

Investigation of jack-up leg extension for deep water operations

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ABSTRACT: *Since the first jack-up was built, jackups have become the most popular type of mobile offshore drilling unit (MODU) for offshore exploration and development purposes in shallow water. The most pivotal component of the jack-up unit is the leg, which can directly affect the global performance of the unit. In this paper, an investigation into extending the length of the jack up leg is carried out in order to study the enhancement of the rig capability to drill in deeper water approaching the range of the Semisubmersible Drilling Unit (SSDU) (300-1000ft). A study of the performance of a deep-water jack-up unit is performed with different leg lengths. Typical leg scantling dimensions and identical external loads are assigned, and then a detailed Finite Element Analysis (FEA) model is created in order to simulate the jack-up leg unit's structural behavior. A Multi-point Constraint (MPC) element together with the spring element is used to deal with the boundary conditions. Finally, a comparative analysis for five leg lengths is carried out to illustrate their performance, including the ultimate static strength, and weight.*

KEY WORDS: Offshore drilling; Jack-up; Semisubmersible; Leg extension; Finite element analysis.

INTRODUCTION

Jack-up drilling platforms are used for the exploration, drilling and work-over near offshore oil and gas fields. In fact, the combination of mobility, possibility to elevate the platform above the sea level for a range of water depths and to serve as a fixed platform, have made them attractive in the offshore industry over the last 50 years.

Basically, the jack-up platform is a movable object, which is designed to work at any location worldwide, for given maximum water depths and sea states combined with different sea bed conditions. Moreover, the platform is often transported, with the legs in the fully raised position, from one offshore location to another, resulting in completely different loads on the structure (Shabakhty, 2004).

Providing a very stable drilling environment, in comparison with other types of offshore drilling rigs, jack-ups can drill in waters up to 350 *ft* deep. Once drilling is required in waters that are deeper than the capabilities of a jack-up, semisubmersibles and drillships become a more logical choice for exploration and development operations.

Since the conception of jack-up and semisubmersible rigs, the prevailing opinion was that a jack-up rig will always be preferred over a semisubmersible rigs assuming both are capable of drilling the well. Historically, jack-up rigs have had a lower day rate, are simpler units to operate, and require less knowledge of marine environments and equipment. For water depth less than 600 *ft*, the overall economics and operational efficiency of deep-water jack-ups generally make them more favorable than shallow water semisubmersibles (Childers, 1989). On the other hand, semisubmersible rigs become unattrac-

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tive due to their bad motion characteristics during drilling. However, semisubmersibles generally have more deck space and are less dependent on weather when moving on and off location. They also can move easily off location in the event of emergency or well blow-out. Semisubmersibles have the capability to drill more wells through a given template and generally, have faster mobilization speed and in many cases require less towing requirements if outfitted with propulsion assist systems (Paik and Thayamballi, 2007).

The aim of this work is to address the practical use of modern structural analysis techniques such as SAP2000, and stability assessment of offshore jack-up rigs in order to increase the working water depth (more than 400 ft) by increasing the length of the three legs. Constellation II, a jack-up mobile offshore drilling unit located in Egypt offshore in the Mediterranean, North of Alexandria, at Taurt gas field, is selected, as a case study, to examine the possibility of extending the jack-up leg to be able to work in deeper water without any complications related to the structure and stability aspects. Investigations have been conducted for 50 year return period storm conditions in five different water depth scenarios as shown in Fig. 1.

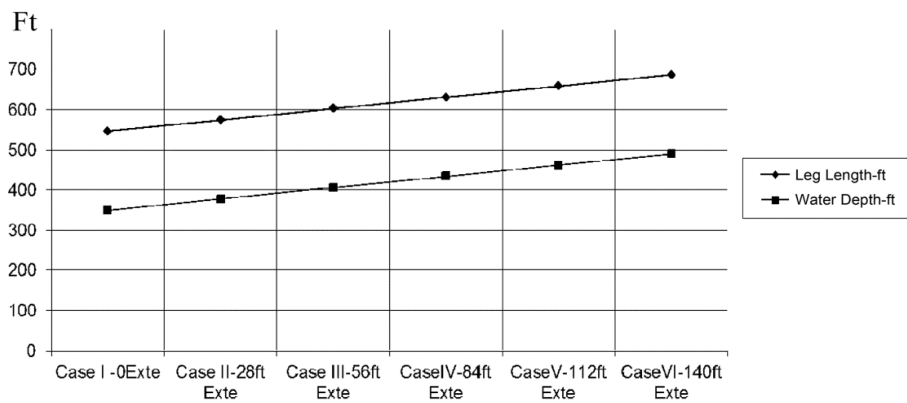


Fig. 1 Leg extensions and water depth development scenarios.

JACK-UP LEGS

Whether a jack-up design involves three or four legs, there are two main types of legs that are used on jack-ups. The first type incorporates open-truss legs, which resembles the towers of electricity, as shown in Fig. 2(a). Open-truss legs are made of tubular steel sections that are crisscrossed, making them strong, but lightweight. Jack-ups can also have tubular legs as shown in Fig. 2(b) made of huge steel tubes. While tubular legs are less expensive than open-truss legs to fabricate, they are less stable and cannot adapt to stresses in the water as the open-truss legs. For this reason, columnar-legged jack-ups are not used in waters that are more than 250 ft deep. In addition to their legs, jack-ups are supported on the sea floor by two different systems of stabilization, either via mats or spudcans, as shown in Fig. 3.

