifuge model test data

Centrifuge modelling has played a major role in resolving geotechnical issues in the development of offshore structures (Rowe, 1983). Principles and practice of centrifuge modelling for a variety of onshore and offshore geotechnical applications are described by Schofield (1980, 1981), Craig (1984), Craig et al (1988), Corte (1988), Ko and McLean (1991), Taylor (1994), Leung et al (1994), and others.

In this section, simulation results are compared with centrifuge model test data for event 7 of test YT2–3L–C reported by Dean et al (1992b) and Tsukamoto (1994). In this centrifuge test, a jackup model was landed and preloaded on a 119mm deep layer of fine saturated Leighton Buzzard 100/1 70 silica sand. The soil layer rested on a rigid base. The centrifuge gravity varied from approximately 113g at the soil surface to 128g at the base of the 119 mm thick soil layer. The vertical spudcan loads at the start of event 7 were $V_1=V_{23}=W/3=0.7kN$. During event 7, the centrifuge model was subjected to four slow two-way cycles of increasing amplitude of net horizontal load H_T, at approximately constant net vertical load $W=2.1kN$.

The centrifuge model is shown in elevation in Figure 6. The model was hung from a support frame. The net loads consisted of (a) the model weight W* in the centrifuge gravity, (b) an upthrust U from the hanger, and (c) a horizontal load H_{APP} applied by cables to the hull reference point marked "HRP". The model spudcans were flat based, with overall diameter $B=57.8mm$ and with a small conical tip. The spudcans were instrumented to measure axial loads (Pi), shear loads (Qi), and moment loads (Mi). The axial and shear loads could be resolved to obtain the spudcan vertical loads (Vi) and spudcan horizontal loads (Hi). The sum of the spudcan vertical loads was taken to be the net rig weight W. The sum of the spudcan horizontal loads was taken to be the net horizontal load HT.

The legs of the model jackup were not equal in length. Model dimensions were in the ranges $S=72.2\pm0.9mm$, $L=248.4\pm2mm$, $Y=34.3\pm2.3mm$, and $L^*=355\pm1.2mm$. However, in the numerical simulation, it was assumed that $S=0$, $L=L^*=354.4mm$, and $Y=O$. The leg spacing D was 186mm in the centrifuge test and in the simulation. The leg flexural rigidity in the simulation was taken as $EI=0.234x10^6 kN.mm^2$, based on the measured leg cross-section dimensions and the value $E=70kN/mm^2$ for the duraluminium material of which the physical model legs were made. The parameters a and β in equations 10 and 12 were taken as $\alpha=0.35$ and $\beta=0.625$. The coefficient

R_{RE} in equation 13 was taken as 0.7 kN$^{1/2}$/degree. The values $V_{M1}=V_{M23}=2.8$kN were considered appropriate, based on estimates obtained using an extrapolation of the measured vertical load-penetration relations during preloading and on the measured average vertical penetration of the centrifuge model spudcans at the start and end of the sequence of horizontal load application in event 7 of the model test.

Figures 7-9, which are discussed below, show comparisons of the numerical simulation with centrifuge data. The sign conventions for load and displacement quantities in these figures are the same as the sign conventions illustrated in Figures 2 and 3. For example, horizontal hull displacement h_{HULL} is taken positive when the hull translates rightwards in the simulation and in the centrifuge model. Checks confirmed that the loads on the spudcans on legs 2 and 3 in the centrifuge model were close to equal, and the suffix "23" in Figures 7-9 denotes average values for these spudcans.

In the simulation and in the centrifuge test, the general behaviour of the spudcan loads was as follows. When the horizontal load H_T increased positively, so that the load was directed towards leg 1, the vertical load V_1 on the spudcan on leg 1 increased above 0.7kN, and the vertical loads V_{23} on the spudcans on legs 2 and 3 decreased below 0.7kN. When the horizontal load increased negatively, so that the load was directed towards legs 2 and 3, the vertical load V_1 on the spudcan on leg 1 decreased, and the vertical loads V_{23} on the spudcans on legs 2 and 3 increased. The terminology "heavily loaded" and "lightly loaded" is sometimes used, referring to vertical spudcan loads. The spudcan on leg 1 is "heavily loaded" when the net horizontal load H_T is positive, but is "lightly loaded" when H_T is negative. The spudcans on legs 2 and 3 are "lightly loaded" when the net horizontal load is positive, and are "heavily loaded" when H_T is negative.

Figure 7 shows aspects of the hull behaviour, and of the interactions between the spudcan on leg 1 and those on legs 2 and 3. Because the simulation assumes complete vertical fixity, the vertical settlement and rotation of the hull are not simulated, and only the predicted relation between net horizontal load and hull displacement is available. It may be seen that the simulation results indicate non-linear loadsharing between the spudcans, and that non-linear loadsharing occurred in the model test. When the net horizontal load H_T was applied towards leg 1, the spudcan on leg 1 took a higher share of the horizontal load. When H_T was negative, the spudcans on legs 2 and 3 took a higher share of the load.

