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On-Bottom Stability of Jackups

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ABSTRACT

A new approach to assessing the on-bottom stability of jack-up rigs during preloading is presented. A leaning instability is described, which may appear similar to a punch through, but is associated with soil stiffness and rig flexure. Suggestions for avoiding this instability are given.

INTRODUCTION

Jack-up foundation failures during preloading are generally associated with a so-called "punch through". When a strong soil layer overlies a weak layer punch through may occur. The typical example is a sand layer, or sand lens, above a weak clay. If spud can load exceeds the bearing capacity of the sand layer, the spud can will penetrate into the weaker layer. This may happen suddenly and penetration into the weaker layer may be deep. Buoyancy support on the hull may eventually prevent further spud can penetration.

In soft uniform soils, where bearing capacity increases continuously with depth, punch through failures are not expected. However, there have been foundation failures in such conditions, which appear to be punch throughs, but cannot be explained geotechnically by the normal punch through model. Ingram & Dutt (Reference 1) describe such an event in the Gulf of Mexico in 1982.

This paper describes a new method for calculating elevated stability of jack-ups during preload, where spud can loads are steadily increased. It shows how unstable leaning, leading to rapid leg penetration, can occur in soft soils where punch through cannot be the failure mechanism. For the purposes of this paper, the term *rapid leg penetration* is used to describe leg penetration rates which are faster than the rig's jacking rate. This typically means 1.5 feet per minute. As will become evident in the paper, the speed at which events take place is a critical factor.

STABILITY REQUIREMENTS

Stability requirements (Operations Elevated) for Mobile Offshore Drilling Units are normally addressed by classification societies along with governmental regulatory bodies.

These requirements vary from being quite extensive as pertains to Environmental Forces, Soil Particulars, Overturning Moments, Air Gaps and various Safety Factors, to being just a general statement in regards to these variables.

The U.S. Coast Guard (USCG) and the American Bureau of Shipping (ABS) make a general statement in regards to Operations Elevated/Stability On Bottom. The ABS, in their publication **Rules for Building and Classing Mobile Offshore Drilling Units**, Section 3; Part 3.13, state:

Units Resting on the Sea Bed

> "Units which are to rest on the sea bed are to have sufficient positive downward gravity loadings on the support footings or mat to withstand the overturning moment of the combined environmental forces from any direction. Realistic variable loads are to be considered."

Underwriter-approved Marine Surveyors can provide Location Approvals for Mobile Offshore Drilling Units, Operations Elevated.

It is standard in the industry that these location approvals be based on compliance with the approved Rig Operations Manual. Additionally, it is standard in the industry that a recognized Meteorologist/Oceanographer provide the Environmental Conditions for the specific location under consideration. If these environmental conditions appear to fall outside the range of conditions found in the Rig Operations Manual, an independent

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References and figures at end of paper

study should be made to assess the adequacy of the rig for the new location. This study, as a minimum, should provide analysis of the three basic criteria that an independent leg jack-up should pass in order to be approved by an Underwriter-approved Marine Surveyor for a specific location.

a) It must have sufficient stability to withstand overturning in environmental conditions anticipated.

b) No individual leg load (vertical soil reaction) as a consequence of operating weight distribution and environmental forces acting on the rig, should be allowed to exceed that to which the leg (soil) was preloaded.

c) No individual structural member load should be allowed to exceed that for which the member was designed.

CALCULATION OF BEARING CAPACITY AND LEG PENETRATION

Prior to rig installation and preloading, a soil bearing capacity versus leg penetration curve should be developed. This curve describes the predicted relationship between spud can penetration and load on the spud can. It is normally extended well beyond the spud can penetration that will occur at maximum preload. Data upon which the curve is based may be obtained from site soil information from prior operations at the location, or soil borings may be taken from the rig before preloading.

In a cohesive soil, to which this paper is primarily addressed, the bearing capacity at any depth is calculated from the product of undrained shear strength, s_u (of the soil) multiplied by the effective foundation (spud can) area, A, multiplied by a bearing capacity factor, N_c, as shown below:

$$B = s_u.A.N_c$$

Additionally a buoyancy term, which is a function of the submerged weight of the displaced soil, may be added, but its contribution is generally small. The bearing capacity factor is a function of the foundation (spud can) geometry and the depth of penetration. Figure 1 shows a bearing capacity versus penetration curve developed for a weak cohesive soil, with s_u increasing uniformly from 0.01 kips per square foot (KSF) at the surface, by 0.01 KSF with each foot of depth. Table 1 shows the make up of individual terms that lead to the final curve in Figure 1. This soil profile is almost identical to that described in Reference 1.

