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Spudcan Fixity: Lessons Learned from the Liftboat Industry

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Abstract

A description of liftboats, their evolution and role in the offshore industry is provided. Comparison of a methodology to calculate liftboat pad rotational restraint provided by soft cohesive seabed soils is made with methodologies presently proposed for jack-up spudcans. In both cases a yield surface criterion is adopted. However, for liftboat pads the concept of a "permanent" rotation being locked in to the pad as further penetration occurs is found to be a plausible explanation of liftboat survival in harsh conditions where traditional jack-up foundation approaches would predict leg failure.

Brief History of Liftboats

Liftboats are self-propelled vessels, generally with barge-shaped hulls, and three or more independent legs. These legs are raised and lowered relative to the hull, driven by hydraulic motors and rack and pinion gear systems. The legs have large footings, or pads, on their lower ends, designed to support the legs on soft seabeds, with their hulls raised out of the water. The main function of these vessels is to provide a work platform for offshore construction and maintenance operations. They generally have one or more cranes and can carry deck cargo and offshore work crews, divers, and special equipment to a work site. Once at the site they elevate their hulls out of the water and serve as stable work platforms. Typical assignment durations at a given location vary from less than one day to several weeks. Figures 1 and 2 show a typical liftboat elevated adjacent to a Gulf of Mexico production platform.

