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Observed Storm Stability of Jack-Up Boats (Liftboats)

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ABSTRACT

A rational approach to establishing overturning loads for liftboats is presented. Resistance to overturning as a consequence of geotechnical forces is shown to be a significant contributing factor to the elevated stability of liftboats. The same calculation techniques can be used also for jack-ups.

Observed conditions in Hurricane Juan where some liftboats failed by overturning, some liftboats had legs broken off but the hulls survived afloat, and some liftboats survived without damage are presented. A general procedure for determining ultimate overturning resistance for liftboats accounting conservatively for pad rotational stiffness is defined.

INTRODUCTION

Liftboats are self-propelled barge shaped vessels which generally have 3 legs. These legs are attached to the hull via jacking towers. The jacking towers connect to the legs through a rack and pinion system enabling the hull to be raised and lowered out of the water on the legs. In many respects, these vessels are similar to jack-up drilling units. However, their mission is not to drill but generally to perform construction and maintenance operations on fixed structures in nearshore and offshore waters. Approximately, 250 liftboats were operating in U.S. waters in 1990, most of these being in the Gulf of Mexico.

Liftboats have recently become subject to the inspection requirements of the U.S. Coast Guard. In 1987, there was a Notice of Proposed Rule Making (NPRM) published in the Federal Register and implemented by Change 1 to Navigation and Vessel Inspection Circular (NVIC) No. 8-81, issued in the spring of 1988. Several further changes have occurred since that time to the requirements for liftboats. The most recent being in the form of a new draft NVIC at the time of writing (February 1991) which will replace the earlier NVICs and their revisions. There is much debate still within the liftboat industry regarding the necessary minimum requirements for the vessels structurally when elevated. Additionally, there is debate regarding the necessary minimum afloat stability requirements for the vessels.

There have been 47 accidents in the last 10 years involving liftboat leg failure of some kind. These include a group of eight vessels which were overturned from the elevated condition during Hurricane Juan. Other accidents involving leg failure have included punch-throughs and improper vessel operations amongst other causes. There have been at least 13 vessel losses in the last 10 years, and 21 deaths associated with liftboat accidents. However, the majority of these fatalities have not been associated with structural failure in the elevated operating condition.

HISTORICAL DESIGN BASIS FOR LIFTBOATS

There has not been a consistent approach to the design of liftboats within the liftboat industry. Liftboats are very flexible in the sway direction when elevated, in comparison to jack-up drilling units. Liftboat legs are typically cylindrical with a diameter to thickness (D/t) ratio of around 60 with 30 inch outside diameter and smaller being quite common. Newer vessels and larger vessels tend to have larger legs. The three most recent liftboats built in the Gulf of Mexico by Bollinger Shipyards, Louisiana, have legs which are 130 feet long with an outside diameter of 42 inches with wall thickness of approximately 0.72

References and figures at end of paper

inches (D/t = 58). Unlike jack-ups, liftboat legs are typically powered by a single rack. Also unlike jack-ups, liftboats spend much time in transit and many of the smaller boats return to port at night. Consequently, liftboats are involved in elevation operations, going on and off location often on a daily basis. The latest Bollinger legs are fabricated of 70 ksi steel with some longitudinal internal stiffeners. The rack is 100 ksi steel and is driven by 4 inch wide 100 ksi pinions with six pinions per leg.

Instead of spud cans at the bottom of their legs, liftboats typically have rectangular pads. These pads exert a relatively low bearing pressure on the sea bed, with the average being in the range of 700 to 1000 psf. Maximum bearing pressures under storm loading may approach 2000 psf. This may be compared to bearing pressures for medium-duty independent-leg jack-ups which have average bearing pressures often in excess of 5000 psf and maximum pressures under storm loading in excess of 7000 psf. Mat-supported jack-ups are in the range of 400 to 600 psf for non-storm conditions with full variable load. Under maximum storm conditions, pressures under the mat edges may vary by as much as +/-40% of the average mat pressures in the absence of storm loads..

The pads of liftboats typically penetrate into soft sea bed soils only around 5 feet with 10 feet being possible in very soft conditions. This may be compared to penetrations for independent leg jack-ups which can exceed 100 feet. For mat-supported jack-ups, penetrations are generally similar to or less than penetrations for liftboat pads.

It is conventional in the liftboat industry to refer to boat size in terms of leg length. Consequently, the boats noted above built by Bollinger are termed the "Bollinger 130 Class", as they have 130 foot long legs. Their hull length is 81 foot. Although the latest vessels represent what may be termed "state-of-the-art" in liftboat design, they have evolved from previous designs which have generally been extrapolated from the early very small vessels, having characteristics which seemed to work quite well in very sheltered areas.

Before the Coast Guard required liftboats to be inspected, there were no hard and fast rules for environmental conditions that the vessels should be able to withstand, either while elevated or afloat. Furthermore, there were no hard and fast rules for structural capabilities. Consequently, the designers of early vessels did not necessarily take into account the large lateral deflections (often referred to as the P-delta effect) increasing bending moments in the legs in the area of the lower guide. Similarly, Euler amplification was not necessarily considered when calculating sway deflections. Dynamic response and stress amplification was not normally calculated. These terms are now generally well understood by designers in the liftboat industry, just as they are now well understood in the jack-up industry.