SIMPLIFIED CALCULATION OF ELEVATED STABILITY

In a similar manner to that in which the stability of a floating vessel may be calculated, the stability of a bottom supported structure may be determined. The approach is to consider the soil as a non-linear, non-returning (compressing only) type of spring system. These soil springs support the structure, which is modeled, initially, as a rigid body. At a given depth, the load to penetrate one additional foot may be equated to a spring constant. The spring stiffness, in kips per foot(KPF) is the slope of the bearing capacity versus penetration curve for the spud can, at that depth. However, the soil is not a simple elastic support, for once a footing has penetrated to a given depth under a given load, the soil will not push it back up if the load is later reduced. Using this approach, the footing load-penetration curve may be closely matched with a piecewise linear set of non-recovering springs, each spring matching a portion of the load-penetration curve.

For the soil/rig example given above, the slope of the curve at a footing load of 6000 kips is around 107 KPF. At this load level the spud can tip will have penetrated 66 feet into the sea bed. The above values are typical for many three-legged jack-ups at an intermediate stage during preload, in soft soil conditions. These conditions also match those for both the soil and the rig, at the time of foundation failure, described in Reference 1. Full preload for this rig corresponds to an average spud can reaction of 8500 kips. At this load, in this soil, the spud can tip penetration will be nearly 90 feet, and the soil stiffness will be to close to 140 KPF

The calculation of the rig's equilibrium position employs an iterative approach. Initially, the rig is assumed to be supported with its hull level and legs vertical. The footing reactions are computed based upon the location of the rig's center of gravity (cg) and the total weight of the rig. The footing reactions are applied to the soil springs, and penetrations (soil spring compressions) are calculated. For the condition of:

i) all leg lengths equal
ii) cg directly above center of area of the footings
iii) all soil springs equal
iv) no lateral environmental forces acting

the penetrations will be equal, and the rig will remain with legs vertical and hull level. This is a position of equilibrium which may be stable, or unstable, as in the case of a floating vessel with negative metacentric height. A small lateral displacement of the cg may be applied and the calculations repeated.

The procedure finds new footing reactions, which will no longer be equal. The resulting penetrations (or soil spring compressions) will not be equal either. One or more springs will be further compressed. Springs which have a reduced load will stay the same length.

Because of differential leg penetrations, the rig inclines and the cg moves further laterally. The footing reactions are recalculated and new soil spring compressions found. It is necessary to "start" new soil springs as penetrations increase, unless the bearing capacity curve is a straight line. This process is repeated until an equilibrium position is found with soil support alone, or until the movement of the rig is such that the hull comes partly back into the water and equilibrium is achieved as a result of additional hull buoyancy forces.

This rigid body mechanism can be used to investigate the stability of any foundation. Hambly (Reference 2) developed an upper and lower bound closed-form solution to the stability limits for bottom-founded structures, based upon the soil stiffness, cg height, and second moment of area of the foundation. A comparison of Hambly's formulae with the above numerical approach has shown good agreement, with this technique finding instability within the range predicted by Hambly's formulae.

ADDITIONAL FACTORS INFLUENCING ELEVATED STABILITY

The above approach is simplified in that it neglects the rotational stiffness provided to the spud cans by the soil, together with lateral soil support provided to deeply embedded legs. It also neglects leg and hull flexure.

From field experience it is found that in most cases of jack-up rapid leg penetration, the spud can path is rarely vertical. Instead, the path is often inclined back towards the other two non-penetrating legs. This is concluded to be in part due to the relatively firm embedment and rotational stiffnesses of the "stationary" legs. The rapidly penetrating leg follows the path of least resistance which is influenced strongly by the rig flexural stiffness once the failure commences.

The authors have performed independent studies with 3-D finite element structural models of jack-ups in order to investigate these effects. For a unit vertical displacement of one spud can, it is found that the difference between lateral movement of the deck with a rigid pinned model and a structural model having the "stationary" legs fully encastré, is around 2.5 to 1.

Figures 2 and 3 show a comparison of the deflected and undeflected geometry for a rig with the "stationary" legs fully encastré. The load case applied is a unit vertical displacement of the bow leg, with the spud can free to rotate and move horizontally. Figure 4 shows the same rig with the same load case, but with the aft two spud cans modeled as hinges. In this latter case, the movement of the structure is a rigid body mechanism and the bow spud can deflection is principally vertical. In contrast, the bow spud can moves both vertically and laterally when the aft legs are restrained from rotation as in Figures 3 and 4. Most importantly, the lateral movement of the deck is 2.4 times greater in Figure 4 than in Figure 5. Thus it is seen that rotational and lateral soil restraint can significantly increase rig stability (although boundary conditions described above are over simplified) by decreasing lateral hull deflections.

When the hull is inclined, secondary bending in the legs (and hull) often referred to as the P-delta effect, increases lateral hull deflections. This secondary bending is also found iteratively. First the lateral deflection of the hull as a consequence of differential leg penetration (allowing for soil restraint) is found. The additional lateral deflection as a consequence of secondary bending is then added to this value and new leg penetrations (soil spring compressions) are calculated. The resulting total lateral deflection is then used to once more find vertical leg reactions, new penetrations, new hull angles, and new secondary bending deflections. This iterative process continues as for the simplified rigid model.

