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Article

Global Structural Behavior and Leg Strength for Jack-Up Rigs with Varying Environmental Parameters

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Abstract: In the mobile jack-up unit, the leg supporting the hull is a very important structure, and it is important to closely examine the changes in accident load, environmental load, and seabed ground during jack-up operation. Generally, jack-up rigs are three-legged structures with a triangular hull that comprises several movable legs used to raise the hull above the sea surface. They can be operated in shallow water at less than 120 m, while large jack-up rigs, which have a structure that can withstand severe environmental loads, can be employed at depths ranging from 150 m to 200 m. However, a complex process is required to finalize the structural design of a jack-up rig, and the influence of various parameters must be comprehensively considered. In other words, the rig will encounter variable environmental conditions with variations in parameters such as wave height, wave period, wind speed, air gap, and so on. A unified procedure is proposed to review the structural strength of legs, hulls, and cantilevers, and different models and analyses can be configured so that it can be solved within a unit flow-chart. Through this process, we can expect that engineering time and cost can be reduced. From survey results, it was possible to determine the inputs to examine the effects of variables, and a large jack-up rig operating under extreme environmental conditions was modeled. In the present study, the jack-up rig was operating in the North Sea, and leg length and water depth were 160 m and 100 m, respectively. The basic environmental characteristics included wave height (20 m), wave period (10 s), wind speed (30 m/s), and air gap (22 m). A parametric sensitivity analysis was performed with varying environmental parameters. Through sensitivity analysis of environmental characteristics, the significance and sensitivity of the effect of each environmental parameter on leg strength was clarified. It is expected that this will be very useful guidance about the effect of parameters during the conceptual design stage of jack-up rigs.

Keywords: jack-up rig; hull; structural engineering; environmental condition; sensitivity analysis

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1. Introduction

Jack-up drilling rigs of mobile offshore platforms are widely used in the offshore oil and gas exploration industry. A jack-up drilling rig is an independent, three-legged self-elevating unit with a cantilevered drilling facility for the purposes of drilling and production. A typical jack-up drilling rig consists of a hull, a derrick, a cantilever, a jack house, accommodation, and legs. The legs comprise a three-chord open-truss X-braced structure with a spudcan, as shown in Figure 1. The jack-up rig was originally designed for use in the relatively shallow waters of parts of the Gulf of Mexico. Due to the demands of oil companies, it has seen a steady increase in capacity in deep water and harsh environments.

Table 1 indicates that both the leg structure dimensions of jack-up rigs and environmental conditions tend to increase in deeper water. In the 1980s, jack-up rigs were only operated in relatively shallow water at depths of less than about 100 m in moderate environments. Additionally, the cantilever with derrick did not extend over an existing platform to perform drilling operations. The design of the jack-up has developed into a large size for use in deep water and hash environments, enabling oil companies to drill all year round in challenging locations. Oil companies requested to allow for much more variable loads to enable deeper wells to be drilled. Recently, jack-ups are capable of withstanding 150 m of water depth and 25 m of wave height.


(**a**) (**b**)

Figure 1. Jack-up drilling rig: (**a**) jack-up drilling rigs (https://ramboll.com/projects, accessed on 1 January 2023); (**b**) spudcan [1].

Table 1. Main characteristics of different jack-up rigs [2].

Project ID	Main Dimensions of Leg Structure			Main Environmental Information			Delivery
	Length (m)	Longitudinal Spacing (m)	Transverse Spacing (m)	Water Depth (m)	H_{max} (m)	Wind Speed (m/s)	
A	111	-	-	92	8.0	30	1980s
B	100	-	-	75	7.5	30	1980s
C	100	-	-	89	12.0	30	1980s
D	107	-	-	89	17.1	30	1980s
E	107	-	-	77	16.4	30	1980s
F	107	-	-	84	9.0	30	1980s
G	107	43.3	39.3	91	21.6	30	1990s
H	154	50	43.3	92	21.0	30	1990s
I	194	64	57.6	137	14.0	30	1990s
J	200	60.6	70	141	28.0	36	2017
K	200	60.6	70	150	28.0	36	2018
L	232	69.3	80	175	29.0	40	Not developed

Figure 2 shows that the jack-up rig is capable of handling water depths of up to 150 m in harsh environments. Additionally, wind speed and leg length have increased with water depth. Wind speed has increased from 30 m/s to 40 m/s and length of leg to over 230 m. The “L” project is not yet commercially available, but the design is complete. However, the development of the design concept of the structure for harsh environmental conditions such as deep water of 170 m or more and the North Sea must be continuously developed.