One difference in design philosophy between jack-up rigs and liftboats is that jack-up designers almost invariably consider the legs to be pin-jointed at the spud cans (jointed to the sea bed) in order to determine ultimate structural capacity of the rigs when subject to environmental loading. Although there has been much research in the jack-up industry into spud can rotational fixity at the sea bed, and although some designs have been approved by classification societies with the inclusion of some moment capacity (provided to the cans at the sea bed), it is still fairly conventional to assume a pin-joint for the purposes of designing the structures. In the liftboat industry, the relatively larger pads in comparison to the leg sizes, has prompted designers to assume that some sea bed fixity is available in the form of moment restraint at the bottom of the legs. There is continued debate in the industry about how much moment restraint is appropriate. This debate is generally centered upon what is an appropriate effective length factor, or K-factor, to be used in the design of the legs. Since the legs are not perfectly fixed to the hull but are restrained from bending by horizontal reactions at the upper and lower guides, an effective length factor of around 2.2 results if the bottom of the leg is considered to be pin-jointed. A K-factor of 2 is generally regarded as a reasonably conservative number for the purposes of design. This K-factor of 2 assumes that some moment restraint is provided by sea bed soils to the pads. The claimed water depth capability of a liftboat is often referred to simply in terms of its leg length using a formula as follows:

Working water depth = A - (B + D + E + F + G)

Where: A = Leg Length
B = 10 Foot Air Gap
D = Leg Penetration Calculated as 10% of A
E = Leg Jacking Tower Height Calculated at 8% of A
F = Hull Depth Calculated at 5% of A
G = Reserve Leg Length Calculated at 3% of A.

This formulation is typically used in the liftboat industry to establish a water depth rating for a liftboat. It must be noted that this water depth rating is in the absence of environmental loading. Some liftboats may be able to withstand a 1-year storm at this water depth while others may not be able to safely withstand a relatively mild storm without suffering leg overstress or other potentially serious failure. Clearly, the 10-foot air gap included in the above definition is inadequate to enable the vessel to operate safely in any kind of wave conditions associated with typical Gulf of Mexico storms where there may also be a storm surge raising the water depth by several feet.

EVOLVING DESIGN CRITERIA FOR LIFTBOATS

Early liftboats were quite small and almost always returned to harbor at night. Consequently, they were not designed to be able to withstand severe environmental loading. As liftboat operations have extended out into deeper waters, their capability to withstand environmental loading has increased. However, there is no common consensus as to what the level of environmental loading is that liftboats can (or should be able to) typically withstand. The Coast Guard have not given any clear guidance in this area. In general, liftboats may not be able to safely withstand even a 1-year storm when elevated to operating air gap at their maximum water depth capability. A SNAME Committee (a sub-committee formed from the Offshore Committee) is presently developing a Technical Research Bulletin which addresses design requirements for liftboats. When complete, this document will be a useful guide to naval architects for the design of future liftboats to consistent and safe standards.

It is generally necessary in the analysis of liftboats to consider hydrodynamic loads on the legs calculated using shallow water wave theory. A reasonable approach resulting in generally conservative numbers is to use the ABS method presented in Appendix A to Reference 1.

Reference 2 provides a comparison of results obtained using the ABS shallow water wave theory for loading on liftboat legs with results obtained using solitarily, cnoidal, Airy, and Stokes' 3rd order wave theories. It is concluded that the ABS method yields consistent results for all wave height-period-water depth regimes, coming close to (but generally slightly above) forces and moments predicted by the most appropriate wave theory for each regime.

A detailed commentary on all appropriate structural analysis and loading calculations for liftboat design and analysis is given in References 2 and 3. The recommended minimum K factor in these references is 2.0 for the design of new liftboats for storm conditions. This is in line with the new draft NVIC noted above. However, it is suggested that lower values may be permissible with different pad design.

Liftboats must now be operated in accordance with instructions contained in an Operations Manual. These instructions must address maximum wind and wave conditions in which the boat may safely remain elevated, at a safe air gap that will prevent wave impact on the vessel's hull. Reference 3 suggests minimum design capabilities in terms of environmental loading for liftboats that will operate offshore. Design storm conditions for (elevated) vessels approved for "restricted" service are recommended to be a minimum wind speed of 70 knots, and a uniform current of 1.7 knots. The minimum wave height and period should correspond to a 1-year return period storm and can be linked (in the Gulf of Mexico) to maximum operating water depth in accordance with industry practice. All forces are to be considered co-linear.

For vessels approved for "unrestricted" service, the design wind speed is recommended to be 100 knots, together with a uniform current of 2.5 knots. Wave height and period (also linked to maximum operating water depth) should correspond to a 100-year return period storm wave. The terms "restricted" and "unrestricted" are defined in the Coast Guard NVICs.

It is unlikely that any unrestricted boats liftboats will be built in the next ten years and none exist. The new draft NVIC suggests only a 50 knot wind speed as a minimum requirement for restricted liftboats in the elevated condition, but offers no guidance as to minimum wave conditions.