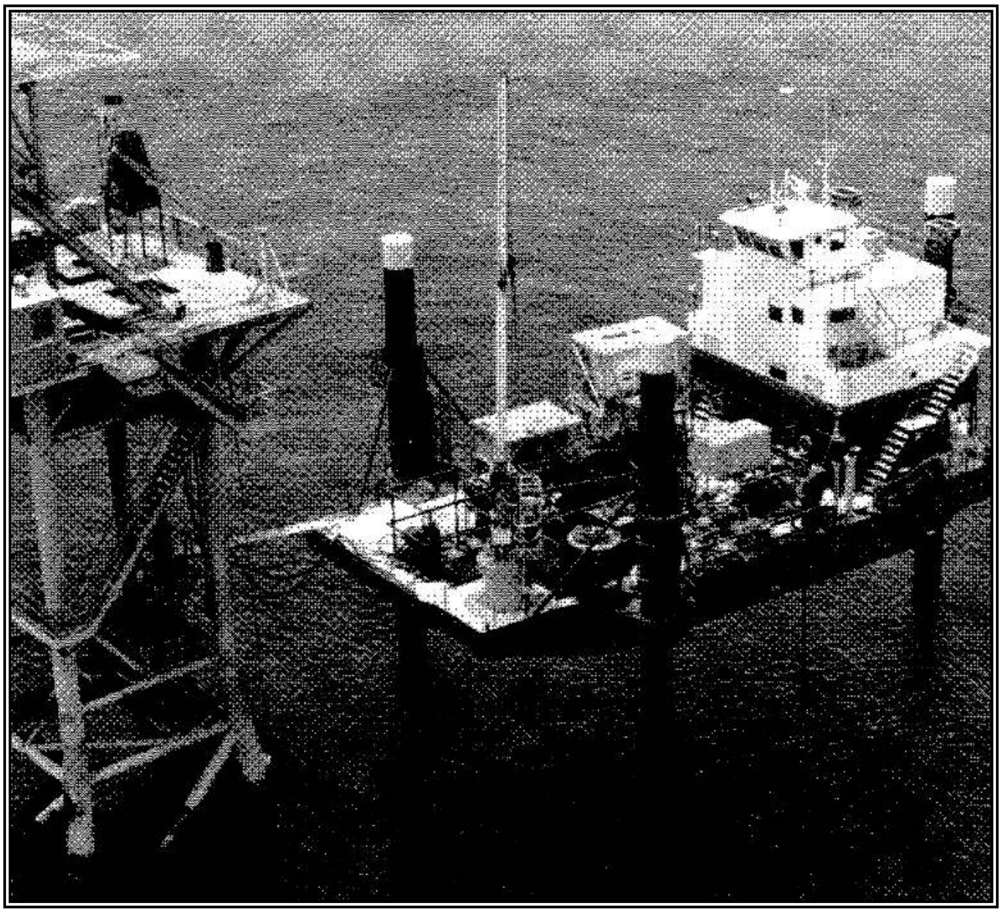

FIGURE 1 – Aft View of Liftboat Elevated Near a Production Platform

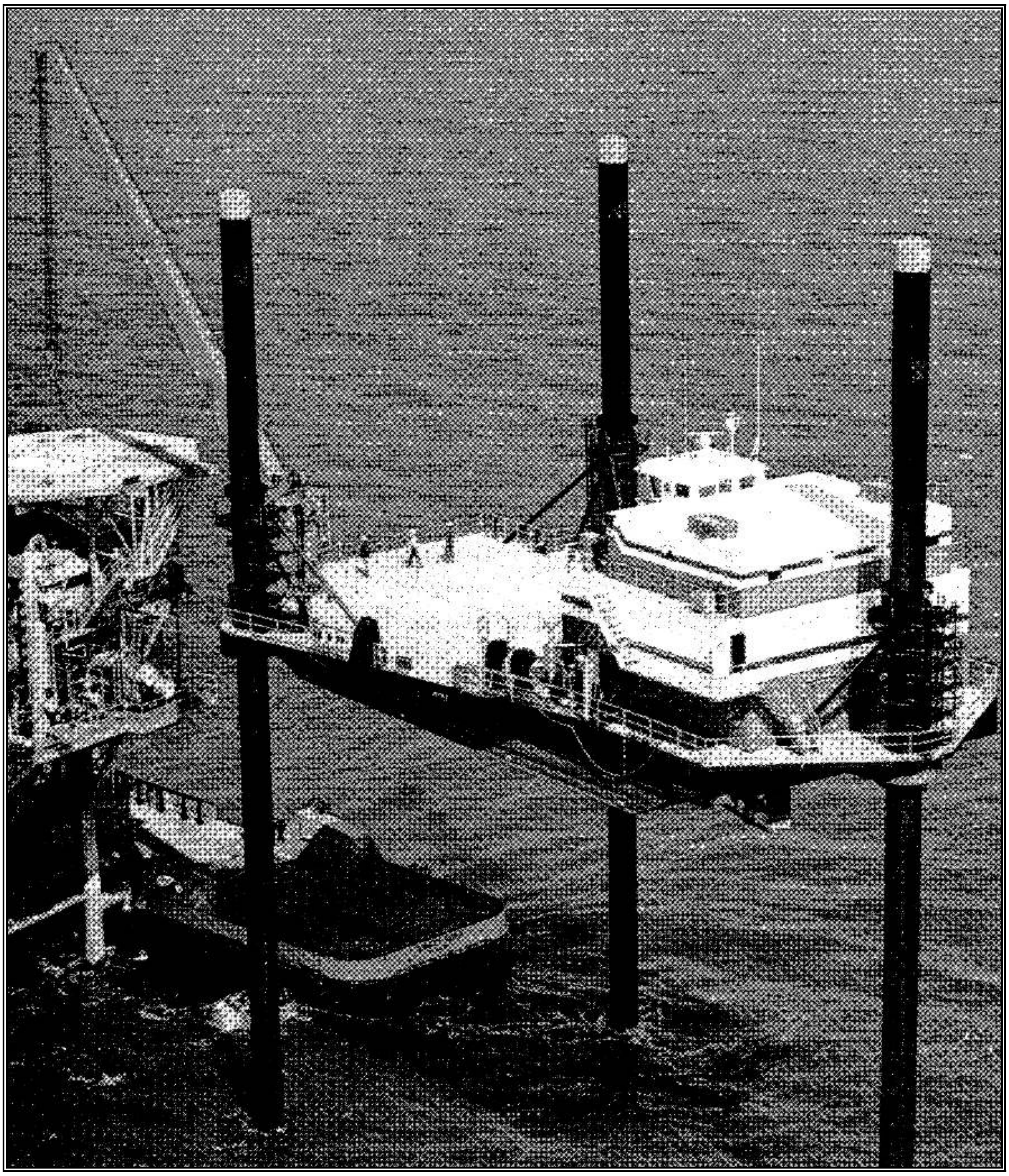

FIGURE 2 – Forward View of Liftboat Elevated Near a Production Platform

There are presently around 250 liftboats in existence (Reference 1) and the great majority operate in the coastal waters of the Gulf of Mexico. They first came into service in the 1970's (Reference 2) and were initially exempted from USCG construction and inspection standards, partly because they were under 300 gross tons, and partly because they were not thought (by the Coast Guard) to carry passengers or freight for hire. They were allowed to operate as "uninspected vessels" subject to the provisions of Sub-chapter C of Title 46 of the Code of Federal Regulations. These regulations are applied to other uninspected vessels such as recreational boats, towboats, and commercial fishing vessels, and (Reference 2) provide only basic, minimal requirements for lifesaving and safety equipment.