Figure 8 compares numerical simulations and centrifuge test data of the loadpaths at the spudcans. The simulation reproduces features of the non-linearity of the paths observed in the centrifuge test. The simulation shows lower peak values of moment-over-diameter, for all spudcans and for both the "lightly loaded" and the "heavily loaded" conditions. The simulation slightly over-predicts the changes of vertical loads at all spudcans.

Figure 9 compares simulations and data of the relations between spudcan moments and rotations, and spudcan horizontal displacements and horizontal loads. The observed values of spudcan displacements and rotations were inferred from measured data of hull displacement and rotations and data of measured spudcan loads, using an elastic analysis for the legs of the physical model similar to that described above for the simulation. The inferred spudcan rotations were relatively insensitive to small potential inaccuracies in the measurements of the dimensions and stiffness of the physical model. The inferred horizontal spudcan displacements were more sensitive to these potential inaccuracies (Tsukamoto, 1994).

Both the test data and the numerical simulation in Figure 9 show noticeable spudcan horizontal displacements and rotations. The simulation results for horizontal displacements show sliding conditions for the spudcan on leg 1 only when the spudcan horizontal load reaches its maximum negative value. This occurs in the two-way load cycles when this spudcan is "lightly loaded". For the spudcans on legs 2 and 3, the simulation shows sliding conditions only at maximum positive horizontal load. This occurs at the different times in the two-way load cycles when these spudcans are "lightly loaded".

For the moment-rotation responses, both the simulation and the data show reductions in tangent stiffnesses at both ends of the load cycles, thus when the spudcans are "lightly loaded" and when they are "heavily loaded". Wong et al (1993) defined the "moment fixity", which they denoted as "x_{dy}", as the ratio of the moment M_i at a spudcan divided by the theoretical moment which would occur if all three spudcans behaved as encastre foundations. In this paper, the notation f is used for fixity, and fixity is defined separately for each spudcan. Assuming equal rotational stiffnesses at each spudcan, Wong et al (1993) derived an equation which, in the notation of this paper, could be written:

$$f_i = K_{RS,i} / \{ K_{RS,i} + (EI/L) \} \quad \text{..} \quad (15)$$

By using equation 8 to substitute for θ_i in equation 6, and noting that the theoretical moment for fully encastre conditions is $H_i.((L/2)+S)$, it may be verified that the analysis here would be consistent with Wong et al's (1993) finding if the analysis had assumed equal rotational stiffnesses at each spudcan. However, the data indicate that rotational stiffnesses were variable during load cycles. In the simulation, the rotational stiffnesses $K_{RS,i}$ at the spudcans are linked to the spudcan vertical loads by equation 13, and the spudcan vertical loads given by equations 4 and 5 are different when the net horizontal load H_T is non-zero.

In conclusion, it may be said that the numerical simulation provided a useful initial interpretation of the experimental data. There are areas where improvements might be useful. For example, the numerical simulation does not incorporate the hysteresis seen in the data.

4. Parametric studies

Although equation 15 was derived assuming equal rotational stiffnesses at all three spudcans, it shows that moment fixity x_{dy} or f_i is not solely a property of the soil or the footing, but is a soil-structure interaction parameter depending on the footing rotational stiffness and on the effective leg rotational stiffness EI/L.

Figure 10 shows numerical simulation results illustrating effects of rotational stiffnesses $K_{RS,i}$, which from equations 11 and 13 are related to $R_{RE}.B.\sqrt{V_i}$ in the simulation. Three values of the coefficient R_{RE} are used in Figure 10, namely 0.5, 0.7, and 0.9 $kN^{1/2}$/degree, representing variations of about ±30% compared to the value $R_{RE}=0.7$ used in the comparisons with centrifuge data. In all three cases, the leg flexural rigidity is taken as $EI=0.234\times10^6$ kN.mm^2, and the height L* of the line of action of the net horizontal load is taken as 354.4mm. The simulations indicate that, in the vicinities of the parameter values that were used, horizontal displacements of the spudcans are relatively insensitive to the implied values of rotational stiffness.

The reason for this is believed to be as follows. Differentiation of equation 11 gives $K_{RS,i}=K_{RE,i}.B$ around $\theta_i=0$ (ignoring differentials associated with change of vertical spudcan load). For $R_{RE}=0.7$ kN"*/degree and an average spudcan vertical load of 0.7 kN, the stiffness $K_{RE,i}$ given by equation 13 is $0.7\sqrt{0.7}=0.6$kN/degree or 33.6 kN/radian, so the rotational stiffness $K_{RS,i}$ is 33.6x57.8mm = 1942kN.mm/radian for

a spudcan diameter B = 57.8mm. For the parameters of the numerical simulation, the leg length L was taken equal to the height L*, so EI/L was $0.234 \times 10^6/354.4$ = 660 kN.mm/radian. From equation 15, the fixity at small displacements was around 1942/(1942+660) = 75%. As shown by Wong et al (1993), differentiating equation 15 and re-arranging the result gives $(df_i/f_i) = (1-f_i).dK_{RS,i}/K_{RS,i}$. If f_i = 75%, a change $dK_{RS,i}/K_{RS,i}$ =30% in rotational stiffness produces a change df_i/f_i of only about (1–0.75)x0.30 = 7.5%. From equations 6, 8 and 15:

$$\frac{M_i/B}{H_i} = \frac{L+2S}{2B} \cdot f_i \dotfill (16)$$

The slope of the loadpath in terms of spudcan moment-over-diameter and spudcan horizontal load is therefore altered by only about 7.5%. It seems reasonable to assume that the slopes of the vertical-horizontal loadpath will also be altered by only a small value. Therefore, a 30% change in rotational stiffness does not have much effect on the positions on the yield loci towards which the spudcan loadpaths move.