The above information on accident history and the evolution of liftboat design criteria is provided in order to give the reader a better appreciation for the explanation of events during Hurricane Juan.

OBSERVATIONS DURING HURRICANE JUAN

During Hurricane Juan, there were approximately 25 liftboats on location in the Gulf of Mexico. Ten boats suffered serious damage. Eight of these collapsed from their elevated position, and of those, three sank and five survived with their hulls upright and afloat, but with their legs broken off. Two remained upright and elevated but with bowed legs. All of these vessels had been evacuated. Approximately 15 other vessels which were also evacuated, survived the hurricane in the elevated condition without any significant damage. No injuries or deaths were incurred by any crew members or contract service personnel aboard any of the liftboats that were operating in the Gulf at the time of these casualties. Of the above ten damaged vessels, six were greater than 150 gross tons and four were less.

Four of the liftboats exposed to the hurricane have been studied in some depth. These four boats varied in size and other characteristics as shown in Table 1. The three smallest boats were all in relatively shallow water (not greater than 30 feet). The largest boat was in 80 foot of water as Hurricane Juan passed by. The locations of the boats compared to the path of the Hurricane are shown in Figure 1.

Estimates of the wind and wave conditions during Hurricane Juan on the critical days of 28 through 31, October 1985, vary somewhat, but two analyses of the conditions by reputable weather service organizations put maximum sustained wind speeds during this period at around 75 knots. One rig is said to have reported sustained wind speeds of 75 to 80 knots with gusts to 95 knots. Tides were generally 3 - 6 feet above normal along the northern Gulf coast from the upper Texas coast to northwest Florida. The maximum sustained wind speed reported by reconnaissance aircraft was 75 knots on the morning of October 28. Wave heights were reported offshore in the height range of 25 - 35 feet. It is considered that these reported wave heights were maximum wave heights as opposed to significant wave heights.

For the purposes of this paper, it is considered unlikely that any of the four liftboats (positions shown in Figure 1) saw 30-second wind speeds in excess of 85 knots. Because of their geographic position, boats 1 and 3 on Figure 1 probably did not see 30-second wind speeds greater than 75 knots.

PAD ROTATIONAL RESTRAINT

In order to calculate a rational response of the liftboats in a retrospective analysis, soil strength data is used to find pad ultimate moment capacity. Using a plastic analysis, a limiting, or ultimate moment capacity, for the footing of the liftboat can be calculated. The ultimate moment capacity of the footing dictates the maximum rotational footing restraint that may exist at a particular location. This term may be used to find the maximum permissible value of stiffness for a rotational spring at the footing. This rotational spring stiffness may then be used to find the minimum K-factor value that should be used for the liftboat leg at a particular location, under a particular set of load conditions.

The equation below gives the ultimate moment capacity for a rectangular footing loaded by a moment about the lengthwise axis.

$$M_{ult} = 0.25\pi(\text{width})^2\,(\text{length})s_u + 0.0833\pi(\text{width})^3\,s_u \quad \text{....... (1)}$$

Where:

M_{ult} = ultimate moment capacity of footing for this soil and load direction

width = width of rectangular footing

length = length of rectangular footing

s_u = undrained shear strength of cohesive soil beneath footing.

A similar expression can be developed for non-cohesive soils. The value for s_u should reflect the soil strength gradient beneath the footing. If it is uniform, or increasing slowly, the value for s_u may be the average value at a depth equal to half the footing width. Similar expressions can be developed for any footing geometry.

The failure surface is conservatively assumed to be semi-cylindrical, with the bottom of the pad coincident with the diameter of the cylinder. The undrained shear strength is mobilized throughout the failure surface, including the two semi-circular vertical planes beneath the two ends of the pad. A diagram of the failure surface is shown in Figure 4, where the more commonly considered failure surface for principally vertical, eccentric loading is also shown. The conservative cylindrical surface is strictly applicable to pure applied moments with the vertical load at some value less than the pre-load value. The moment capacity may be reduced if applied vertical loads are close to maximum preload levels, although the failure surface will be similar to the one labeled "non-conservative" in Figure 4. Conversely, if the applied vertical load is reduced to near zero, the moment capacity will be reduced, but not by much in cohesive soils, since an upward suction develops beneath the side of the pad being lifted (at wave cycle frequency). The moment capacity will also be reduced by horizontal loads, but this may also be a small effect for typical liftboat pads.

PAD PULL-OUT RESISTANCE

It has been demonstrated that the process of breakout of relatively shallow objects from the sea floor has many common features with the process of soil consolidation under a downward load. Reference 5 provides a good review of this subject and Reference 4 shows experimental data.

When an upward load is applied to an embedded liftboat pad (a relatively shallow foundation) excess negative pore water pressure develops beneath the pad. In cohesive soils where drainage cannot occur quickly, the upward load is carried immediately by the water. If soil failure does not occur and the load is maintained, the excess negative pore pressure gradually dissipates and the upward load is gradually transferred to the soil structure. Under steady upward load conditions under a liftboat pad, soil failure will eventually occur (for example in the case of extracting pads when going off location). However, if the upward load occurs during part of a wave cycle and becomes a downward load for the remainder of the wave cycle, soil failure and pad pull-out may not occur.