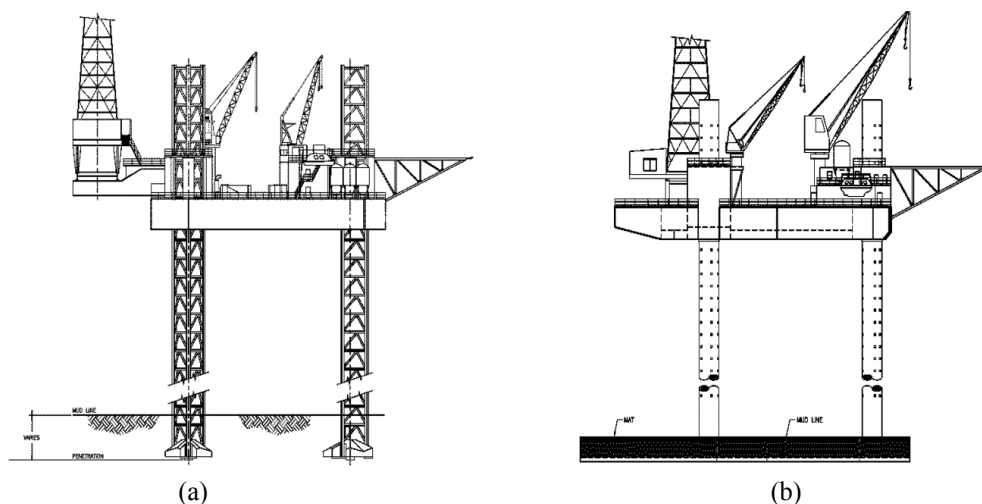


Fig. 2 Types of jack-up legs (Clauss et al., 1992).

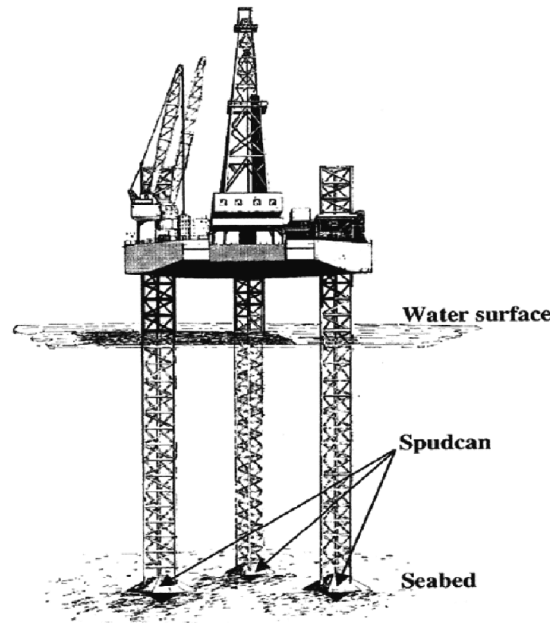


Fig. 3 Jack-up unit and spudcan foundation (Clauss et al, 1992).

A more logical choice for drilling environments that have soft floors, mat-supported jack-ups distribute the weight of the rig across the ocean's bottom, like a snow shoe. Usually shaped like an “A,” mat supports are connected to the bottom of each leg of the jack-up, ensuring that the rig does not punch-through the ocean's bottom.

Usually used on independent-legged jack-ups, spudcans are cylindrically shaped steel shoes with pointed ends, similar to a cleat. Spudcans are attached to the bottom of each leg, and the spike in the can is driven into the ocean floor, adding stability to the rig during operations.

The flowchart shown in Fig. 4 illustrates the sequence of the jack-up analysis. In this study, the jack-up is considered in the storm condition, which is more severe than the normal operation mode. This general analysis method is applied to all load cases.

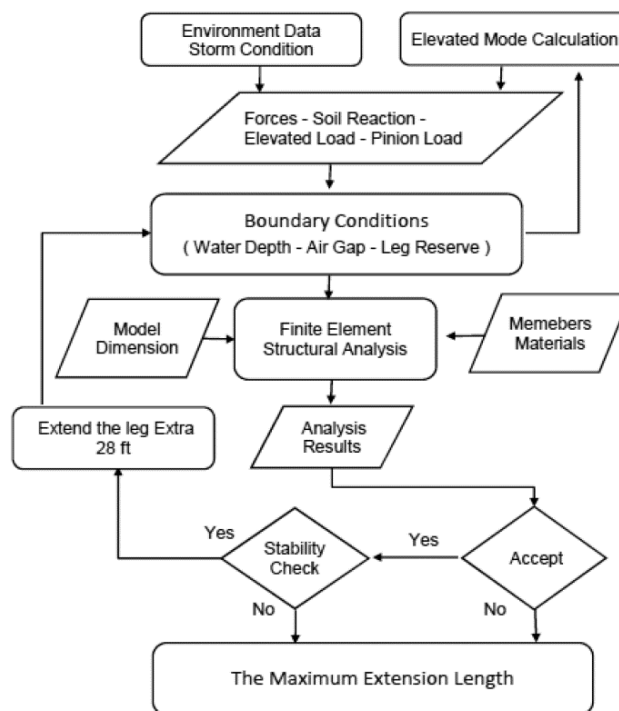


Fig. 4 Analysis Sequence of jack-up leg structure.

JACK-UP LEG STRUCTURAL DESIGN PARAMETERS

The conventional jack-up design has three vertical legs. Each leg is normally being constructed of a triangular framework. The triangular column lattice structure for a jack-up rig consists of three chords, horizontal braces and diagonals. A lattice structure assembled with tubular members is normally adopted for the leg structure in deep waters to reduce the wave forces on the structure to a minimum. The jack-up basic design involves numerous choices and variables. Typically, the most important variables are in the following sections (Elosta, 2009).