As the numbers of liftboats increased, they also began operating in deeper waters and venturing further from safe havens. Casualties increased and led the Coast Guard to conclude that they should apply "Offshore Supply Vessel" (OSV) regulations to liftboats. In 1987 there was a Notice of Proposed Rule Making (NPRM) to this effect, published in the Federal Register, and implemented by Change 1 to Navigation and Vessel Inspection Circular (NVIC) Number 8-81, issued in the spring of 1988. In the NVIC Change, liftboats were made subject to some OSV regulations and some self-elevating MODU (mobile offshore drilling unit) regulations.

On November 16, 1995, the US Federal Register published an Interim Rule. This publication applies to new offshore supply vessels (OSVs), including liftboats, and is essentially a complete set of regulations (a whole new subchapter L). The interim rule, published for comment, became effective on March 15, 1996. In the discussion section of the November Federal Register, the Coast Guard included the following words:

The high rate of casualties experienced by self-elevating OSVs (liftboats) requires the development of specific regulations that address liftboats' design, construction, and operations. The Coast Guard anticipates the promulgation and enforcement of the regulations in this Interim Rule will render new liftboats substantially safer than their predecessors.

In addition the Coast Guard wrote

The Coast Guard conducted its review of the available history of casualties from 1980 to 1987. The review showed that over 20% of the approximately 250 liftboats in the fleet had been involved in reported casualties, resulting in 10 deaths, 33 serious injuries, constructive total loss of 13 vessels, and overall physical damage exceeding $20 million. Many of these casualties were directly attributable to inadequate design or improper operating procedures.

Since the Coast Guard's review of liftboat casualties, and despite the Coast Guard's new inspection requirements, there have been further liftboat casualties and further loss of life. The majority of these casualties has been in transit conditions and that is not the subject of this paper, although the authors believe that afloat stability requirements for liftboats are presently inadequate.

The world's largest operating largest liftboat is the *Irish Sea Pioneer* (Reference 3). This vessel has been operating successfully for BHP on the Liverpool Bay Project for the past year and a half, providing wireline and other services to three unmanned platforms and various other facilities in the field. This vessel is unique in its maneuverability, having four azimuthing thrusters and four lattice legs with infinitely variable speed control using AC motors. The vessel also has a ratchet chock system and "conventional" spudcans typical of jack-up designs.

US Coast Guard Inspection Process

The Coast Guard inspection process is mandatory for liftboats operating in US waters. It covers design, operation, and maintenance. It does not replace classification or loadline requirements.

The Coast Guard require the structural standards for liftboats to comply either with the American Bureau of Shipping (ABS) "Rules for Building and Classing Mobile Offshore Drilling Units" or with "the standard of any classification society, or other established standard acceptable to the Commandant." The inspection requirements call for the designers of liftboats to use an effective length factor "K" of not less than 2.0 for liftboat leg design <u>if the designer has elected to comply with the ABS Rules</u>. In practice, virtually no liftboats are designed and inspected in full compliance with ABS Rules since virtually all liftboats deliberately have very large pads with low bearing pressure in comparison to jack-up spudcans. The Coast Guard now accepts that these pads provide rather large rotational stiffness to the bottom of the legs. This results in K factors significantly less than 2.0.

The Coast Guard use a computer program supplied by the authors to calculate liftboat elevated structural response as an independent check on calculations submitted by designers. The effective length factor for the legs is calculated from the pad and leg geometries. The result is compared with the K factor submitted by the designer where appropriate. This procedure began around seven years ago.

Liftboat Toppling

Reference 4 notes that in the years 1981 to 1991 there were 47 accidents involving liftboat leg failure of some kind. This included a group of eight vessels that were "knocked down" from the elevated condition during Hurricane Juan in October 1985 in the Gulf of Mexico. Three of the vessels sank, and five survived with their hulls upright and afloat, but with their legs broken off beneath the hull. Two other liftboats were seriously damaged. These remained upright and elevated but with bowed legs. All of these vessels had been evacuated. Approximately fifteen other liftboats, which were also evacuated, survived the hurricane in the elevated condition without any significant damage. No injuries or deaths occurred. Six of the ten damaged vessels were greater than 150 gross tons and four were less.