Figure 11 shows numerical simulation results illustrating effects of leg flexural rigidity. Three values of EI were used in these calculations, namely 0.134×10^6, 0.234×10^6, and 0.334×10^6 kN.mm^2. These values correspond to variations of about ±40% around the value of 0.234×10^6 kN.mm^2 appropriate for the centrifuge model test. The coefficient R_{RE} was taken to be 0.7 kN$^{1/2}$/degree. L* was taken equal to L, and was set at 354.4mm. The simulation results show a small effect on the values of horizontal loads at which the horizontal load-displacement curves flatten. In these calculations, moment fixities have been evaluated separately for the spudcan on leg 1 (f_1) and the spudcans on legs 2 and 3 (f_{23}). The results show that, as the leg flexural rigidity decreases, the fixity at a given horizontal load increases, although the hull would then be subjected to larger horizontal displacements. It can be seen that moment fixity degrades as the horizontal loads increase.

Figure 12 shows numerical simulation results illustrating effects of leg length or height of horizontal load application. Three different values for L* are considered, namely 304.4mm, 354.4mm, and 404.4mm. This corresponds to a variation of about ±14% on the value of 354.4mm. The leg flexural rigidity was taken as EI=0.234×10^6 kN.mm^2. The coefficient R_{RE} was taken to be 0.7 kN$^{1/2}$/degree. The simulation results indicate that there is a noticeable effect on the values of horizontal loads at which the horizontal load-displacement curves flatten, indicating onset of sliding

conditions at one or other of the spudcans. The results show that, as the distance L* increases, the fixity at a given horizontal load increases, but that degradation of fixity as the horizontal loads increase is a more important effect.

5. Conclusions

This paper has described, and examined the performance of, a numerical simulation method for 3-leg jackups in which linear-elastic behaviour of the structure has been combined with a non-linear model for footing response incorporating one of the several yield surfaces that have been proposed in the literature. The simulation assumed that the footings could move horizontally, as well as rotate, but that no vertical spudcan displacements would occur.

Comparisons with centrifuge model test data showed that this simulation approach has good potential. Significant general features of the test data were observed in the simulation results, including the degradation of rotational stiffness and the possibility of sliding at a spudcan during those parts of a load cycle when the spudcan is "lightly loaded". A significant feature of the numerical simulation, not present in previous analyses, was that the rotational stiffnesses were allowed to be different at different spudcans as well as at different parts of a load cycle.