Leg model definition

The legs of a jack-up unit are normally vertical. However, slant leg designs also exist (PAFA Consulting Engineers, 2001). The design variables for jack-up legs may involve the following considerations. The model definition file consists of:

- Definition of the analysis type
- The mud-line elevation and water depth.
- Member joints definition / sizes (member groups and sections)
- Soil data
- Joint coordinates
- Distributed load surface area definition
- Wind area definition
- Member or group overrides
- Description of Airy wave through the structure
- Loading directions of the wave
- Details of the hydrodynamic leg-modeling procedure
- Consideration of gravity loads and buoyancy
- Importance of leg buoyancy
- Emphasis of the effects contributed from spud can during the analysis
- Finally, the load cases, which will include dead and live loading, environmental-loading, crane loads, etc.

Material properties

The material properties for all the leg elements are listed in Table 1.

Table 1 Leg components material properties.

	Horizontal braces	Chord	Diagonal braces	Span barker	Spudcan
Material ID	API 5LX65	A517GRQ Mod	API 5LX65	ASTM A106 GR B	ABS AH38
$F_{Y,Min}$ (Kips/in ²)	65.013	100.087	65.013	34.997	65.013
$F_{T,Min}$ (Kips/in ²)	77.00	136.34	77.00	60.00	80.00

where:

- $F_{Y,Min}$ Steel minimum yield strength
- $F_{T,Min}$ Steel minimum tensile strength
- E Young's modulus = 29.15×10^6 Kips/inch²
- G Shear modulus = 11604.29 Kips/inch²
- ρ Steel Density = 480.75 Ib/ft³
- μ Poisson's ratio = 0.3

Water levels

The water depth plays an important role in the calculation of the wave and current loads. The reference water depth in the various calculations represents the distance between the sea bed and the Lowest Astronomical Tide (LAT). The tidal range is the

range between the Highest Astronomical Tide (HAT) and the LAT. Mean Water Level (MWL) is the mean water level between the HAT and LAT. The Still Water Level (SWL) is the highest astronomical tide including the storm surge. The storm surge (SWL) includes the wind and pressure induced effects.

Soil data

Due to the lack of data in this section, soil data from other locations has been used for the selected site. The stiffness of the footings was based on an assumption of G_{soil}/S_u ratio of 50, where G_{soil} is the soil shear modulus and S_u is the undrained shear strength of soil beneath the footings (taken as 29 lb/in^2). A reduced value of 8.7 lb/in^2 was assumed for the undrained shear strength in the horizontal direction. Poisson's ratios for clay and sand were taken as 0.5 and 0.3, respectively. Vertical, horizontal and rotational spring stiffness values were taken as $36.48 \times 10^6 \text{ lb/ft}$, $7.27 \times 10^6 \text{ lb/ft}$ and $115.69 \times 10^8 \text{ lb.ft/rad}$, respectively. The soil profile below the mud line was taken from borehole records as indicated in reference (PAFA Consulting Engineers, 2001) and is shown in Table 2

Table 2 Summary of soil layers characteristics (PAFA Consulting Engineer, 2001).

Depth (ft)	Description
0.0 to 16.0	Siliceous Carbonate coarse sand, very gravelly
16.0 to 30.0	Siliceous Carbonate G, very sandy
30.0 to 55.0	Siliceous Carbonate fine to medium sand, clay with gravel

Marine growth

In the absence of site specific data, and to allow for extra wave and current loading caused by the presence of marine growth, an increase of 0.7 inch in the radii of tubular elements was used for all members below MWL +6.5 ft. (PAFA Consulting Engineers, 2001)

Buoyancy

Buoyancy was automatically included for all tubular members that were "wet" at the solution time. It was necessary to apply chord buoyancy manually based on the construction detailed drawing of Constellation II. This was achieved by utilizing buoyancy elements. The diameter of the spherical shaped buoyancy elements was calculated to give the same internal dry volume per foot as that of the chord.

Air gap

Air gap to the underside of the hull was calculated in accordance with SNAME 5-5A (Arockiasamy and Reddy, 1991). It was defined as the sum of the distance of the extreme still water level above LAT, the extreme wave crest height and 6.5 ft clearance. It is recommended that two positions of the lower guide relative to the chord should be investigated, one at a node and the other at mid span of a leg bay. In the first instance, the minimum airgap was achieved for the center of the lower guide shoe located at a leg chord node, and secondly, for the lower guide located at the mid span of the next bay up. The hull was elevated to maintain the required air gap.

Hydrodynamic properties

Hydrodynamic coefficients were applied to brace members in accordance with (Section 4.7.2 of SNAME 5-5A) (Arockiasamy and Reddy, 1991). Values of $C_D = 0.65$ and $C_M = 2.0$ were used for brace members above MWL + 6.5 ft. Below this elevation, C_D was taken as 1.0 and C_M as 1.8. Marine growth of 0.7 inch was applied to the brace members located between MWL +6.5 ft and mudline. An allowance was made for the drag force resulting from the gusset plates by adding an increase to the hydrodynamic diameter of the horizontal bracing.

Boundary conditions and output values

The calculations are carried out at storm mode for all leg extensions scenarios with constant air gap, penetration and leg reserve. These calculations are based on mathematical equations included in the marine operation manual of Constellation II, which has been approved by ABS. These are performed to determine:

- Total elevated weight
- Longitudinal Center of Gravity (LCG)
- Transverse Center of Gravity (TCG)
- Elevated load distribution on each leg
- Actual leg reaction
- Actual foundation bearing pressures
- Actual leg loads
- Actual pinion loads
- Total elevated load and total overall load

In Table 3, leg extensions scenarios boundary conditions have been applied, and output values for the bow leg, which is subjected to the maximum load, are included.

Table 3 Leg extension scenarios boundary conditions together with the output values.