TYPICAL PRELOADING STABILITY RESULTS IN SOFT SOIL.

A computer model incorporating rig hull and leg stiffness properties, together with rotational soil restraint of the "stationary" legs and lateral support of all legs is used. Lateral soil support is analyzed in the same way as for a pile in soft clay, using an elastic-plastic behavior model. Rotational spud can stiffness is modeled as a linear rotational spring.

During preload operations, the overall rig cg is constantly moving. Lateral cg movement at a rate of around 0.001 ft/second results from a pumping rate of 1800 gpm into a single outermost preload tank. In 10 seconds a lateral cg movement of around 0.01 ft is typical during preloading of individual legs.

Figure 5 shows the results for the iterative stability calculation for the rig characteristics documented in Table 2. (See also Reference 1). The initial cg position is deliberately offset by 0.01 feet in both lateral directions away from the center of the foundation area. All leg lengths are equal. A stable equilibrium position is reached at a heel angle of approximately 0.3 degrees and a trim angle of approximately 0.15 degrees. The changes in leg forces (spud can vertical soil reactions) are shown in Figure 6. The forward and port legs have a load reduction of around 33 kips each. The starboard leg has a corresponding load increase of 66 kips. Figure 7 shows heel and trim changes in terms of lateral hull movements. Figure 8 shows changes in spud can penetration with iteration number. The cans for the forward and port legs remain at the same depth, while the starboard leg penetrates an additional 0.6 feet before reaching equilibrium.

In the above scenario small initial offsets of the cg result in relatively large lateral hull deflections as equilibrium is established. The large number of calculation iterations before finding stability suggests that out of balance forces are small and that the inclination rate will be slow. When leaning occurs slowly during preloading, the rig mover will compensate for the lean by lowering the hull on the high side. Figure 9 shows changes in heel and trim for the same starting conditions as for Figure 5, but with forward and port leg lengths reduced by 0.1 feet. Equilibrium is found quickly (with few iterations) compared to figure 5; heel and trim angles are much smaller. Figure 10 shows spud can penetrations for this new condition. Again, equilibrium is established relatively rapidly, and penetration changes are small. However, the rig is sensitive to load distribution and is difficult to keep level in this soft soil.

At full preload, rig weight is 25,500 kips, resulting in an average spud can reaction of 8,500 kips. Can tips are close to 100 feet of penetration (see Table 1) legs have been extended to 280 ft, and the soil spring stiffness has increased to 140 KPF. Figure 11 shows one result of best efforts to keep the rig from leaning in these conditions, by careful adjustments of leg lengths. Stability has not been found and the rig is creeping slowly (in terms of degrees per iteration) towards a non-recoverable leaning situation. The method predicts a rapid increase in leaning rate as angles increase.

Thus far the method shows 0.3 degrees as being the maximum stable *static* hull angle at the 18500 kips preloading stage. Larger hull angles will lead to instability, **if leg penetrations progress faster than corrective jacking (lowering the high side) can reduce leg extensions.** As rig weight increases, *static* equilibrium angular range reduces (to zero at full preload).

EFFECTS OF INTERACTIVE JACKING

Counteracting the leaning of a jack-up during preloading, by operating the jack motors, naturally helps keep the rig stable. Provided that reaction and response time to counteract a lean, are shorter than the time the lean takes to become unstable, interactive jacking can keep the rig vertical in situations where it would otherwise topple. This is more difficult to simulate since a time element has to be introduced into the calculations. However, as described above, interactive jacking compensation of only 0.1 ft reduced additional leg penetration by 0.6 ft. At a typical jacking speed of 1.5 feet per minute, the correction would take the jack motors 4 seconds to achieve. Human decision making and reaction time, plus system reaction time and inertia would increase this somewhat. This time is similar to that taken for the filling rate of an outermost preload tank to move the cg by the original offset that resulted in the 0.3 degrees lean.

Interactive jacking for the 250 ft. leg length case is taking place in a situation where the rig is sensitive, but will find a stable leaning position, within a +/- 0.3 degrees hull angle range. Some directions are more sensitive than others as a consequence of leg spacings. With twice the soil stiffness and undrained shear strength, the stable range is extended to +/- 0.45 degrees and larger tolerance in cg eccentricity can be accommodated. The cg movement to create a 0.45 degrees trim with a 214 KPF soil is 0.35 feet and the number of iterations to find stability is 10, compared to 50, in Figure 5. The rig is less sensitive and easier to keep level.

In the final stages of preloading, with 280 ft leg lengths, there is no stable angle for the rig away from the perfectly level condition of unstable equilibrium. The slightest out of level condition, or lateral environmental load increase, is predicted to result in instability. Constant adjustment of the jack motors is predicted to be required while preload is being added.