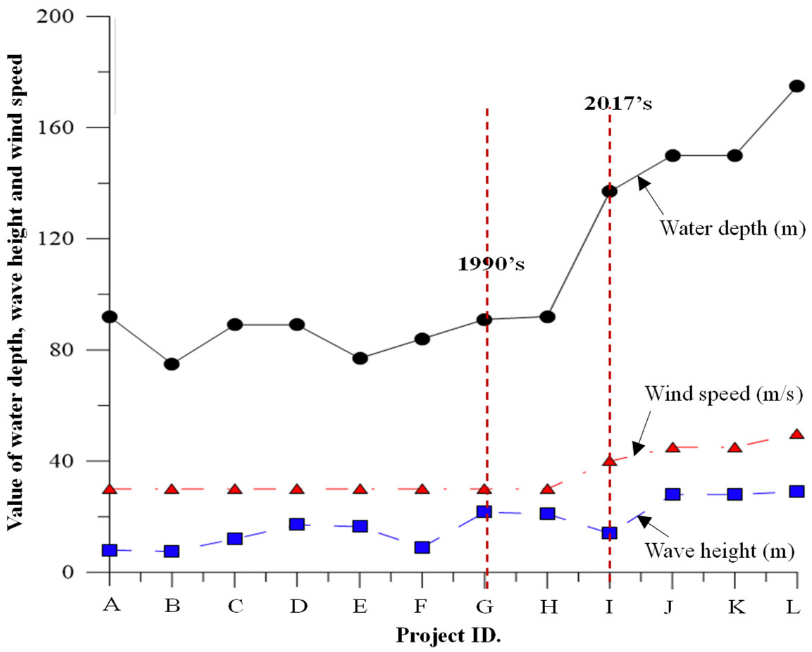


Figure 2. A comparison of the environmental parameters according to projects for jack-up rigs.

Figure 2 compares the water depth, maximum height of the wave, and wind speed data of the installed/operating jack-up rigs. Prior to 1990, the water depth was maintained at 90 m before being increased to 150 m from 2000 onwards, which indicates that developments in the oil/gas field were focused on ensuring operations in deeper waters. Moreover, the wind speed and maximum wave height also gradually increased with the water depth.

Figure 3 shows the relationship between the water depth and year of delivery of the jack-up rigs. The square symbols indicate the site information and the rhombus symbols indicate the completed designs. The circular symbols represent the predicted upper design limit based on the information available for the above two factors. The newly developed jack-up rigs facilitate deeper deployment.

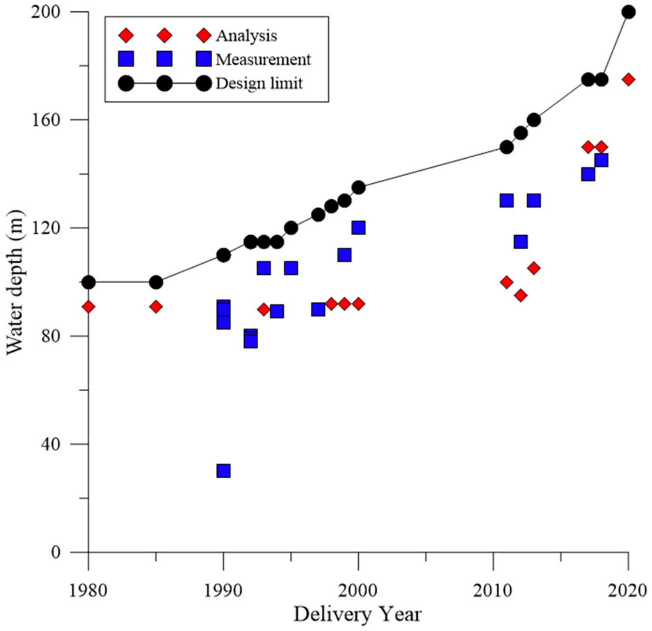


Figure 3. Distribution of the water depth according to delivery year for jack-up rigs.

However, beyond 200 m, there is no cost advantage in designing jack-up rigs for deeper water, as the size of the rig needs to be rapidly increased to accommodate longer legs and the resistance of large overturning moments against harsh environmental loading. Instead, in waters deeper than 200 m, a semi-submersible rig may be employed.

Figure 4 shows incident causes, including overturning and tilting of legs, which account for 8% of all incidents.