In order to calculate upward short-term pull-out resistance of a pad, the normal bearing capacity equation should be modified as shown below.

$$q_b = k_c s_u N_c + k_\gamma \gamma' B N_\gamma - k_q \gamma' D N_q \quad \text{.. (2)}$$

Where:

q_b = break-out bearing capacity

k_c = dimensionless shape factor

s_u = soil undrained shear strength

N_c = dimensionless bearing capacity factor

k_γ = dimensionless shape factor

γ' = soil effective unit weight

B = pad width

N_γ = dimensionless bearing capacity factor

k_q = dimensionless shape factor

D = pad depth in soil

N_q = dimensionless bearing capacity factor

Maximum upward load for immediate undrained break-out is given by:

$$Q_{max} = q_b A \quad \text{.. (3)}$$

Where:

A = pad area

The soil stress history prior to upward loading must be considered. In downward loading analysis, the $\phi = 0$ method of analysis is generally used to investigate the stability of saturated clay foundations. The undrained shear strength is used with angle of internal friction (ϕ) set to zero. However, with time drainage occurs and the soil becomes stronger. Break-out resistance will be under-estimated with $\phi = 0$. An exception to this is when cyclic soil loading occurs, as under liftboat pads in storms. In this case, break-out resistance may be better represented with $\phi = 0$.

Based upon the soil data for the liftboat locations studied, the above method (using the remolded clay shear strengths) results in pad predicted pull-out resistance in the range 250 to 300 kips for the smaller three boats, and around 350 kips for the larger boat that suffered leg failure.

RETROSPECTIVE ANALYSIS

Liftboats 1, 2, and 3 survived the hurricane event. Liftboat 4 had its legs broken off. The hull survived upright and afloat and was subsequently recovered. A retrospective analysis has been performed for these liftboats (characteristics in Table 1) with the environmental conditions shown in Table 2.

It is interesting to note that analysis of the three surviving vessels confirms that they appeared theoretically to have a good reserve of elevated stability enabling them to remain upright and to resist any structural damage, in particular at the area of the leg and the lower guide). This was in fact the case. The wind speeds were taken to a maximum of 85 knots in each analysis, although boats 1 and 3 are unlikely to have seen much above 75 knots. Nevertheless, this demonstrates their reserve load capacity. Maximum probable wave heights at the respective locations are estimated from available information to have been 15 feet at boats 1 and 3, 20 feet at boat 2, and 25 feet at boat 4.

Table 3 summarizes the results of the retrospective analysis. Boats 1, 2, and 3 show adequate factors of safety against overturning.

Stress Checks

Unity stress check results are shown in Table 3 for three different formulae. The stress check formula considered most appropriate for liftboat legs is that from DnV MODU Rules (Reference 6) with further explanation of its application in DnV Classification Note 31.5 (Reference 7). This is the only rational check of the three which considers the large lateral deflections and secondary bending stresses induced in liftboat legs. While the 1988 ABS unity check jumps (when axial stress exceeds 15% of allowable) to a formulation which considers "compression members in frames subject to joint translation (sideways)" the application of the formula to stresses that have been calculated correctly accounting for secondary bending results in overly conservative unity check values. From preliminary results it seems that the old (pre-1988) ABS unity check gives results which are very similar to those obtained using the rational DnV formula when applied to liftboat legs where secondary bending stresses have been accounted for in the overall stress formulation.

Boats 1 and 3 easily pass all unity stress checks. For Boat 2 a unity stress check of 1.25 (DnV method) is found. However, the legs did not suffer damage.

Pad Ultimate Moment Capacity

The ultimate moments that can be supported by the footings about their narrow axis, according to the formula presented above are shown in Table 3. For the particular loading for each boat, the rotational spring stiffness at the bottom of the legs has been changed until the maximum moment induced at the pads matches the ultimate moment value, or the term Gfactor (defined below) reaches 1000. The K factor resulting from this bottom stiffness is also reported in Table 2. A more accurate investigation would consider the time history of induced moment beneath each leg during the passage of the wave. A non-linear stiffness should be modeled to better reflect the real soil behavior. A linear spring and a check on merely the maximum moment value has been considered here.

Pad Rotational Spring Calculations

The pad rotational spring is found from the analogy of a disk on an elastic half-space, as documented in References 2 and 3, using the formulae below.

$$k_s = \frac{8Gr^3}{3(1-\upsilon)} \qquad (4)$$

$$G = s_u G_{factor} \qquad (5)$$

Where:

k_s = pad rotational spring stiffness

G = soil shear modulus

r = equivalent pad radius

υ = soil Poisson's ratio (=0.5)

G_{factor} = factor on shear strength for soil shear modulus

K Factors

The effective leg lengths, or K factors for the three smallest boats range from 1.19, for Boat 1, on relatively strong soil, to 1.84 for Boat 2 on nearly the weakest soil. The K factor for Boat 4 is found to be 1.97. Although Boat 4 is not on the weakest soil, its pads are subjected to the largest rotations in response to the environmental loads. Using the linear rotational spring model, a lower stiffness must be used as the rotational response increases, if the actual moment generated is to remain less than or equal to the pad ultimate moment capacity.