Hull angles (monitored on bubble gauges) are the main feedback to rig movers as they perform the preload operation. Consequently they become used to identifying very small changes in hull inclination and reacting quickly to correct the inclination. They become capable and familiar with a practice of keeping the rig to better than within +/- 0.3 degrees from perfectly level. This tolerance is typical of that required in the Rig Operations Manual.

Field experience shows that rigs have been successfully preloaded with conditions similar to those for the 280 ft leg length case. Field experience also shows that there have been failures when the rig is **more** stable than it would be in these conditions (Reference 1). This indicates that the rig mover's skill is of great importance.

AFTER FULL PRELOAD IS REACHED

In the soft soil conditions described, the soil beneath the spud cans and fallen soil in the hole above the spud cans continues to gain strength, and more importantly, stiffness, after full preload is reached. Hence in situations where a stable leaning position has been achieved at full preload, it will become more stable with time, as preload is held constant. In cases where the rig has marginal static stability, the soil strength and stiffness necessary to provide stability in a +/- 0.2 degrees range may well develop shortly into the typical four hour time period for which preload is held. In less stable cases there may be considerable jacking intervention required during the preload period, with the consequence of working the rig from side to side and adding further penetration to the legs. When this occurs the preload period may be extended as the rig mover will interpret the rig behavior as continuing to settle.

In all cases where the stability is small, the rig will be made unstable by relatively small lateral environmental forces.

IMPLEMENTATION OF THE METHOD ON A PC

The figures showing changes in jack-up angle, etc. produced in this paper are "time-windows" of the rig's behavior, but are without true time calibration. Spud can penetration rates have not been explicitly established. Nevertheless, empirical relationships between forces, accelerations, and velocities have been postulated by the authors and built into a real-time interactive jacking computer program which has been used both for the training of rig personnel (simplified version) and as a basic research tool. The program is also used offshore on one fleet of rigs.

Interactive control of the jack motors is provided by the use of individual command keys on the PC keyboard. A complete simulation of elevating and preloading, including the simulating of various pumping rates to fill tanks, can be accomplished.

PRECAUTIONS TO AVOID LEANING INSTABILITIES

The following precautions are suggested if the method is applied and points to the potential for a leaning instability during the preload operation:

i) Comply with all normal stability requirements.

ii) Ensure that the weather forecast for the preloading period is good. It is critical that large lateral forces do not occur.

iii) Bring as much preload out of the water as can be carried by the jacks, commensurate with other safe operations constraints.

iv) Minimize large free surface effects. These contribute to the magnitude of the P-delta effect. They will also contribute to the magnitude of damage in the event of rapid leg penetration.

v) If the weather window permits the time, preload legs individually and minimize the total rig weight at any point during the operation. This will minimize P-delta effects and reduce the magnitude of damage in the event of rapid leg penetration.

vi) When preloading one leg at a time, keep the hull high, by say 0.15 degrees average, on the leg side that is being preloaded. The potential for leaning instability is minimized during the preloading of the second and third legs, if the hull on the side of the first preloaded leg is kept lowest.

vii) Use the method to predict maximum stable hull inclinations for various stages of preloading. Ensure that the rig mover and crew understand this information.

v) Whether preloading one, or all legs simultaneously, once full preload has been reached, if the rig is unstable and if the soil has increasing bearing capacity with depth, do not attempt to hold the preload and balance the rig for more than say ten minutes. There is little to gain and a lot to lose.

CONCLUSIONS

1. A new method for analyzing the on-bottom stability of jack-ups during preloading has been developed.

2. The method can be used to predict the range of hull angles for which the rig will be stable in any soil condition.

3. The method provides an explanation for one previous documented failure, and possibly explains many other jack-up foundation failures.

4. The fundamental methodology produces results which closely match those obtained in other published approaches to the problem (Reference 2)

5. Suggestions are offered for minimizing the risk of this type of failure in future rig moves.

6. Indications of typical times before leg penetration rates exceed leg jacking rates are provided, but further work is required in this area.

7. Empirical soil restraints limiting instability have been suggested, but further work is required in this area.

8. The method suggests that the skill of rig movers may be the principal prevention of rig failures in soft soils.

ACKNOWLEDGEMENTS

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REFERENCES

1. Ingram, W.B., and Dutt, R.N.:"Punch Through Instability of Jack-Up on Seabed," Discussion on April, 1985 paper of same title by Hambly, *Journal of Geotechnical Engineering*, ASCE, April, 1987, Vol. 113, No. 4

2. Hambly, E.C.:"Soil Buckling and The Leaning Instability of Tall Structures," *The Structural Engineer*, Vol. 63A, No. 3, March, 1985

TABLE 1 - Calculation of bearing capacity with depth for jack-up footing.