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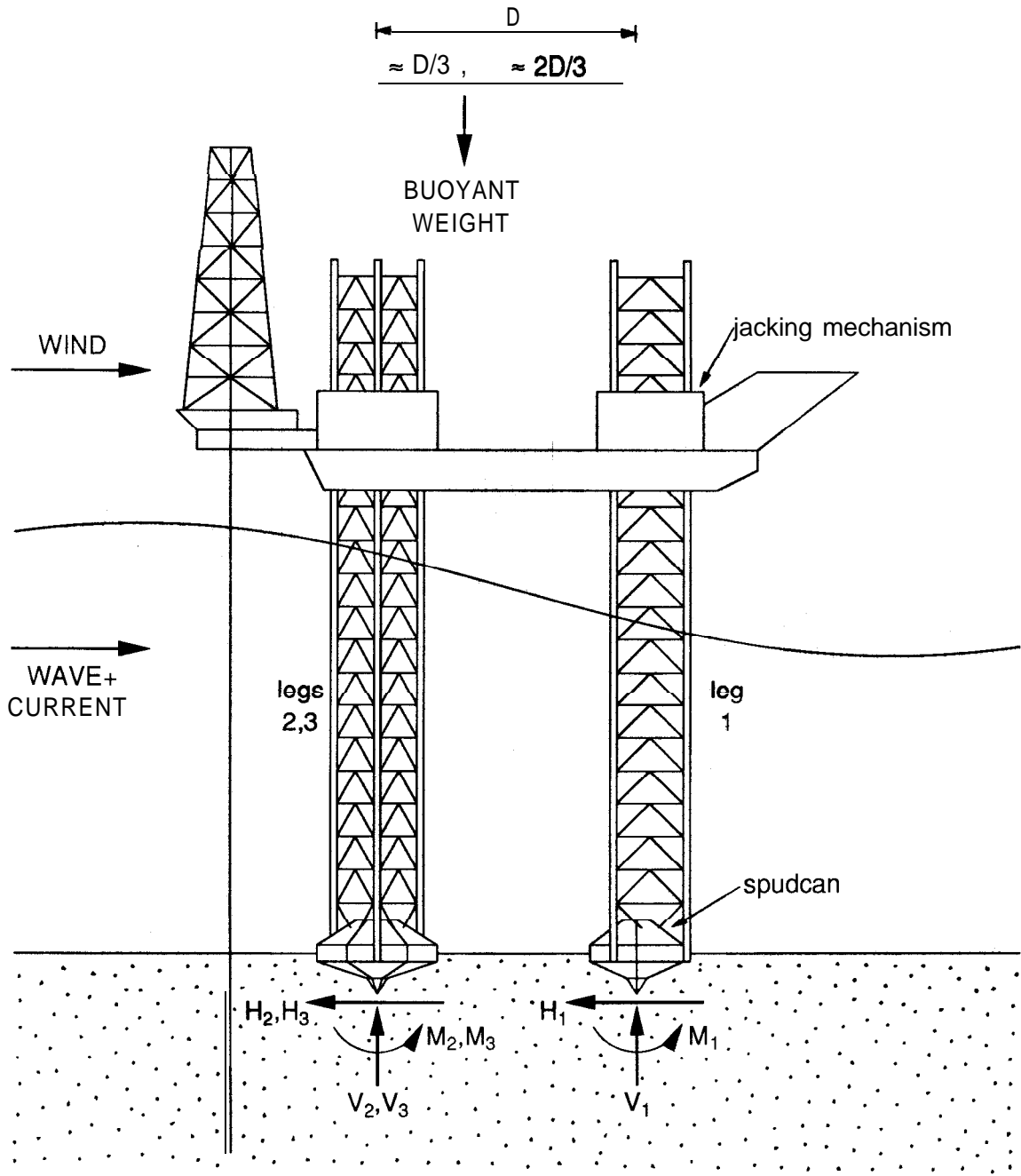
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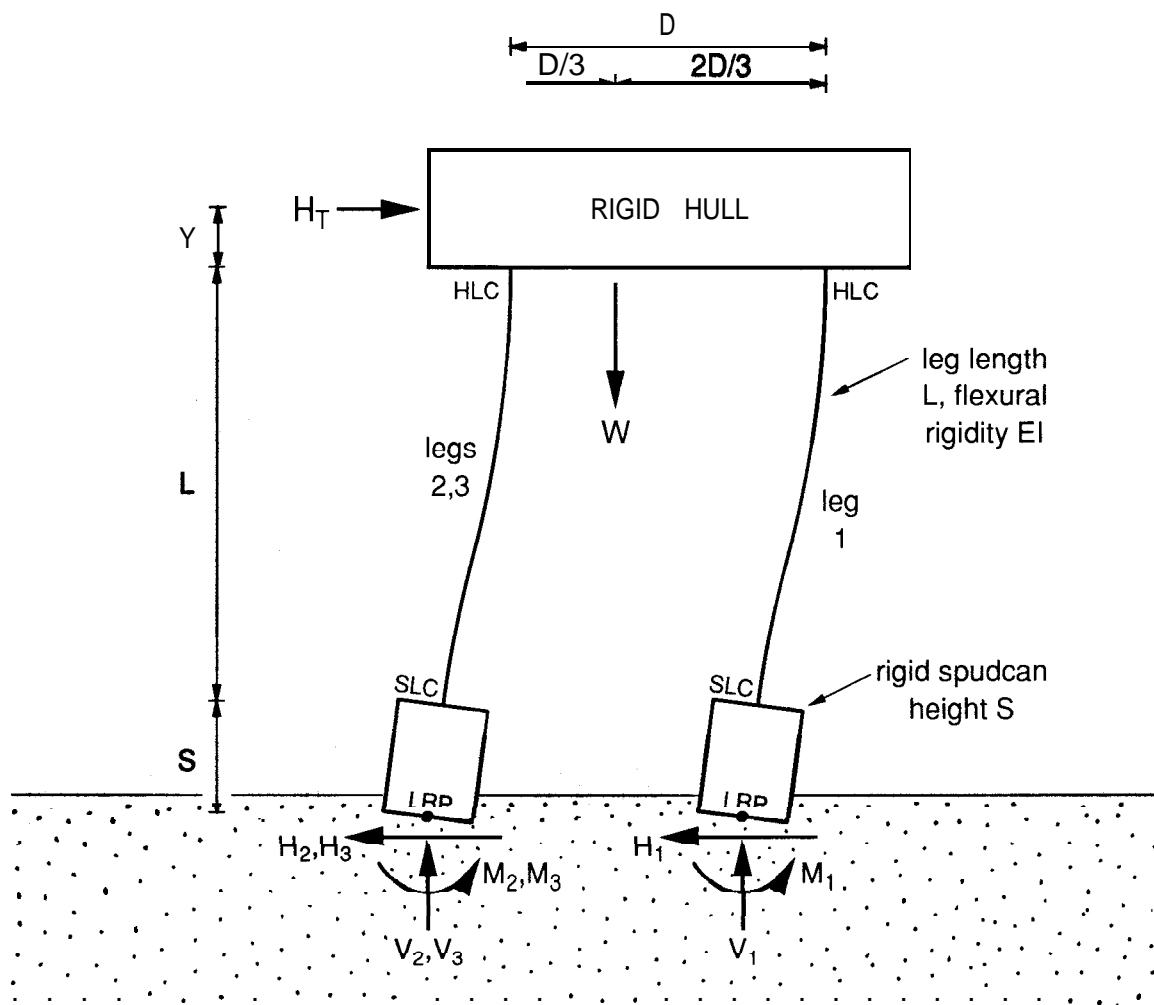
Figure captions