Leg Plastic Moment Capacity

The plastic moment, M_p, for an unstiffened intact tubular section is given by:

$$M_p = f_y D^2 t \qquad (6)$$

Where:

f_y = yield stress of leg steel

D = mean diameter

t = wall thickness

The leg plastic moment capacities for each of the liftboats (about weakest leg axis) are shown in Table 3 with the response results.

The maximum moment induced in the largest liftboat leg is predicted to have been 9682 ft-kips, which exceeds its plastic moment capacity of 7014 ft-kips. The induced maximum leg moments in two of the three smaller boats are predicted to have been much less than the leg plastic moment capacities (as reflected by satisfactory unity stress checks). The surviving boat with a unity check in excess of 1.0 has a plastic moment capacity of 2625 kips, which is 35% greater than the calculated maximum moment induced in the leg by the storm.

It should be noted that the steel in the legs may have had a yield strength in excess of the nominal 50 or 60 ksi called for in the design. However, slight imperfections in the legs will cause a reduced plastic moment capacity compared to that for a perfectly cylindrical leg. Consequently the above formula is considered reasonable for the purposes of this retrospective analysis.

Failure Mode For Boat 4

The three smaller boats had no damage and no failure as predicted by the retrospective analysis (although some slight yielding of part of the leg section of Boat 2 may have occurred). However, the larger boat broke its legs. The results in Table 3 show that both leg buckling and overturning are predicted (leg plastic moment capacity is less than induced leg moment, and pad uplift force occurs). However, from examination of the time history of pad reactions during the passage of the maximum wave (see Figure 2) it is seen that pad uplift occurs during only part of the wave cycle on pad 1 only. The environmental loading is applied in the direction having the least resistance to overturning. Note that Figure 2 shows pad vertical reactions both before calculation of sway response (dashed lines) and after calculating sway response (solid lines).

From Figure 2 and from Table 3, the maximum value of the uplift is 224 kips. It is noted above that the break-out force to remove the pads of boat 4 from the sea bed is around 350 kips. Consequently it is concluded that the hurricane was not of sufficient strength to cause overturning because insufficient (short-term) uplift forces existed to cause pad break-out. However, the maximum bending moment induced in the legs exceeded the plastic moment capacity of the legs and leg buckling therefore occurred. The failure mechanism would probably have been the formation of a plastic hinge in one leg, followed immediately by a plastic hinge at the same point (the level of the lower guide) in the second and third legs, resulting in lateral collapse of the hull into the water. If overturning had occurred before leg buckling the hull would probably not have survived. This should be considered in the design of new liftboats by performing ultimate capacity analysis. While a condition of no failure is desirable, failure by leg buckling may generally result in less damage with a good possibility of hull survival. Failure by toppling will generally result in the whole vessel sinking. In new liftboat designs toppling resistance may be increased by wider spacing of the forward legs.

Additional Factors Influencing Failure

Air Gap

It should be noted that the air gap of Boat 4 was not known with certainty, but was thought to be approximately 15 feet (above the storm surge level). This is approximately the crest elevation above still water for a 25 foot high wave with 10 seconds period in the 80 feet water depth at the site. Hence wave impact on the hull could have been a contributory factor to the leg failure. However, the plastic moment capacity of the leg is exceeded by about 5% in the same conditions with a wave height of 20 feet, which would have had a crest elevation of only around 12 feet. Consequently it is concluded that collapse would probably have occurred as the sea conditions built and before a maximum wave height of 25 feet occurred.

It must be noted that a 15 feet air gap should not have been considered adequate to prevent wave impact on the hull in hurricane conditions. The reason for leaving an evacuated liftboat with such a small air gap has often been that the last man off has to either jump or climb down a small rope onto a supply boat deck. A proper flexible ladder should always be on board a liftboat to enable safe evacuation at a larger air gap.

Preload

It is unlikely that the pads of Boat 4 were preloaded to a level equal to the maximum loads seen during the storm (up to 649 kips, see Table 3). Hence further pad penetration would probably have occurred past the original preload level during the storm. However, as the soil at the location of Boat 4 has fairly rapidly increasing strength with depth, this further penetration is estimated to have been only 10 to 15 inches past the preload point. This would correspond to a hull inclination in the range 0.6 to 1.3 degrees.

Inertial Resistance

Another phenomenon not addressed in this paper which also contributes to liftboat overturning resistance is inertial resistance to movement. By this it is implied that a liftboat (or any vessel) must be accelerated in rotation from an upright position in order to overturn it. With cyclic wave forces, the inertial resistance to overturning may contribute significantly to elevated stability.