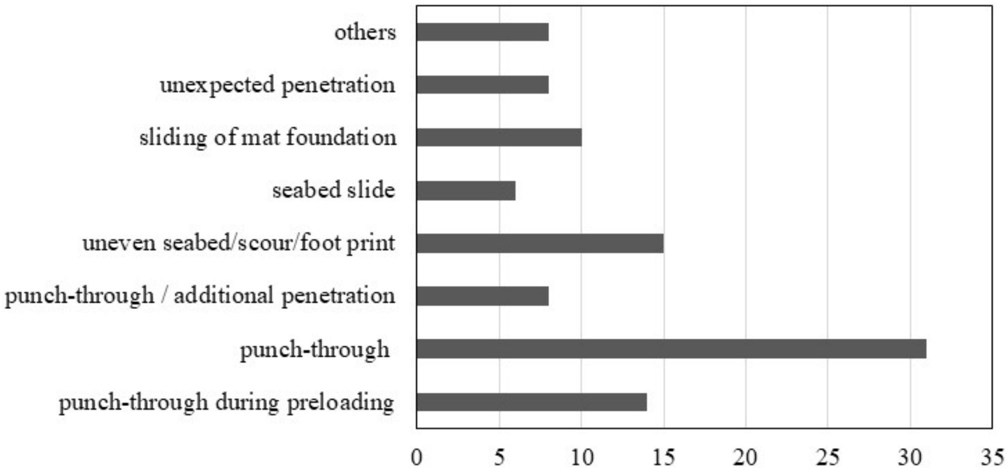


Figure 4. Case histories classified according to the cause of failure [3].

The leg design is the most important task in the jack-up. It plays a very important role in the dynamic response of the structure because the additional leg length is exposed to hydrodynamic loads. Additionally, this environmental load acts predominantly in the horizontal direction and can be expressed in terms of a base shear and overturning moment at the spudcan. Among the technical issues for jack-up rigs, the P-Δ effect is the most important when it comes to performing their functional operation at the offshore site.

The intention of this paper is to describe a global in-place analysis of a large-sized jack-up drilling rig against environmental loading from wave, wind and current via a parametric sensitivity analysis study. The overall strength of the leg and the overturning stability of the unit are verified.

A brief review is made of previous research related to leg structure using parametric studies.

Tan et al. [4] proposed an innovative method in order to minimize localized failure and collapse during installation. Numerical simulations are carried out with varying loadings and boundary conditions. These data are helpful for re-design of the structure and could be used as guidance for site installation.

A report from Noble Denton Europe and Oxford University [2] introduced the idea that each structural model is first subjected to a 10 MN impulse load at deck level, to allow a comparison between the NDE (Noble Denton 3-leg model) program and the jack-up analyses in which pinned footing and elastic springs were examined with site study. The stiffness values resulting from the proposed formulations are given and compared with stiffness based on SNAME (Society of Naval Architects and Marine Engineers). It can be seen that rotational stiffness has increased by a factor of at least 2. Using the Noble Denton JUSTAS program, the benefits of the increased foundation fixity from the proposed 'calibrated' formulations were evaluated.

Zhang et al. [5] investigated with a combined numerical and experimental study via a plasticity foundation model. The results of such analysis of a jack-up under quasi-static push-over load are discussed to highlight the impact of the model in the context of site-specific assessment of jack-up rigs in soft clay. The response of jack-ups to environmental loads is highly affected by the interaction between all footings (spudcans) and the underlying soil, an interaction still challenging to describe under general 3D loading.

Hu et al. [6] proposed a mobile jack-up capable of operating for extended periods under deep waters and harsh environmental conditions. In this study, both the size of the spudcan footings and the operational bearing pressures were increased. Therefore, they parametrically studied the six centrifuge test results simulated for spudcan installation, and analyzed them using the finite element (FE) method with a large deformation to consider the effect of strain softening on the soil response. The results yielded a new expression for the bearing capacity factor when predicting the complete penetration resistance profile for spudcan installation.

Jun et al. [7] indicated that the horizontal force and moment induced on a spudcan as it penetrates next to an existing seabed footprint are among the key challenges in the offshore oil and gas industry. They conducted a large deformation finite element (LDFE) analysis under varying skirt length of the spudcan and using an underside profile with an optimized spudcan shape. The result yielded a spudcan with a flatter underside profile with holes, which could significantly reduce the horizontal force and moment induced during reinstallation next to an existing footprint.

Pisanò et al. [8] suggested that the response of jack-ups to environmental loads is highly affected by the interaction between all footings (spudcans) and the underlying soil, an interaction still challenging to describe under general 3D loading. Additionally, a 3D finite element (FE) model was set up by including strain-hardening soil plasticity and geometrical non-linearity in the P-Δ effect. The results presented support 3D continuum modelling as a suitable approach to analyze spudcan fixity.

Kim et al. [9] investigated a continuously penetrating spudcan in two-layer sand deposits through three-dimensional large deformation finite element (3D LDFE) analyses. Parametric analyses were undertaken varying the top layer thickness, relative density of sand, and spudcan diameter.

Pisanò [10] indicated that the response of jack-ups to environmental loads is strongly affected by the interactions between all footings (spudcans) and the underlying soil, which is challenging to describe under general 3D loading. They developed a 3D FE model by including strain-hardening soil plasticity and geometrical non-linearity under the P-Δ effect. The obtained results validated the feasibility of 3D continuum modelling for analyzing spudcan fixity.