Reference 4 explains the failure mechanism by the formation of a plastic hinge in one leg, followed immediately by a plastic hinge at the same elevation (the level of the lower guide) in the second and third legs. This resulted in lateral collapse of the hull into the water, with the legs eventually breaking off beneath the hull. The paper also concludes that the failure would not have occurred in this manner without a significant contribution to pad pullout resistance coming from large, short-term soil suction effect.

It should also be noted that wave impact on the hulls of evacuated liftboats almost certainly occurred to some of the damaged boats during Hurricane Juan. This hurricane approached quickly and most of the vessels would have used supply boats to evacuate the crew as they were not equipped with helidecks. This means that the last man off has to either jump or climb down a rope onto the boat deck below. Hence the reason for a relatively small air gap.

Pad Design

Liftboat pads are very stiff steel structures, rectangular in plan view, and with a very shallow tip. Typical dimensions are around 16 ft (4.9 m) by 34 ft (10.4 m) on a 48 in (1.2 m) outside diameter cylindrical steel leg. The pad height is only around 3 ft (1 m) high. Total leg length for this diameter leg and pad size is around 150 ft (46 m). The pads are usually dry internally (as are the legs) and have numerous full depth radial stiffening plates. These pads exert a relatively low bearing pressure in the range of 700 to 1000 psf (34 to 48 KPa) in operating conditions. Maximum pressures under storm loads may approach 2000 psf (96 KPa) compared to, say, 7000 psf (335 KPa) for jack-up spudcans. Bearing pressures beneath mat supported jack-ups are around 400 to 600 psf (19 to 29 KPa) for non-storm conditions with typically a 40% increase at the edges under storm conditions.

The pad connection to the leg is designed to carry axial and shear forces, as well as a moment generally set equal to the maximum allowable moment that the leg can carry. The connection must also be designed to resist fatigue. Typically the moment at the leg-pad connection will be equal to the moment in the leg at the lower guide. This is because these vessels have rather restricted service and are not intended to be elevated in severe weather conditions. Consequently they spend much of their time elevated in mild conditions with the pads providing very large rotational restraint to the bottom of the legs. Fatigue cracks at the leg-pad connection are a common problem. However, since liftboats move so frequently, rarely spending more than a week at one location, fatigue cracks are generally discovered before ultimate failure of the connection occurs. It is not uncommon for a leg to be raised that has become flooded. The rate of leg raising, typically 6 ft/min (2 m/min) is faster than the water can drain out. This results in a relatively large list, and a prudent skipper will immediately detect that he has a problem.

Pad-Soil Interaction

Traditionally jack-ups have been designed assuming their spudcans to be pinned at the seabed. Joint industry projects, ongoing work by SNAME and IADC (References 5 and 6), and numerous technical papers (for example, Reference 7) are gradually changing this approach. For more than a decade, the Det norske Veritas (DnV) Rules (Reference 8) have permitted spudcan fixity to be permitted in jack-up rig design. As part of their research efforts involved with crafting an inspection plan for liftboats, the US Coast Guard published “Liftboat Leg Strength Structural Analysis” (Reference 9) seven years ago. This document provided an initial approach to determining the rotational stiffness of liftboat pads. Over the last few years, a calculation method has evolved and been embedded into a computer program used by several liftboat designers and by the US Coast Guard (Reference 10). This method is described below:

1. Specify undrained shear strength of cohesive soil.
2. Specify pad length and width.
3. Calculate maximum pad bearing pressure in storm condition.
4. Set preload to be equal to or greater than maximum storm load.
5. Calculate soil bulk modulus required to provide the calculated bearing capacity.
6. Calculate pad penetration.
7. Calculate properties of equivalent rotational spring.
8. Recalculate pad maximum storm load using rotational springs and iterate through steps 4 through 7 checking to insure the ultimate soil moment capacity is not exceeded.