CONCLUSIONS

1. Analytical techniques described in this paper have been shown to correctly predict the observed failure behavior of one, and survival of three, liftboats during Hurricane Juan in 1985.
2. Geotechnical forces resisting pad break-out from the sea bed have been quantified and the results appear to explain the observed failure mechanism of one of the four liftboats observed.
3. Liftboats have a larger resistance to overturning in wave conditions than predicted by previous methods which neglect the pad break-out force.
4. The failure mechanism of leg buckling and the hull landing upright in the water (and surviving) rather than failure by toppling over is due in part to pad break-out force contributing to overturning resistance. While the design of future liftboats should ensure adequate leg strength and resistance to toppling, it may reduce the cost of losses which do occur if leg buckling happens before toppling. Toppling resistance can be increased in new designs by wider spacing of the legs, in particular the forward legs.

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TABLE 1: CHARACTERISTICS OF LIFTBOATS STUDIED

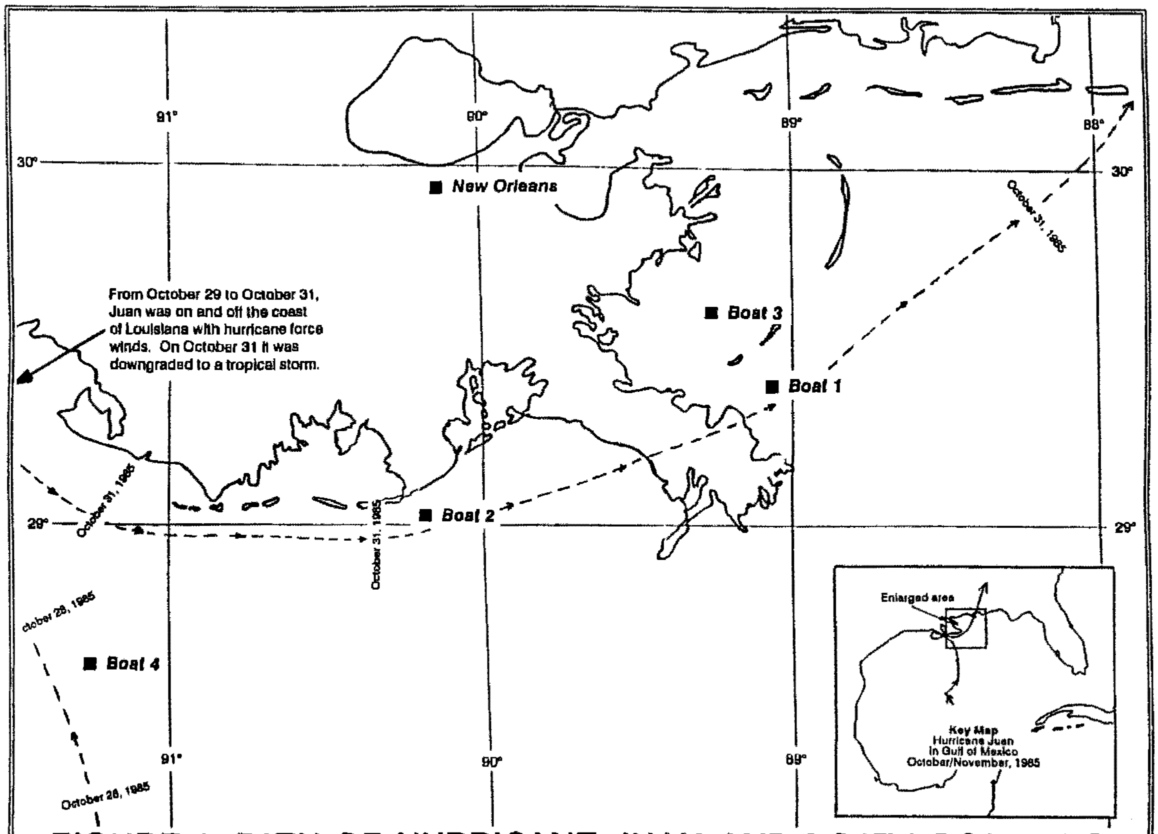
Vessel characteristic	*Boat 1*	*Boat 2*	*Boat 3*	*Boat 4*
Hull length (ft)	74.0	74.0	74.0	100.0
Hull width (ft)	32.0	32.0	42.0	46.0
Hull depth (ft)	7.0	7.0	7.0	8.0
Leg length (ft)	105.0	105.0	130.0	150.0
Leg OD (in)	36.0	36.0	42.0	48.0
Leg wall thickness (in)	0.500	0.500	0.625	0.625
Leg steel yield stress (ksi)	50	50	60	60
Pad length fwd (ft)	24.0	24.0	24.0	25.0
Pad length aft (ft)	24.0	24.0	24.0	32.0
Pad width fwd (ft)	12.0	12.0	12.0	14.0
Pad width aft (ft)	12.0	12.0	12.0	16.0
Pad thickness fwd (ft)	1.5	1.5	1.5	2.0
Pad thickness aft (ft)	1.5	1.5	1.5	3.0
Total weight (kip)	613	613	760	988
cg location fwd of aft leg (ft)	42.3	42.3	41.0	56.1
Effective lateral wind area (sqft)	1850	1850	1941	3356
Distance aft to fwd legs (ft)	58.5	58.5	58.5	85.5
Distance between fwd legs (ft)	45.0	45.0	55.0	57.0