	Case I - 0 ft Extension	Case II- 28 ft Extension	Case III- 56 ft Extension	Case IV- 84 ft Extension	Case V- 112 ft Extension	Case VI- 140 ft Extension
Leg length - ft.	547	575	603	631	659	687
Water depth - ft.	350	378	406	434	462	490
Total steel weight addition kips per leg	0	360	721	1081	1442	1802
Air gap - ft.	65	65	65	65	65	65
Penetration - ft. L	25	25	25	25	25	25
Leg reserve - ft.	107	107	107	107	107	107
Bow leg	Case I - 0 ft Extent	Case II- 28 ft Extent	Case III- 56 ft Extent	Case IV- 84 ft Extent	Case V- 112 ft Extent	Case VI- 140 ft Extent
Elevated leg load (Kips)	11860	12226	12587	12910	13437	13805
Percentage of total elevated load	33.300%	33.300%	33.333%	33.335%	33.333%	33.336%
Percentage of elevated load limit	87.095%	89.779%	92.471%	95.164%	97.856%	100.54%
Jacking weight (Kips/Pinion)	988	1019	1049	1076	1120	1150
Leg reaction (Kips)	14357.80	14696.1	15030.34	15326.55	15826.13	16194.58
Can bearing pressure (kips/ft ²)	5.25	5.38	5.50	5.61	5.79	5.92

Figs. 5 to7, show the output loads compared with the original design limitation in order to confirm that the results are within the acceptable limits.

As shown in Fig. 7, the pinion load will be greater than the design pinion load. For this reason the rack shock is used with maximum holding capacity of 6750 kips. This system, as a fixation system, is composed of mechanical locking devices which are engaged on each cord rack to secure the legs. The chocks are set using deck hydraulic power systems and can be engaged at any point on the leg cord rack, they are used both when the platform is afloat and elevated and can take the load of the elevated platform.

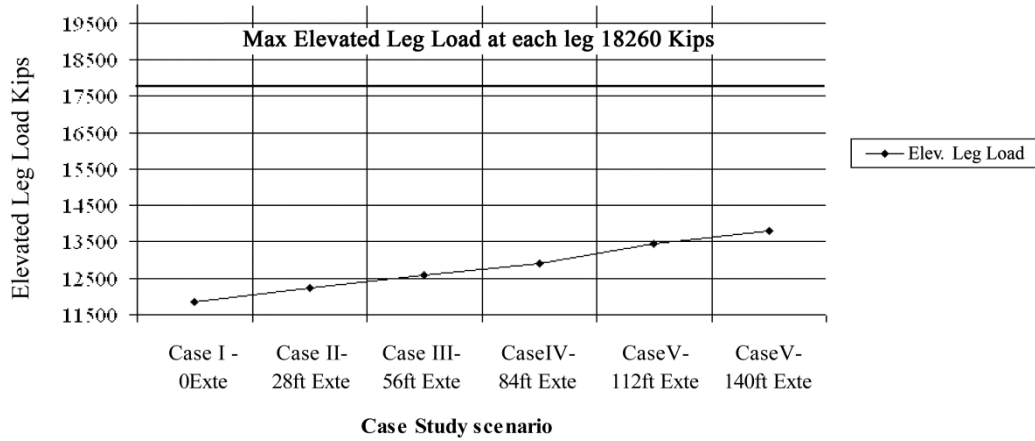


Fig. 5 Elevated Leg Load values for all cases.

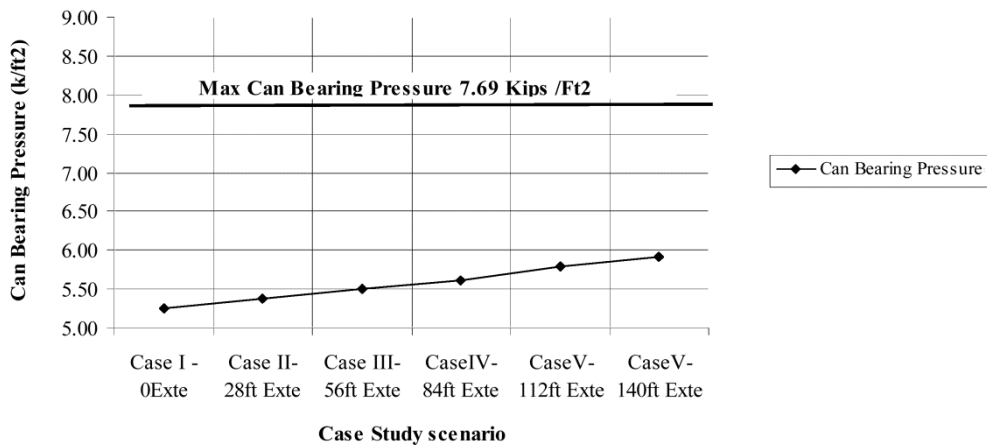


Fig. 6 Can Bearing Pressure values for all cases.

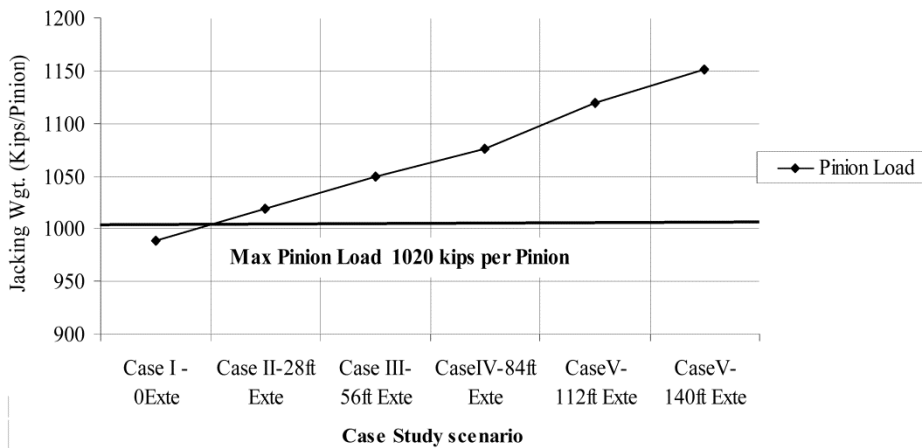


Fig. 7 Pinion Load values for all case.