Tip Pene. (ft)	Found. Depth (ft)	Eq. Area sq.ft.	Eq. Diam. (ft)	cu (KSF)	Nc	Net Ul. BC (kips)	Sub. Wt. (KCF)	Buoy. Term (kips)	Gross UBC (kips)
10	0	1170	38.60	0.1	6.00	702	0.030	66	768
20	10	1170	38.60	0.2	6.31	1477	0.031	302	1779
30	20	1170	38.60	0.3	6.62	2324	0.031	308	2632
40	30	1170	38.60	0.4	6.93	3245	0.032	314	3559
50	40	1170	38.60	0.5	7.24	4238	0.033	320	4559
60	50	1170	38.60	0.6	7.56	5304	0.033	327	5631
70	60	1170	38.60	0.7	7.87	6443	0.034	333	6776
80	70	1170	38.60	0.8	8.18	7655	0.034	339	7994
90	80	1170	38.60	0.9	8.49	8940	0.035	345	9285
100	90	1170	38.60	1	8.80	10297	0.036	351	10648
110	100	1170	38.60	1.1	9.00	11583	0.036	358	11941
120	110	1170	38.60	1.2	9.00	12636	0.037	364	13000
130	120	1170	38.60	1.3	9.00	13689	0.038	370	14059
140	130	1170	38.60	1.4	9.00	14742	0.038	376	15118
150	140	1170	38.60	1.5	9.00	15795	0.039	383	16178
160	150	1170	38.60	1.6	9.00	16848	0.039	389	17237
170	160	1170	38.60	1.7	9.00	17901	0.040	395	18296
180	170	1170	38.60	1.8	9.00	18954	0.041	401	19355
190	180	1170	38.60	1.9	9.00	20007	0.041	407	20414
200	190	1170	38.60	2	9.00	21060	0.042	414	21474

TABLE 2 Rig and soil properties during preload

Total weight on cans	18000	kips	K SOIL	107.00	KSF
Length Leg 1	250.00	ft	LCG Leg 1	30.00	ft
Length Leg 2	250.00	ft	LCG Leg 2	145.00	ft
Length Leg 3	250.00	ft	LCG Leg 3	145.00	ft
LCG	106.68	ft	TCG Leg 1	0.00	ft
TCG	0.01	ft	TCG Leg 3	60.00	ft
VCG relative to keel	-6.23	ft	TCG Leg 3	-60.00	ft
I (hull)	780	ft4	I (leg)	535	ft4