In mild conditions the ultimate soil moment capacity is unlikely to be exceeded and a relatively large rotational stiffness is automatically used. In severe environmental conditions the program can be set to find the largest rotational stiffness that will not result in soil failure beneath the pad. The program uses a single degree of freedom (SDOF) dynamic analysis technique. Natural sway periods of liftboats are often in the 5 to 7 sec range where thunderstorm generated waves often have relatively large energy. It is therefore quite common to perform regular wave analysis using waves of almost exactly the same period as the estimated sway period. In order to provide some mitigation of very large responses in resonant conditions, the Coast Guard requested an ability for "automatic" increase of hydrodynamic damping. The calculation procedure now iterates until hydrodynamic damping and response are matched according to Equation 1 shown graphically in Figure 3:

$$2 + 5 \times \frac{amplitude\ of\ response}{0.5 \times leg\ diameter} \qquad \text{Equation 1}$$

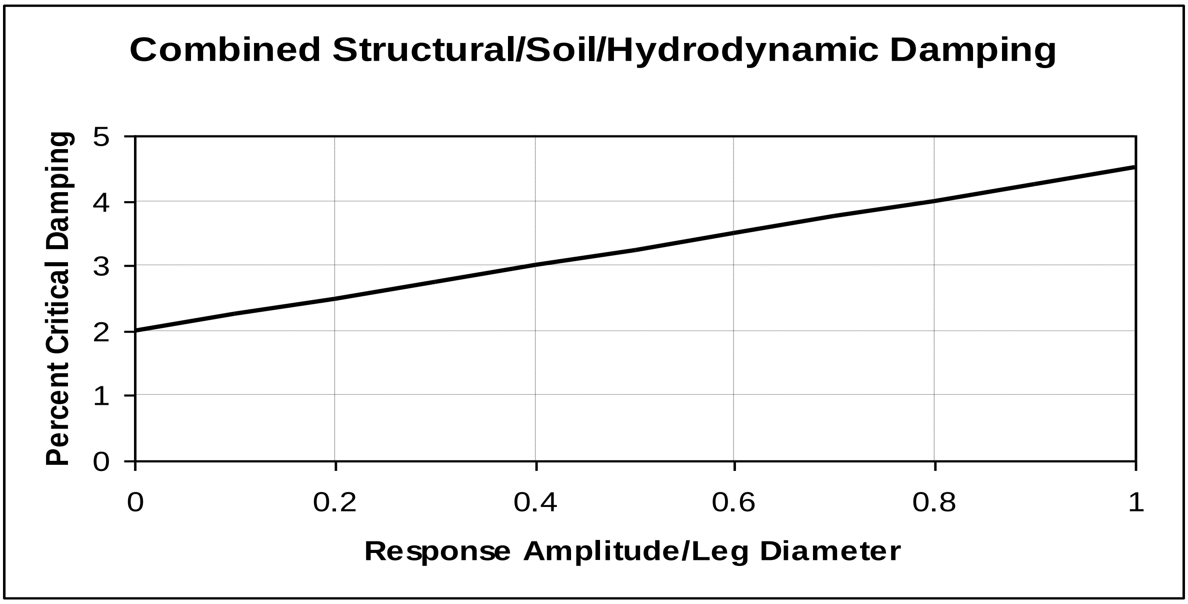

FIGURE 3 – Damping versus Response

There is little theoretical justification for this approach; rather it is a pragmatic solution to a complicated subject.

The program now checks for the maximum spudcan moment as a function of the horizontal and vertical loads as shown in Reference 5, revision 1, May 1997. However, a modification is made which is felt to be appropriate to soft cohesive soils where the liftboat pads typically penetrate in excess of 8 ft. This modification is described in the next section.

Moment Capacity of Pads and Spudcans

It is becoming accepted that the maximum moment capacity of a fully embedded spudcan in clay can be described by the yield function given below (Reference 5):

$$16\left[\frac{F_{VHM}}{V_{L0}}\right]^2\left[1-\frac{F_{VHM}}{V_{L0}}\right]\left[1-\frac{F_{VHM}}{V_{L0}}\right]-\left[\frac{F_{HM}}{H_{L0}}\right]^2-\left[\frac{F_M}{M_{L0}}\right]^2 = 0 \quad when\ F_{VHM} \geq \frac{1}{2}V_{L0}$$

$$1-\left[\frac{F_{HM}}{H_{L0}}\right]^2-\left[\frac{F_M}{M_{L0}}\right]^2 = 0 \quad when\ F_{VHM} < \frac{1}{2}V_{L0} \qquad \text{Equation 2}$$