Environmental loading acting on leg structure

Morison’s formula is used to derive the wave and current forces on tubular members of leg structures in sea water and wind forces above the water level. The hydrodynamic forces, recalculated on the basis of the static assumption and only horizontal forces are considered for the wave direction in each horizontal level of leg structure assuming that the current and wind directions are identical to the waves.

In the detailed calculations of the hydrodynamic forces, the acting forces, due to the particle motion of wave and current, are calculated on each tubular member of leg structures such as chords, horizontal braces, and diagonal braces, taking the following assumptions into consideration:

- a) The distance between chords is constant in way of leg structures.
- b) The diameter of the horizontal braces is also constant in connection with diagonal braces.

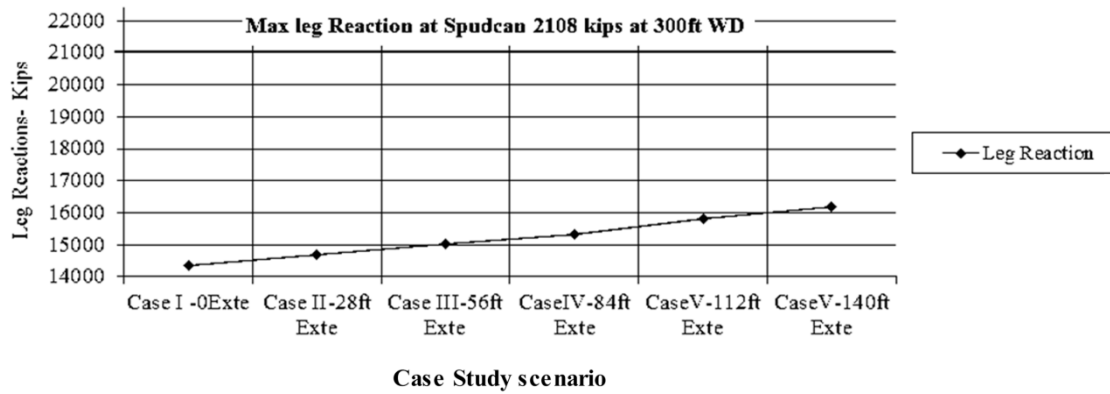


Fig. 8 Leg Reactions values for all cases.

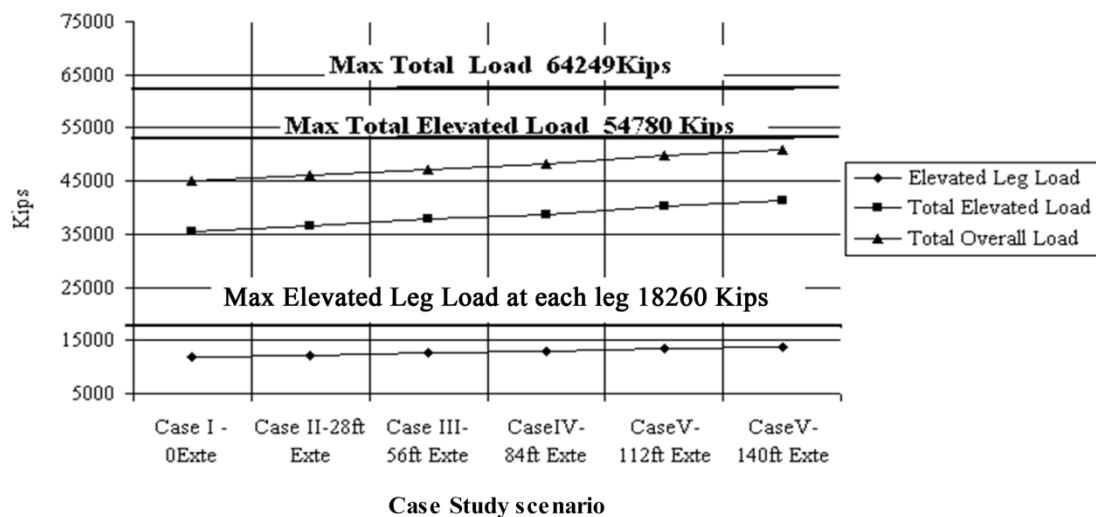


Fig. 9 Total Elevated Load values for all cases.

JACK-UP LEG FINITE ELEMENT MODEL

Leg Finite Element (FE) model has been completed using SAP2000, v15, and prepared in accordance with guidelines given in (SNAME, 1994). The design concept of the leg modeling is such that it has a fixed jacking system and unopposed pinions, but no rack shock is included. The absence of a rack shock means that there will be significant local bending moments in the leg chords between bracing nodes when chord/guide contact occurs. As the pinions are unopposed, local chord bending moments will arise due to the horizontal pinion load component (due to the pressure angle of the rack/pinion). Vertical pinion load acts at an offset position from the chord neutral axis and will, therefore, generate local chord bending moments.

All leg members were modeled using SAP2000, v15 as shown in Fig. 10 in beam-column elements. The elements are capable of capturing geometric non-linearity due to large displacements. They also allow plastic hinges to develop at nodes and at midspan but this non-linear capability is not required, and is, therefore, suppressed. The model incorporates all main members in each bay.