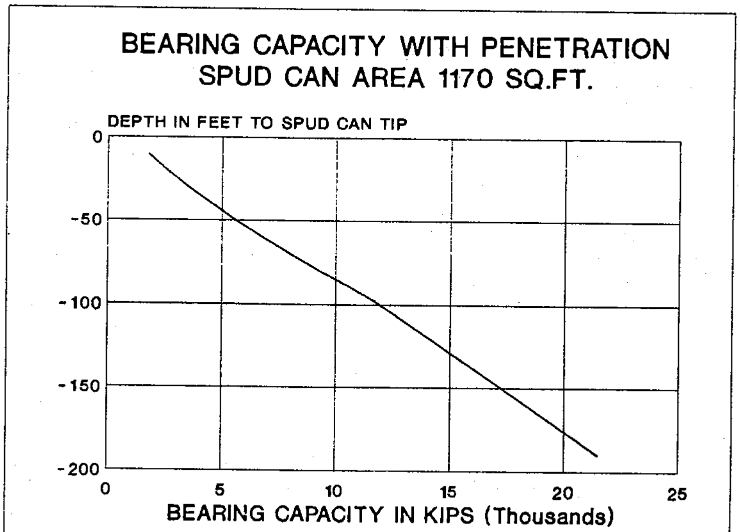


FIGURE 1

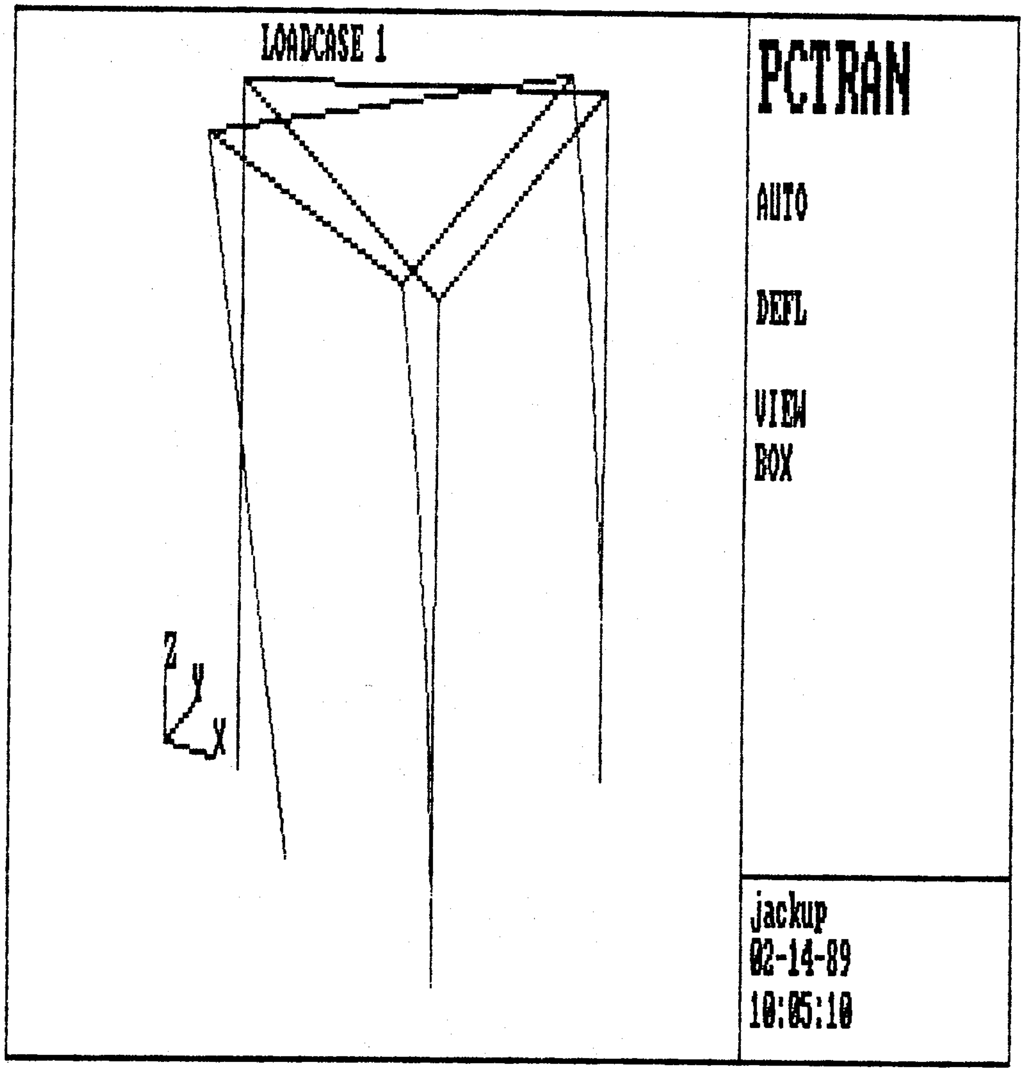