TABLE 2: ENVIRONMENTAL CONDITIONS AT EACH BOAT

Environmental Condition	*Boat 1*	*Boat 2*	*Boat 3*	*Boat 4*
Max. 30 sec wind speed (kt)	85.0	85.0	85.0	85.0
Max. wave height (ft)	15.0	20.0	15.0	25.0
Associated wave period (sec)	8.0	8.0	8.0	10.0
Water depth with storm surge (ft)	25.0	30.0	25.0	80.0
Pad penetration to top of pad (ft)	5.0	7.0	6.0	5.0
Air Gap (ft)	15	15	18	< 15
Undrained soil shear strength at surface (psf)	250	< 100	100	175
Undrained soil shear strength at 10' (psf)	300	200	225	> 300
Current (kt)	3.0	3.0	3.0	3.0
Average leg drag coefficient	0.7	0.7	0.7	0.7
Average leg mass coefficient	2.0	2.0	2.0	2.0

TABLE 3: ANALYSIS SUMMARY RESULTS

Response Parameter	*Boat 1*	*Boat 2*	*Boat 3*	*Boat 4*
Pad min. ultimate moment capacity (ft-kip)	871	554	538	1027
Av. undrained soil shear strength used (psf)	275	175	170	225
Soil shear modulus used (psf)	275000	6825	20230	2441
Max. calc. soil moment at any pad (ft-kip)	760	553	538	1026
Equivalent K-factor	1.19	1.84	1.74	1.97
Maximum sway period (sec)	1.10	1.95	1.43	5.11
Dynamic amp. factor on wave amplitude force	1.02	1.08	1.03	1.32
Wind force (kips)	57.0	57.0	67.0	95.0
Mean wave/current force (kips)	22.0	33.0	26.0	63.0
Max. wave/current force inc. DAF (kips)	49.5	84.9	55.9	160.7
Max. overturning moment inc.P-delta (ft-kip)	4793	6753	6072	25711
Max. hull sway deflection (ft)	0.30	0.91	0.33	5.27
Initial stabilizing moment (ft-kips)	8622	8114	12290	14112
Maximum vertical pad reaction (kip)	290	312	331	649
Minimum pad vertical reaction	92	32	126	-224
Maximum pad rotation (deg)	0.03	0.99	0.33	3.84
Maximum leg bending moment (ft-kip)	733	1719	1220	9682
Leg minimum plastic moment (ft-kip)	2625	2625	5350	7014
Max. ABS 1988 Rules unity check	0.56	1.24	0.46	7.74
Max. ABS 1985 Rules unity check	0.56	1.20	0.46	2.65
Max. DnV usage factor	0.39	0.98	0.35	3.21
Max. equiv. DnV unity check	0.49	1.25	0.44	4.01
Minimum overturning factor of safety	1.80	1.20	2.02	0.55



From October 29 to October 31, Juan was on and off the coast of Louisiana with hurricane force winds. On October 31 it was downgraded to a tropical storm.