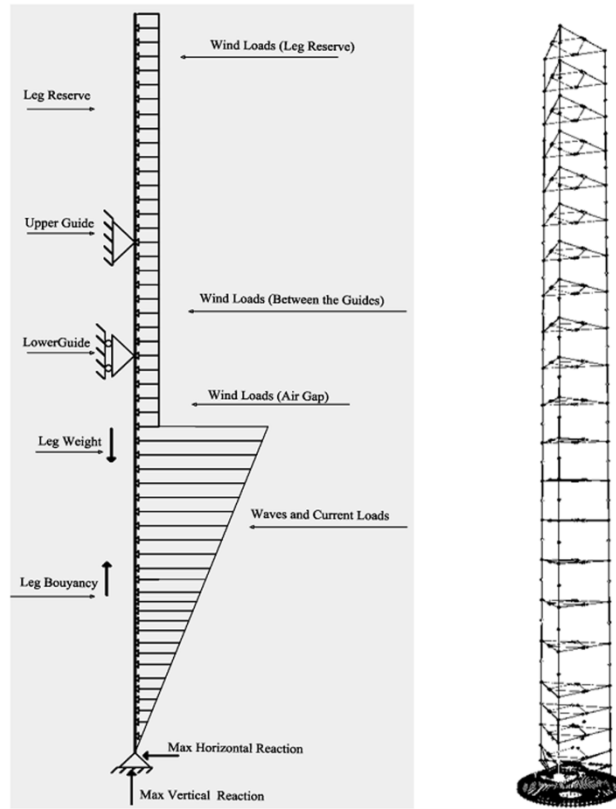


Fig. 10 Finite element model for the jack-up leg.

The braces were modeled as tubular members. Their section properties and buoyancy were automatically calculated by SAP2000, v15. Horizontal and diagonal bracing of the Constellation II unit intersect with the chord at its neutral axis. More details of the finite element structural modeling are found in (Hegazy, 2013).

GLOBAL ORIENTATION OF THE LEGS

Based on SNAME 5-5 guidelines (PAFA Consulting Engineers, 2001), the overall behavior for an independent three legged jack-up unit is investigated on soft clay at storm condition in two different loading configurations and the amount of fixity of the spudcan footings experienced during the test is shown in Fig. 11.

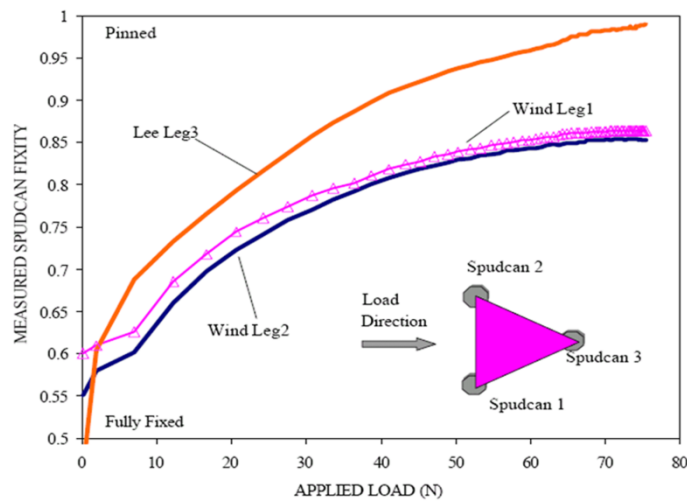


Fig. 11 Spudcan fixity of single leg to Leeward Mode (Elosta, 2009).

The results indicate rapid loss of fixity for all legs in the “single leg to windward” mode, while fixity is still evident in the “single leg to leeward” mode. The “single leg to leeward” orientation appears to be more critical than “single leg to windward”. Consequently, in all scenarios of the study, the single leg to leeward, which is the bow leg, is considered, as shown in Fig. 12.

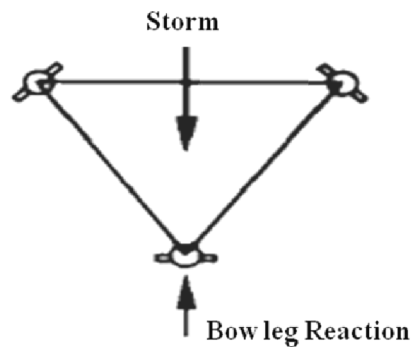


Fig. 12 Storm Direction in the case study.

STRUCTURAL REDUNDANCY

When assessing the leg structural redundancy for Constellation II, the following conditions shall apply: The leg structure shall be able to withstand the loss of any slender bracing member without causing overall collapse of the leg structure according to the American Petroleum Institute (API, 2000).

Structural redundancy will be based on the applicable requirements of dead loading, wind, wave and current loadings, and loadings due to vortex shedding and operation. The structural behavior beyond first member failure depends not only on the ability of the structure to redistribute the load, but also on the post failure behavior of the system, e.g. the ductility of the individual members and joints (Skjong et al., 1995).

API ACCEPTANCE CRITERIA

The main purpose of structural analysis is to synthesize a structure in such a manner that a satisfactory level of reproducing the actual response of the structure to some applied load is obtained. In undertaking such a task, engineering judgment is applied as a means to achieve a practicable solution to the physical problem at hand. It is necessary to check the maximum stress in the leg chord and leg bracing. This generally occurs at the leg connection to the hull (Winkworth, 2001). The internal member forces and moments determined from the finite element analysis are stored for input to the post processing programs which check the individual elements. All bracing members are checked as beam columns against an appropriate code, API Recommended Practice RP 2A-WSD.

STRUCTURAL EVALUATION OF THE SELECTED SCENARIOS

All members' strength checks were performed in accordance with the requirements of API 2A-WSD. The maximum equivalent stresses for bow leg members of Constellation II, in the five selected scenarios, are shown in Fig. 13. This determines the ability of the leg structure, after extension, to operate in deeper water without substantial loss in its serviceability.