1.   Three-leg jackup rig

2.   Simple idealisation of geometry and loads for three-leg jackup rig

3.   Simple idealisation of displacements and rotations

4.   Linear elastic bending analysis of i-th leg (neglecting effect of V_i–times–deflection)

5.   Formulation of spudcan load-interaction and load-displacement behaviour

6.   3–leg model jackup and support frame, model properties, directions of positive loads H_{APP}, W^*, and U, and directions of positive soil reactions Pi, Q_i, and M_i

7.   Comparison between simulation and centrifuge data – hull behaviour and loadsharing between spudcans

8.   Comparison between simulation and centrifuge data – spudcan loadpaths

9.   Comparison between simulation and centrifuge data – spudcan load-displacement and rotation responses

10. Parametric investigation – numerical simulation of influence of foundation rotational stiffness

11.   Parametric investigation – numerical simulation of influence of leg flexural rigidity

12.   Parametric investigation – numerical simulation of influence of leg length or height of load application

D

$\approx D/3$, $\approx 2D/3$

BUOYANT
WEIGHT

WIND

jacking mechanism

WAVE+
CURRENT

legs
2,3

leg
1

spudcan

H_2, H_3 M_2, M_3 H_1 M_1

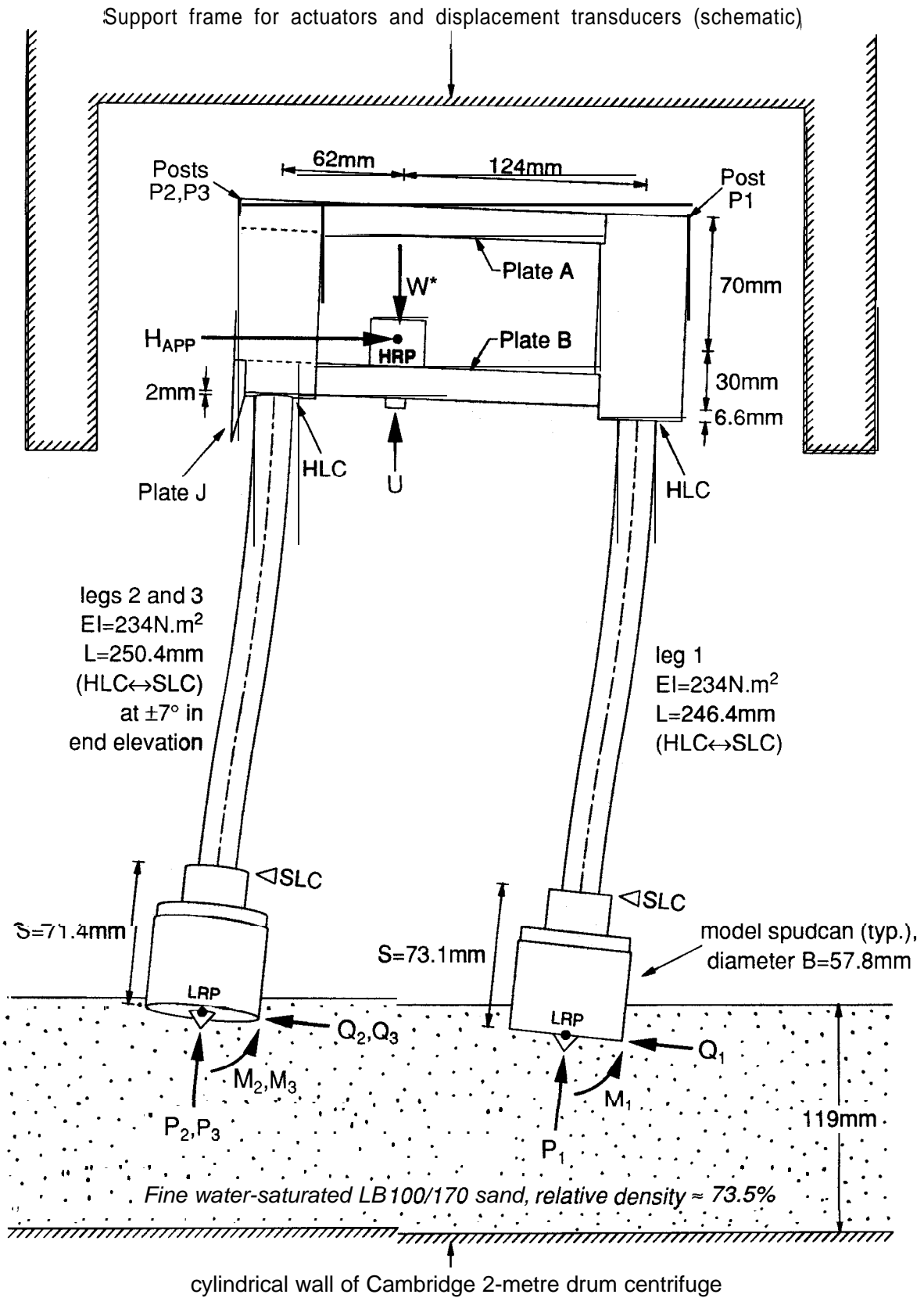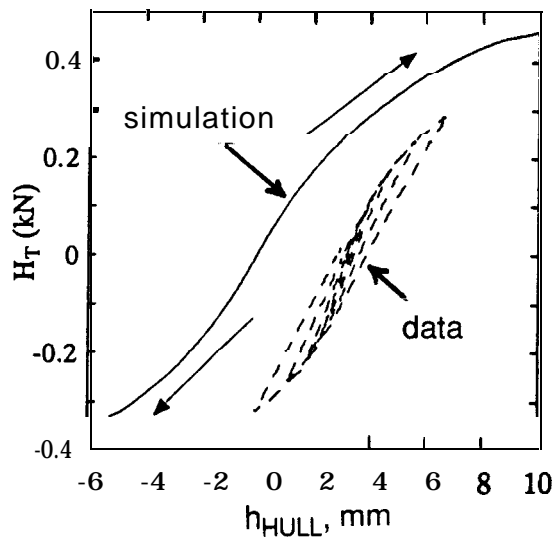V_2, V_3 V_1