FIGURE 1 PATH OF HURRICANE JUAN AND BOAT LOCATIONS

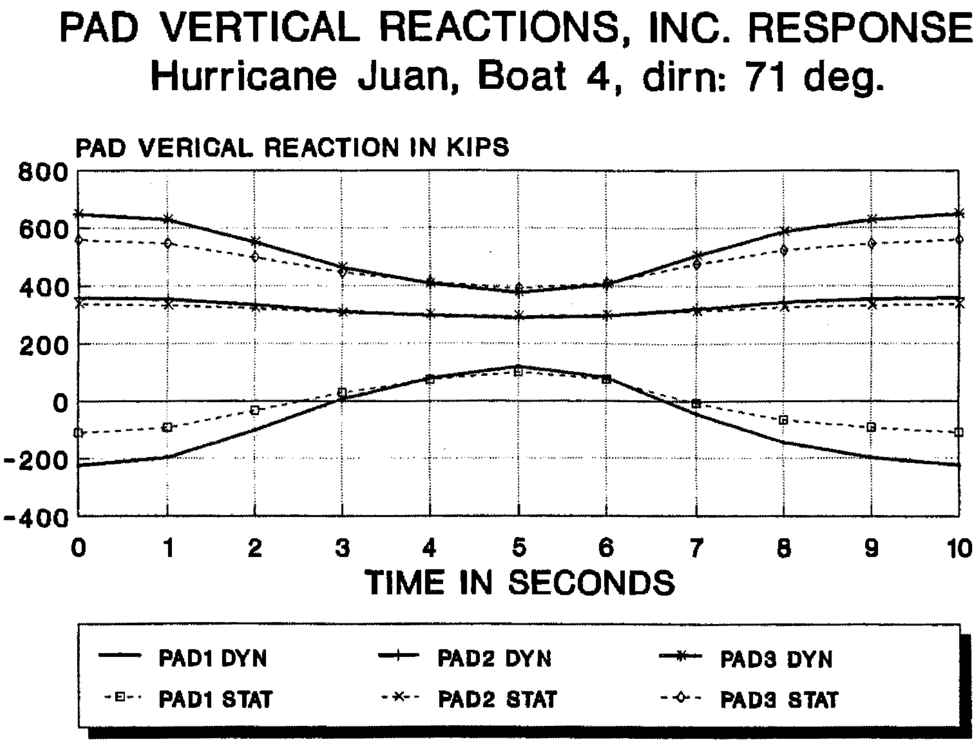


FIGURE 2

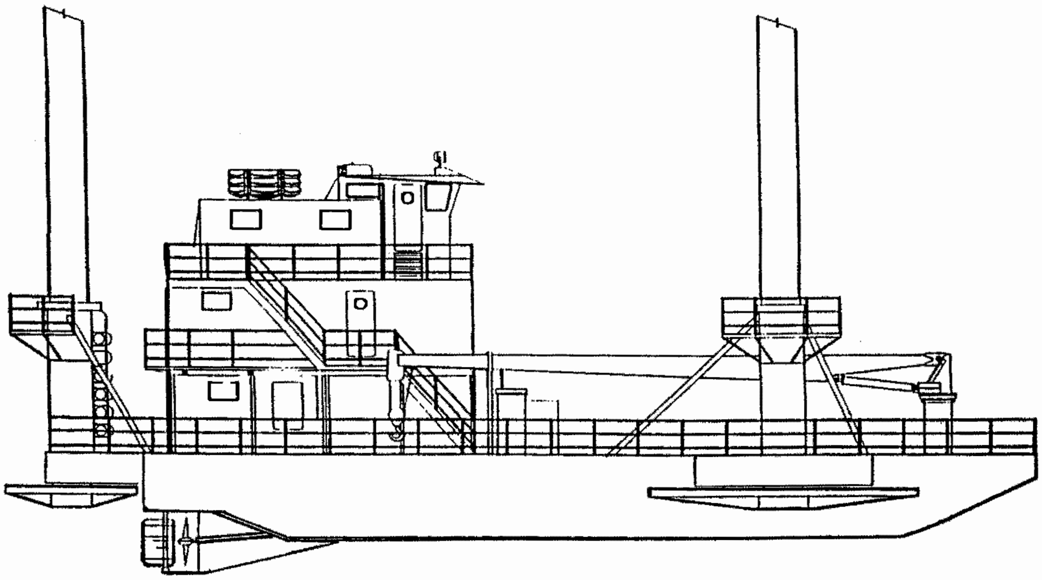
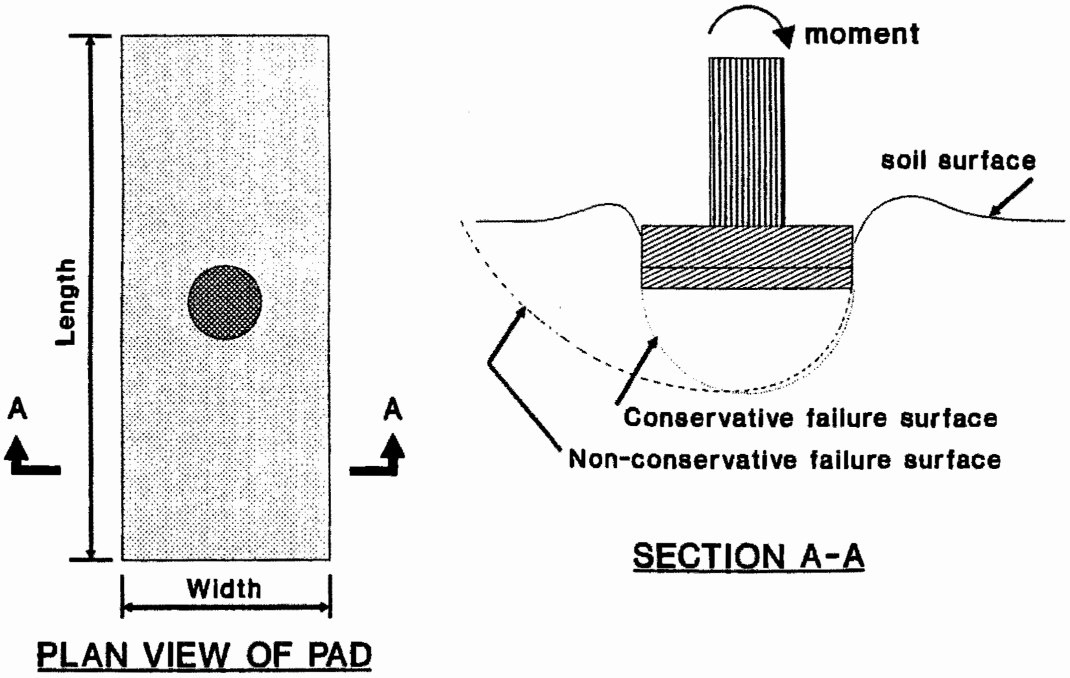


FIGURE 3 MEDIUM SIZED LIFTBOAT WITH LEGS ELEVATED

ULTIMATE MOMENT CAPACITY: LIFTBOAT FOUNDATION PADS



PLAN VIEW OF PAD

SECTION A-A

FIGURE 4