Fig. 2

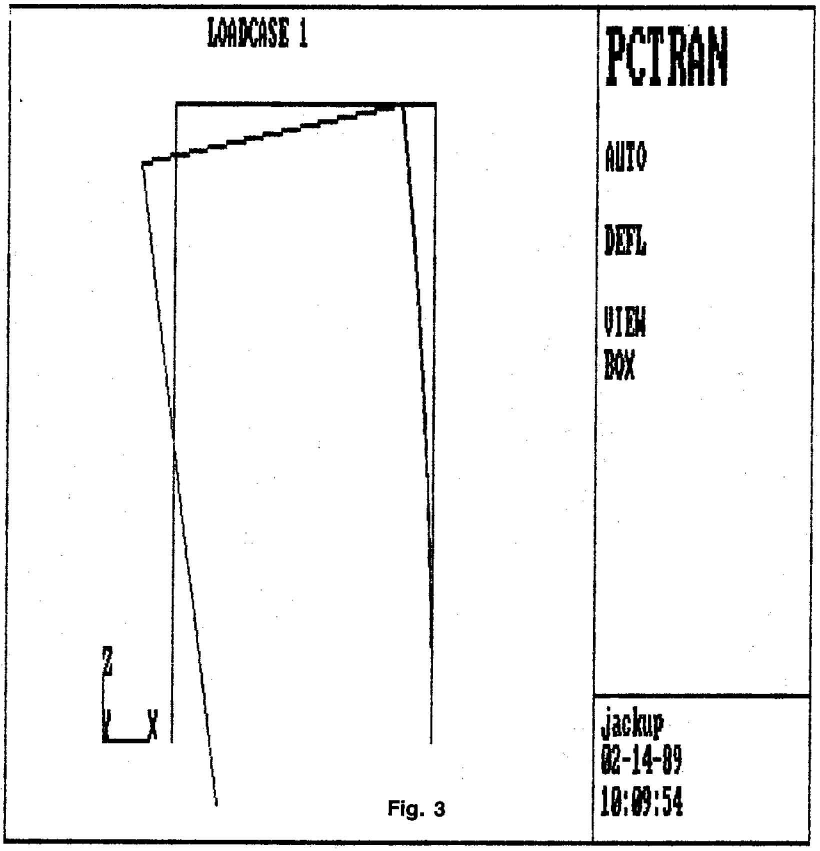
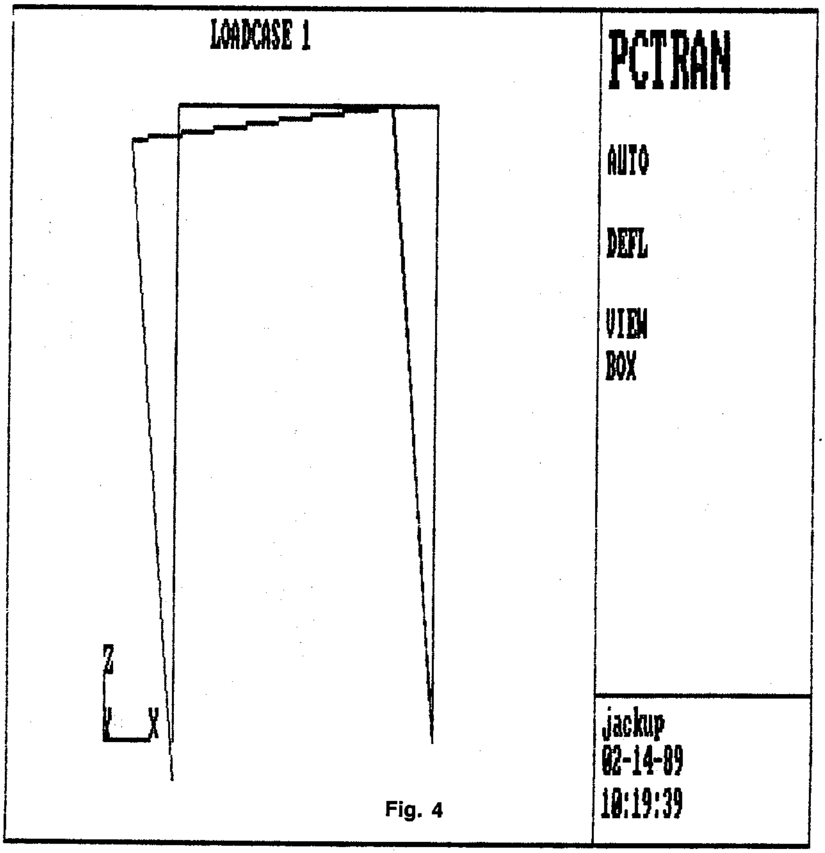