For the first four scenarios, the structure can endure the environmental loading, typical of the selected site, without any problem. For the last scenario (V), of 659 *ft* leg length as shown in Fig. 14, the structure failed to pass the API acceptance criteria. The stresses in the leg members, include the axial and bending stress, and the additional effect of saddle stresses induced from the bearing of the guide system. This means that the maximum extension length is 84 *ft* and the total leg length is, therefore, 631 *ft*.

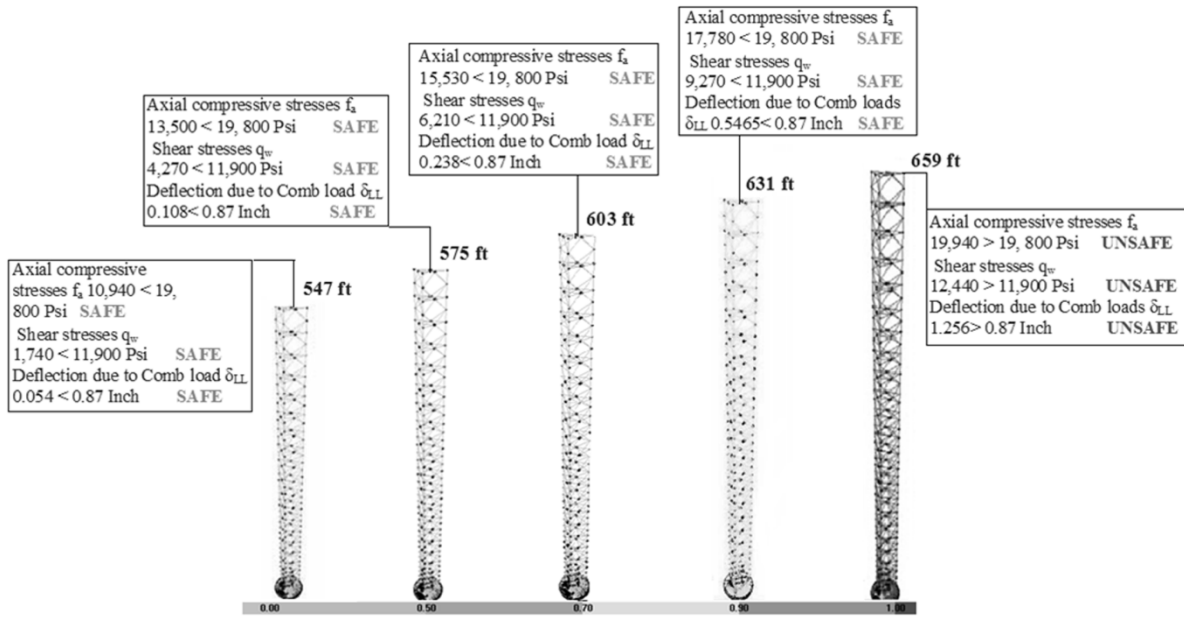
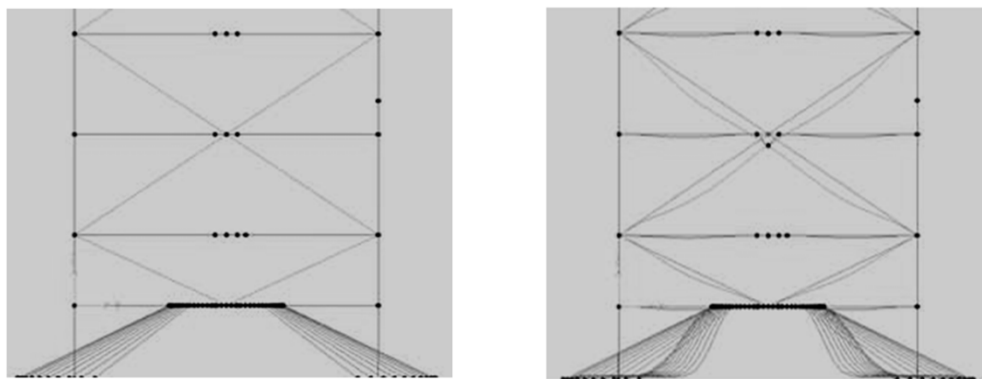


Fig. 13 Maximum equivalent stresses for all cases.



(a) Zero loads.

(b) During the loading condition.

Fig. 14 Leg truss damage due to excess loading, Case V 659 ft.

STABILITY EVALUATION FOR ALL CASES

All jack-up units should have positive stability in calm water equilibrium position, for the full range of draughts, in all afloat modes of operation, and for temporary positions when raising or lowering. In addition, all units should meet the stability requirements set forth for all applicable conditions in accordance with IACS Requirements (IACS, 2012).

Intact stability

All units are to have sufficient stability (righting ability) to withstand the overturning effect of the force produced by a sustained wind from any horizontal direction, in accordance with the stability criteria, for all afloat modes of operation. Realistic operating conditions are to be evaluated, and the unit should be capable of remaining in the operating mode with a sustained wind velocity of not less than 36 m/s (70 knots) (IACS, 2012).

Allowable VCG/LCG VALUES

The allowable VCG is the minimum value which can exist without jeopardizing the stability of a jack-up drilling unit. This is one of the factors affecting the GZ or righting moment curve. If the actual VCG is greater than the allowable VCG the area

ratio (The ratio between the areas under the righting moment and the wind heeling moment curves) will be less than required. For this reason, and to eliminate lengthy calculations, a curve of maximum allowable VCG values is prepared for reference. An increase in draft results in an increase in the underwater volume, thus resulting in a consequent change in KB and KM. Fig. 15 shows the relationship between KM, VCG and GM (Bennett Offshore and Offshore Technology, 2005).