where

F_{VHM} = vertical foundation capacity in combination with horizontal and moment load,
F_{HM} = horizontal foundation capacity in combination with moment,
F_M = moment capacity of foundation,
V_{L0} = maximum vertical foundation load during preloading,
$H_{L0} = A\ c_{u0} + (c_{u0} + c_{u1})\ A_s$, the maximum sliding capacity factor in clay (occurring at $V = 0.5\ V_{LO}$ and $M = 0$),
$M_{L0} = 0.1\ V_{L0}\ B$, maximum moment capacity (occurring at $V \approx 0.5\ V_{L0}$ and $H = 0$)
A = spudcan effective bearing area based on cross-section taken at uppermost part of bearing area in contact with soil,

A_s = spudcan laterally projected embedded area,
B = effective spudcan diameter at uppermost part of bearing are in contact with the soil (for rectangular footing B = width),
c_{u0} = undrained cohesive shear strength at maximum bearing area (D below mudline,
c_{u1} = undrained cohesive shear strength at spudcan tip,
D = distance from mudline to spudcan maximum bearing area.

The load combination (vertical, horizontal, and moment) lies outside the yield surface if the left hand side of Equation 2 is less than zero and inside the yield surface if greater than zero.

Equation 2 can be rewritten so that the maximum permissible spudcan moment (on the yield surface) becomes a function of the horizontal and vertical loads as is shown in Equation 3:

$$F_M = M_{L0} \left\{ 16\left[\frac{Q_V}{V_{L0}}\right]^2 \left[1-\frac{Q_V}{V_{L0}}\right]\left[1-\frac{Q_V}{V_{L0}}\right] - \left[\frac{Q_H}{H_{L0}}\right] \right\}^{0.5} \qquad \text{Equation 3}$$

where:

Q_V = applied vertical load,
Q_H = applied horizontal load.

For a given combination of applied vertical and horizontal loads, the moment at the spudcan cannot exceed the value defined above (Reference 5). If the maximum permissible spudcan moment is exceeded during a wave cycle, there will be plastic deformation of the soil. The path in unloading will be different from the path when the maximum loads were reached. Stable conditions are unlikely to develop after a single wave cycle but will tend towards a condition where a permanent rotation is locked in. This is especially true where the leeward leg of a vessel is loaded close to, or even above, its preload level. This commonly occurs with liftboats and further pad penetration during storms is simply compensated for by jacking the hull up. When the pad penetrates further into the soil, under a large vertical load, simultaneously experiencing a rotation caused by the environmental overturning moments, the pad ends up at an angle. The upper bounds for the final pad angle may be the pad angles that would occur during the wave cycle if the leg was pinned. However, because of some plastic resistance of the soil to the pad rotation, the maximum equivalent pinned angle is unlikely to be reached.

The liftboat analysis procedure used by the US Coast Guard now uses the pad mean angle calculated as if the soil rotational stiffness was correctly assessed. Then the amplitude of pad rotation about this mean is used to determine the maximum pad moments during a wave cycle. This procedure assumes that the pads will bed down during a storm as has been suggested by Hambley (Reference 11). The geotechnical portion of Reference 5 was verified and improved upon in 1996-1997 following a study performed by SINTEF (Reference 12) commissioned by SNAME. SINTEF cited Hambley's work and noted that he suggested *"this condition may be approached analytically by calculating the deformations due to the "static" wind + current loads with a pinned foundation, and then evaluate the rotation foundation stiffness for the wave loads only. The dynamic analysis would then only include wave loads"*.

This paper suggests that the mean pad inclination angle should correspond to the mean angle during a wave cycle, given the full environmental load (wind, current, and waves) and a cyclically degraded soil shear modulus for rotational loading. As the pad rotates to this mean angle, there will be some further penetration. The cyclic motions of the pad caused by further wave loading will then result in pad moments oscillating about a zero mean value, with pad rotations oscillating about a nonzero value. An iterative (trial and error) process is required to find an allowable stiffness for the equivalent linear rotational spring representing the soil.