CUED ID-Soils/ TR290	THREE-LEG JACKUP RIG	FIG.NO. 1

D

D/3 2D/3

H_T →

Y

RIGID HULL

HLC   HLC

legs
2,3

W

leg length
L, flexural
rigidity EI

L

leg
1

SLC   SLC

rigid spudcan
height S

S

LRP   LRP

H_2, H_3 ← H_1 ←

M_2, M_3 M_1

V_2, V_3 V_1

SIMPLE IDEALISATION OF GEOMETRY AND
LOADS FOR THREE-LEG JACKUP RIG

h_{HULL}

initial
position

displaced
position

HLC

HLC

legs
2,3

leg
1

θ_2, θ_3

θ_1

ILRP

LRP

LRP

LRP

h_2, h_3 δ_2, δ_3

h_1 δ_1

CUED	SIMPLE IDEALISATION OF	FIG.NO.
ID-Soils/	DISPLACEMENTS AND ROTATIONS	3
.TR290		

$$V_i$$

$$H_i.(L+S)-M_i$$

$$y \quad \text{HLC} \quad H_i$$

bending moment in i-th
leg at distance x below
HLC is $H_i.(L+S-x)-M_i$

$$\theta_i$$

$$x$$

SLC

S

LRP

$$H_i$$

$$M_i$$

$$V_i$$

L

$$\delta_i$$

LINEAR ELASTIC BENDING ANALYSIS OF i-th LEG
(NEGLECTING EFFECT OF Vi-TIMES-DEFLECTION)

FIG.NO.

4

FORMULATION OF **SPUDCAN** LOAD-INTERACTION
AND LOAD-DISPLACEMENT **BEHAVIOUR**

FIG.NO.

5

Support frame for actuators and displacement transducers (schematic)

Posts P2,P3 — 62mm — 124mm — Post P1

Plate A

W*

H_{APP}

HRP

Plate B

2mm

70mm

30mm

6.6mm

Plate J

HLC

U

HLC

legs 2 and 3
$EI=234N.m^2$
$L=250.4mm$
(HLC↔SLC)
at ±7° in
end elevation

leg 1
$EI=234N.m^2$
$L=246.4mm$
(HLC↔SLC)