LOADCASE 1
PCTRAN
AUTO
DEFL
VIEW
BOX
Z
Y
X
jackup
02-14-89
10:09:54

Fig. 3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PCTRAN
AUTO
DEFL
VIEW
BOX
Z
Y
X
jackup
02-14-89
10:19:39

Fig. 4

HEEL & TRIM ANGLE ITERATIVE CHANGES TO REACH EQUILIBRIUM

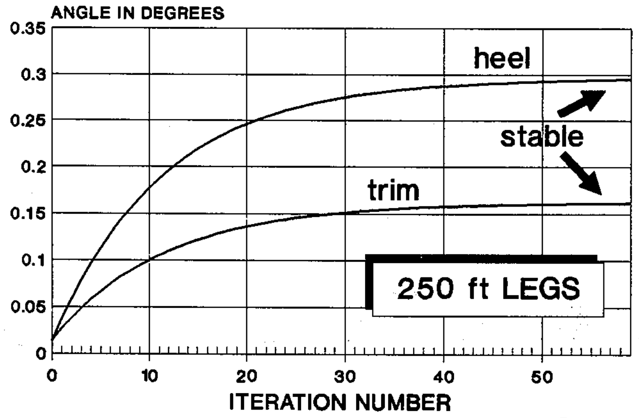


FIGURE 5

LEG FORCE ITERATIVE CHANGES TO REACH STABLE EQUILIBRIUM

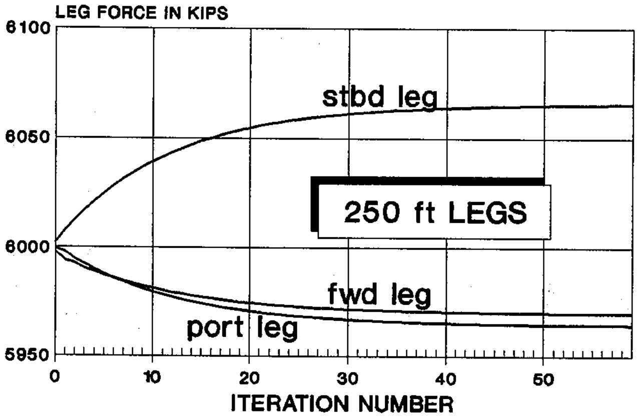


FIGURE 6

LATERAL HULL DISP. ITERATIVE CHANGES TO REACH STABLE EQUILIBRIUM

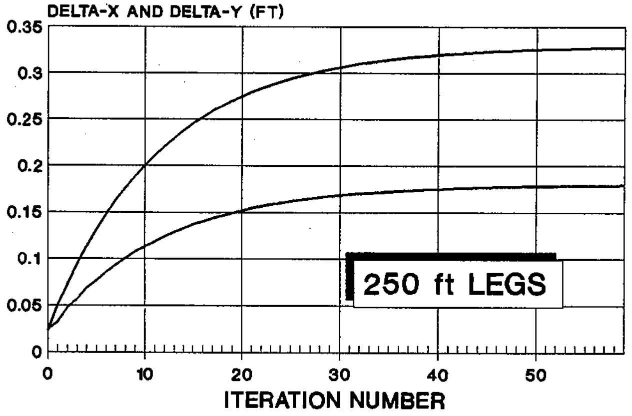


FIGURE 7

SPUD CAN PENETRATION ITERATIVE CHANGES TO REACH EQUILIBRIUM

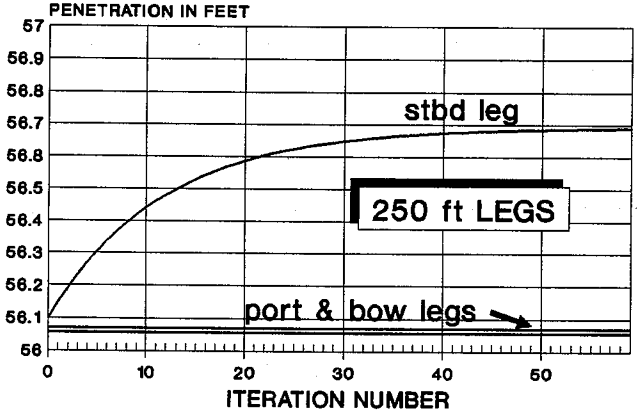
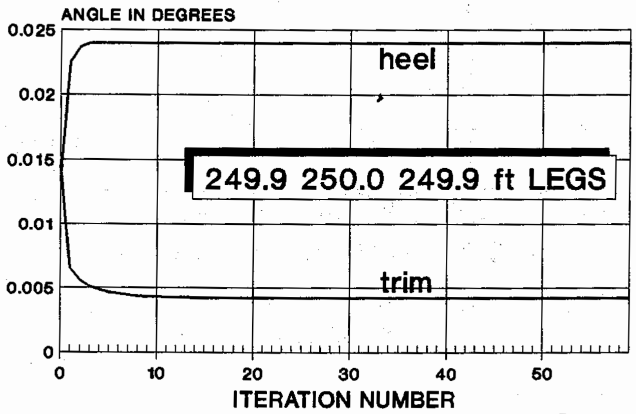
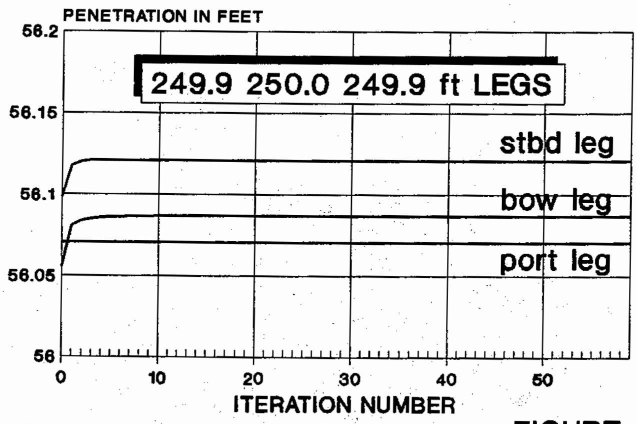


FIGURE 8



HEEL & TRIM ANGLE ITERATIVE CHANGES TO REACH EQUILIBRIUM

FIGURE 9



SPUD CAN PENETRATION ITERATIVE CHANGES TO REACH EQUILIBRIUM

FIGURE 10

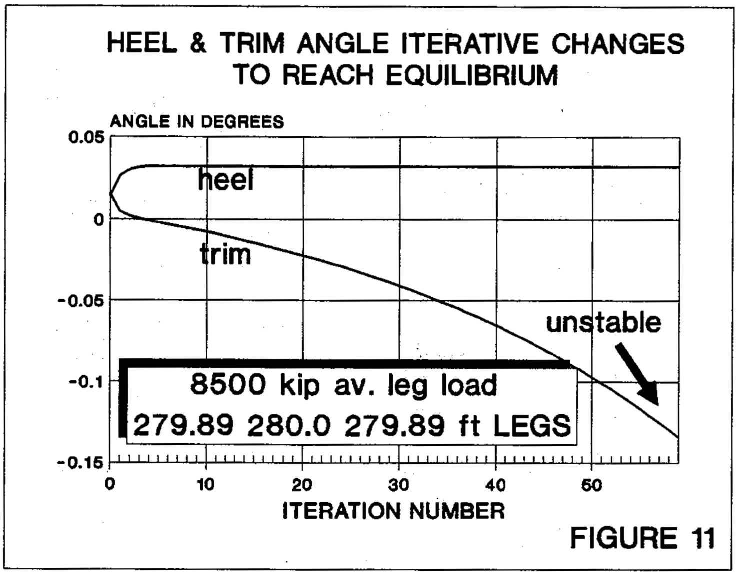


FIGURE 11

Fig. 12