This paper goes on to suggest that where the leeward leg induces soil moment amplitudes which peak outside the yield surface but the windward legs have load conditions inside the yield surface, then the average of the maximum allowable moments should be taken. For simplification of the dynamic response analysis each pad is considered to have the same horizontal load and the same moment (same rotation) at every instant during the wave cycle. Provided that the amplitude of this induced moment is less than the average allowable moment (calculated using Equation 3) the vessel is considered to be responding reasonably. In order to achieve this balance, the shear stiffness of the soil (G/s_u) is adjusted manually. For liftboat pads in storm conditions experience has shown that shear stiffness values in the range of 15 to 50 are required when this methodology is applied. In the mild conditions generally associated with liftboat "design" much larger values of shear stiffness, sometimes up to 1000, are possible. However, values larger than 200 are generally not used.

It is considered that in storm conditions, where the leeward leg moment at the pad fails to stay within the yield surface after the pad has ceased to penetrate further, the time history of the moment at the pad will be as shown idealized in Figure 4. The nonlinearity induced by the elasto-plastic behavior of the pad moment induces hysterisis which is not accounted for in the linear SDOF approach.

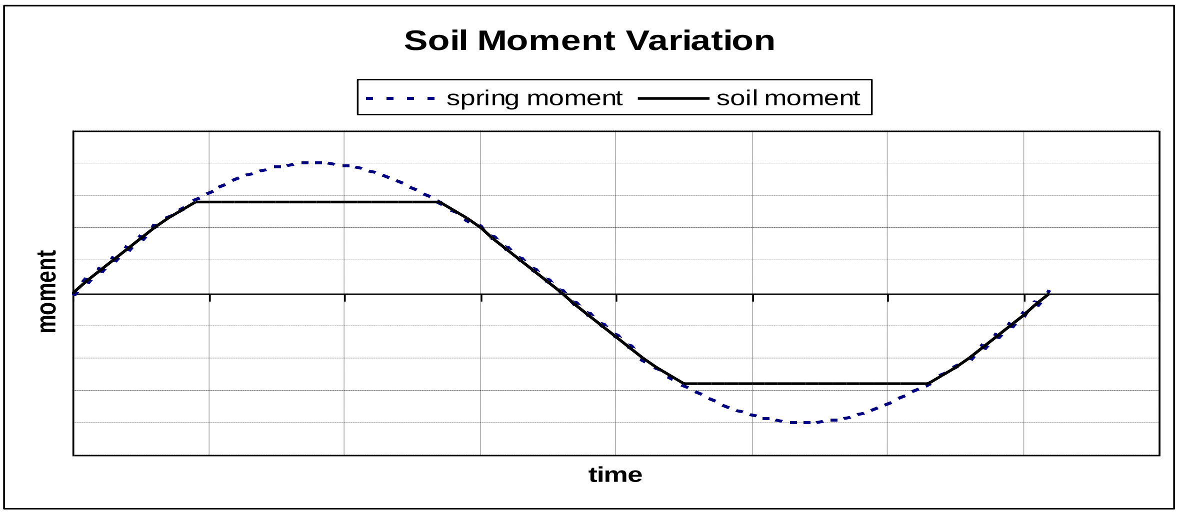

FIGURE 4 – Soil Moment Variation During Passage of Wave

Summary and Conclusions

The US Coast Guard currently regulates Liftboats in the USA. New boats are designed in accordance with the Code of Federal Regulations and are permitted to have relatively large rotational fixity of their pads. Presently the methodology used to calculate this fixity is somewhat different to that proposed for jack-ups. The methodology uses the following assumptions:

1. Maximum allowable pad moments can be calculated from the yield interaction equation in Reference 5.
2. Linear rotational springs can be used to represent soil rotational stiffness at the pads using the method in Reference 5.
3. Horizontal loads at all pads are equal.
4. Moments induced at all pads are nominally equal.
5. Additional penetration of the leeward pad will typically occur in storm conditions and will be compensated for by jacking up the hull.
6. As any pad penetrates further it will be inclined at a mean angle. The mean angle will be equal to the average of the applied moment divided by the soil stiffness.
7. After inclination the pad rotations during a wave cycle will oscillate about the inclined position while pad moments will oscillate about a zero mean value.
8. The soil shear stiffness must be manually adjusted until the average of the maximum value of the pad moments is less than the average of the allowable pad moments calculated using the yield surface approach in Reference 5.

Experience in the liftboat industry indicates that the above approach while relatively simplistic can explain the numerous cases where liftboats have survived storm conditions where failure would have been predicted without the arguments put forward in points 3 through 8 above.

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