◁SLC

◁SLC

S=71.4mm

S=73.1mm

model spudcan (typ.),
diameter B=57.8mm

LRP

LRP

Q_2,Q_3

Q_1

M_2,M_3

M_1

P_2,P_3

P_1

119mm

Fine water-saturated LB100/170 sand, relative density ≈ 73.5%
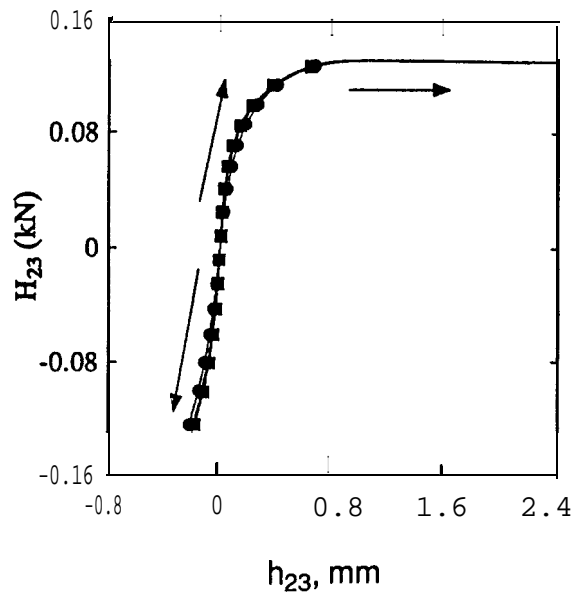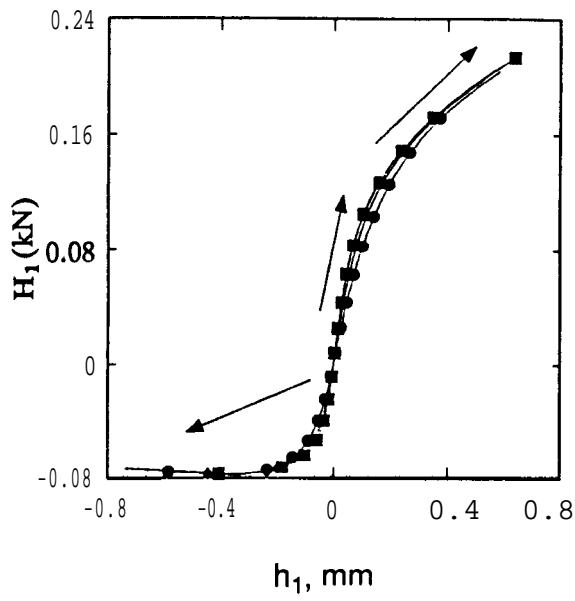
cylindrical wall of Cambridge 2-metre drum centrifuge

3-LEG MODEL JACKUP AND SUPPORT FRAME, MODEL
PROPERTIES, DIRECTIONS OF POSITIVE LOADS H_{APP}, W*, AND U,
AND DIRECTIONS OF POSITIVE SOIL REACTIONS P_i, Q_i, AND M_i
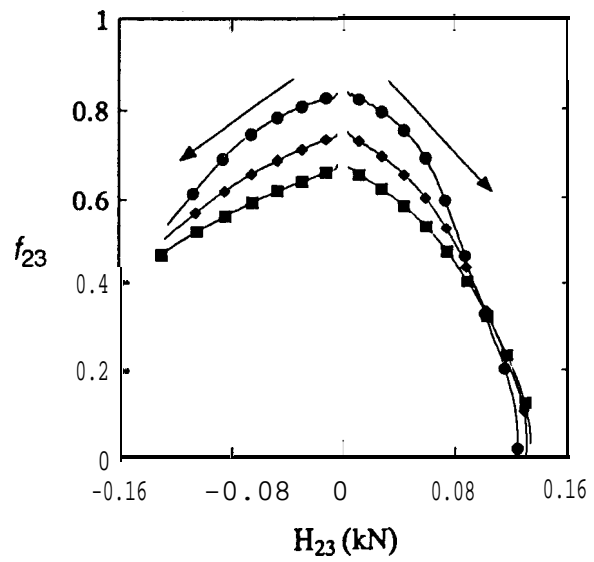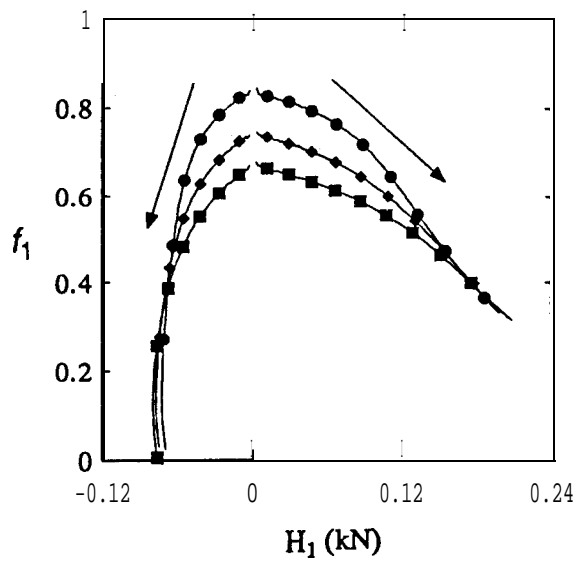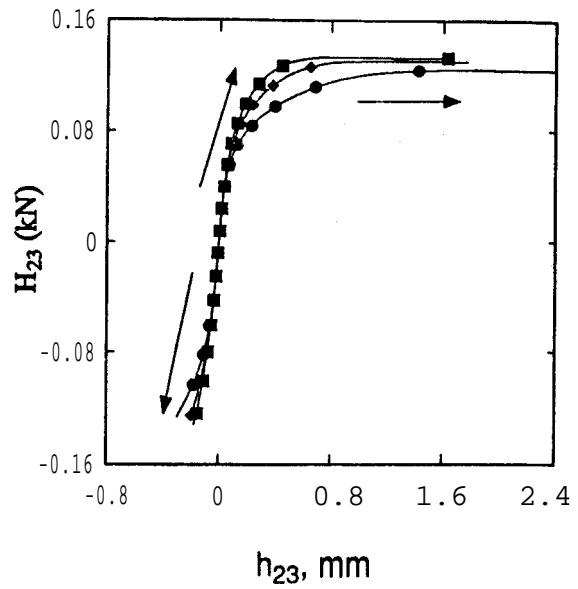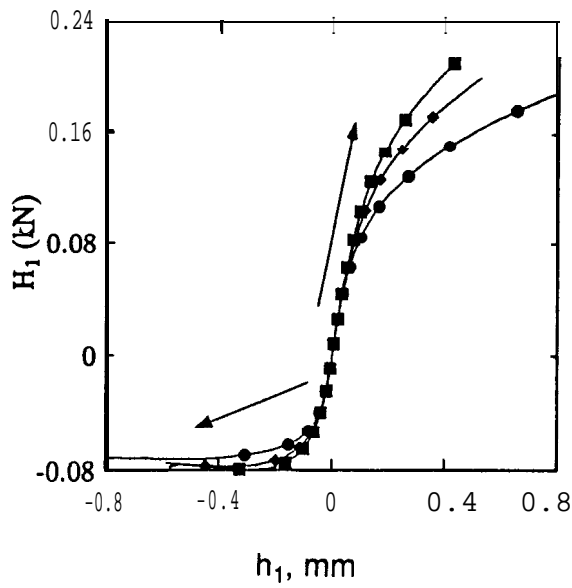
FIG.NO.