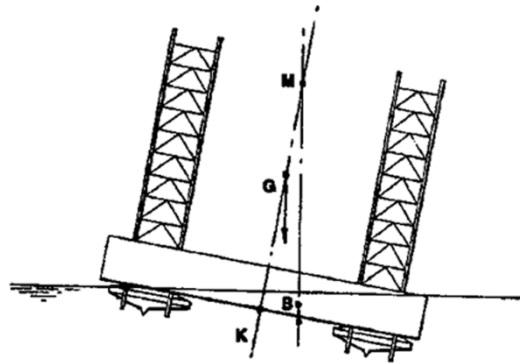


Fig. 15 Relationships between KM, VCG and GM.

Stability calculations, based on Constellation II marine operation manual, have been carried out and the results are shown in Figs. 16 to 18, for all five scenarios. These results include:

- Total displacement
- Calculated draft
- Vertical Center of Gravity (VCG)

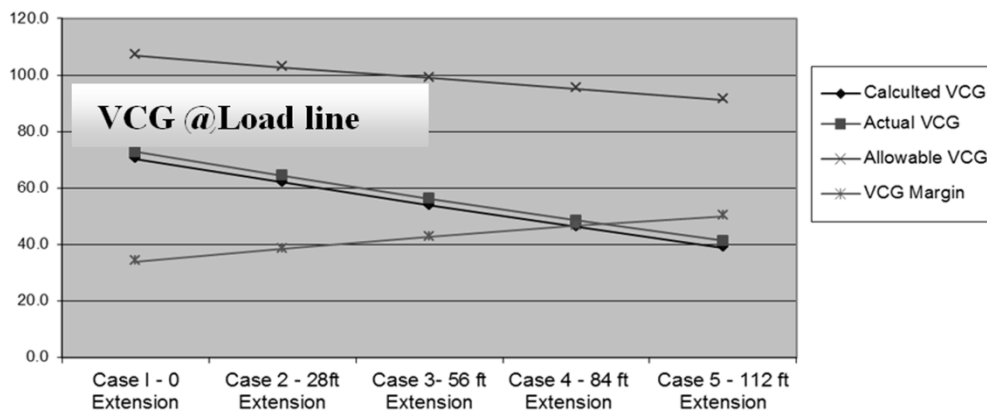


Fig.16 The VCG changes for all scenarios.

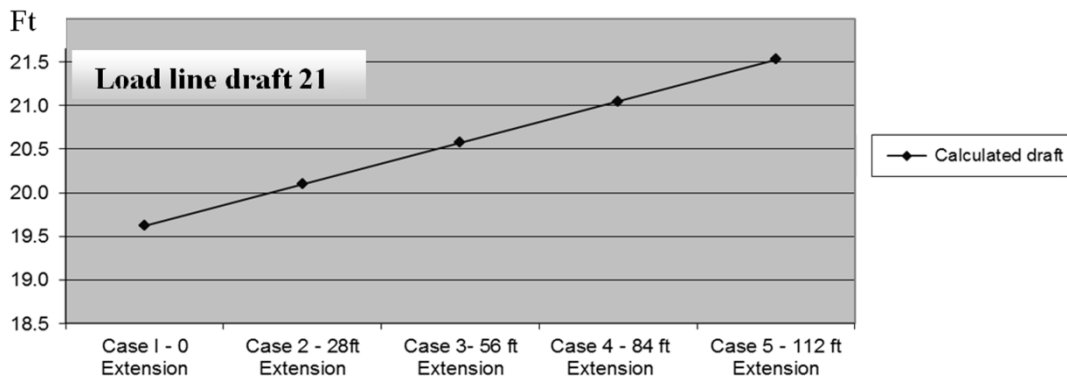


Fig.17 The calculated draft changes for all scenarios.

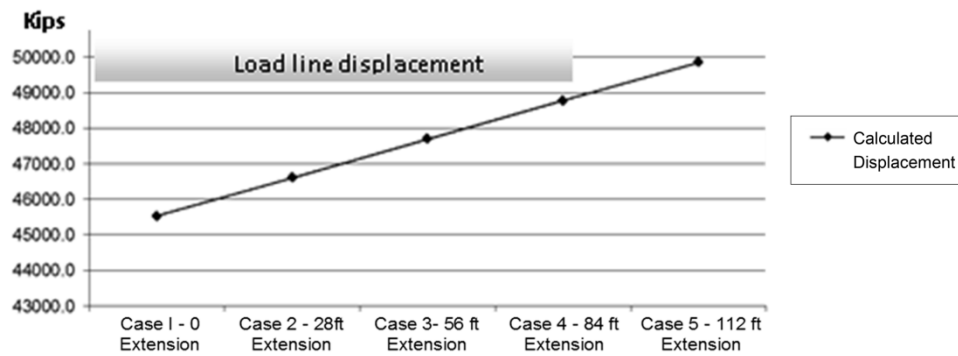


Fig. 18. The calculated displacement changes for all scenarios.

For the first four scenarios the stability was quite satisfactory. The last scenario (V), of 659 *ft* leg, was unsatisfactory and the VCG exceeded the acceptable limit. Therefore, the jack-up Constellation II, may extend the three legs by 84 *ft* to reach a leg length of 631 *ft*. This will enable the unit to drill in water depth of 462 *ft* and replace old generation semisubmersibles.

CONCLUSIONS

The jack-up rig day rate is affected by changing the water depth. Therefore, leg extension capability will enhance the rig potential to drill further in deeper water than semisubmersibles. The leg extension analysis presented in this study could be used for any jack-up rig in order to check the structure serviceability and compliance with stability requirements. The results of the jack-up leg extension carried out show that there is a limitation for leg extension. At a certain limit, the leg members fail to pass the API acceptance criteria due to high stresses in the legs. The jack-up rig, after leg extension, should also satisfy the stability requirements during the transit mode. In addition to stability satisfaction, further investigation needs to be implemented for the best manufacturing technology and cost of this leg extension.

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