6

COMPARISONS BETWEEN SIMULATION AND CENTRIFUGE DATA
– HULL BEHAVIOUR AND LOADSHARING BETWEEN SPUDCANS

FIG.NO.

7.

COMPARISONS BETWEEN SIMULATION AND CENTRIFUGE DATA
– SPUDCAN LOADPATHS

FIG.NO.
8

		EI (kN•mm^2)	RRE	L (mm)
●	——●		0.5	
◆	——◆	0.234×10^6	0.7	354.4
■	——■		0.9	

CUED
/D-Soils/
TR290

PARAMETRIC INVESTIGATION — NUMERICAL SIMULATION
OF INFLUENCE OF FOUNDATION ROTATIONAL STIFFNESS

FIG.NO.

10

	EI (kN·mm^2)	RRE	L (mm)
●——●	0.134x106		
◆——◆	0.234×10^6	0.7	354.4
■——■	0.334×10^6		

PARAMETRIC INVESTIGATION – NUMERICAL SIMULATION
OF INFLUENCE OF LEG FLEXURAL RIGIDITY

FIG.NO.

11

	EI (kN•mm^2)	R$_{RE}$	L (mm)
●———●			304.4
◆———◆	0.234 × 10^6	0.7 3	54.4
■———■			404.4

CUED
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PARAMETRIC INVESTIGATION – NUMERICAL SIMULATION OF
INFLUENCE OF LEG LENGTH OR HEIGHT OF LOAD APPLICATION

FIG.NO.
12

Appendix 1. Notation

B	footing diameter
d	differential
D	distance between leg 1 and legs 2 and 3 in side elevation
e	footing load eccentricity, M/V
EI	leg flexural rigidity
f	moment fixity
h	horizontal displacement relative to a fixed coordinate frame
H	horizontal load
HLC	hull-leg connection
HRP	hull reference point
K_{RE}	stiffness parameter (units of force/angle), see equations 11 and 13
K_{RS}	secant rotational stiffness (units of moment/angle)
L	leg length from hull-leg connection (HLC) to spudcan-leg connection (SLC)
L^*	=L+S+Y, height of horizontal load application above LRP's
LRP	load reference point on spudcan
M	moment
P	axial load
R_{RE}	coefficient for rotational stiffness, see equation 13
S	height of idealised rigid spudcan
SLC	spudcan-leg connection
Q	shear load
U	upthrust applied to centrifuge model (see Figure 6)
v	vertical load
V_M	vertical bearing capacity of footing
W	net rig weight
W^*	weight of model in centrifuge gravity (see Figure 6)
x	coordinate along leg (x=0 at HLC, Figure 4)
y	leg deflection at coordinate x relative to the hull
Y	height of line of action of total horizontal load H_T above the HLC's
α, β	dimensionless factors in equation 10
δ	displacement of hull relative to spudcan
Λ	differential change of (equation 14)
ζ	spudcan moment-over-diameter M/B divided by spudcan horizontal load H
θ	rotation

Subscripts

APP   applied to the centrifuge model (H_{APP} = horizontal load applied by cables, see Figure 6)

HULL of the hull of the jackup

I   quantity for the spudcan on leg i

M   capacity (V_{Mi} = bearing capacity under vertical load at the spudcan on leg i)

RE   referring to calculation for rotational stiffness, see equations 11 and 13

RS   secant rotational (see K_{RS})

T   total, net (H_T = total horizontal load)

1   quantity for the spudcan on leg 1

23   average of quantities for the spudcans on legs 2 and 3