Park et al. [11] used the allowable stress design (ASD) and the load and resistance factored design (LRFD) methods to evaluate the lattice leg structure under different environmental load-to-dead load ratios, and compared the load-to-capacity ratios obtained by these methods. The results showed that LRFD could achieve an optimum design for a jack-up rig. Therefore, this study was based on the API RP 2A LRFD [12] criterion.

Kim et al. [9] investigated a continuously penetrating spudcan in two-layer sand deposits through a 3D LDFE analysis. They also conducted a parametric analysis under varying top-layer thickness, relative density of sand, and spudcan diameter. According to the results, at the relatively thin top-layer with a thickness of less than 5.0 m, the bottom sand layer had minimal influence on the top layer-dominated spudcan behavior.

Previous studies have been limited to the core technology of jack-up rigs, and the overall engineering process and the influence of major variables on initial design have not been reviewed. Therefore, this study aims to review the lack of previous research.

2. Basic Methodology

2.1. Scope of Analysis

The objective of the global in-place analysis of leg structure is to ensure that the unit is capable of structural strength and overturning stability under operating and survival environmental conditions. All the hull loads and environmental loads were included in the simulated model. The code check was calculated based on API RP 2A-LRFD [12] criterion for the tubular members, namely brace and AISC 13th [13], or the non-tubular members such as chord and rack. All static and environmental loads were considered in accordance with the DNV Rule [14] and SNAME-RP 5A-5 [15]. The environmental design parameters were generated in the following angles: from 0 deg to 330 deg with 30 deg increments.

2.2. Design Data

The current blockage effect was considered since leg structure is placed in the wake. The current blockage was considered by reduction of the far field current velocity, depending on the C_D of the leg. The current blockage factor of 0.92 for all loadings was applied in this analysis. The hydrodynamic properties of the leg were calculated in accordance with SNAME [15], and the C_D-values of SNAME were based on tests for both chords and complete legs. The following structural and non-structural elements were considered: chord racks and scales, diagonal bracings, span breakers, and the leg piping. Limited shielding of parts of the leg piping was considered, depending on wave direction. A deterministic/regular wave was used to calculate the hydrodynamic loads on the structure. To account for the conservatism involved in the deterministic approach, a kinematic reduction factor of 0.86 was used in accordance with SNAME-RP [15]. The hydrodynamic loads on individual members were calculated using Morison's Equation. No shielding or interaction effects within the structure were considered. As per DNV [14] requirements, the in-place analysis was carried out for a range of wave periods. Basic environmental loads were applied to the structure in various combinations with the gravity loads.

2.3. Methodology

A flow-chart of the analysis of the leg, hull, and interface structure is shown in Figure 5. The first step shows the initial design of the leg structure. For this stage, environmental and geotechnical data were obtained from the literature survey or site-specific measurements. We collected all the information required for conducting an efficient simulation to gain insight into the various parameters influencing the dynamic response of a jack-up rig.

In order to determine the dynamic response, the in-place analysis first obtained the simplistic DAF (Dynamic Amplification Factor) using the SDOF (Single Degree of Freedom) method, which was then re-analyzed using a time domain analysis if the DAF is too conservative. This simplified model has an advantage of saving computation time, but it is difficult to idealize for hull stiffness and mass. Therefore, it was performed with detailed analysis modelling, which reflects the recent industry practice of design and configuration to obtain a more exact stiffness of the detailed hull structure compared to a simplified analysis model with an idealized hull structure. More accurate results can be expected compared to the simplified model. Therefore, a global in-place analysis of the leg structure was conducted to verify the dynamic response between the hull and environmental excitation under varying parameters.

In the second step, the base shear induced at the end of the spudcan was calculated per heading angle of 30 deg Meanwhile, the natural frequency of the leg structure was calculated using a modal analysis.

During the three-step validation of the local strength of an interfaced structure in the way of the leg structure, the reaction forces were obtained from the global in-place analysis result obtained in the previous step. In the global in-place analysis, the following assumptions regarding the engineering process was developed. The leg is designed to withstand loadings resulting from 1- and 100-year exposure to environmental forces during its service life. The loads applied to the structure under the P-Δ effect (second-order displacement) were analyzed. All information was set up that allows efficient simulation to be done in order to gain insight into the various parameters that influence the dynamic response of a jack-up. Global in-place analysis of the leg is an important task to verify the dynamic response between the hull and environmental excitation under varying parameters.

The new procedure is proposed to review the structural strength of legs, hulls, and cantilevers collectively, and since various models and analyses can be unified at each stage, engineering time and cost can be reduced.

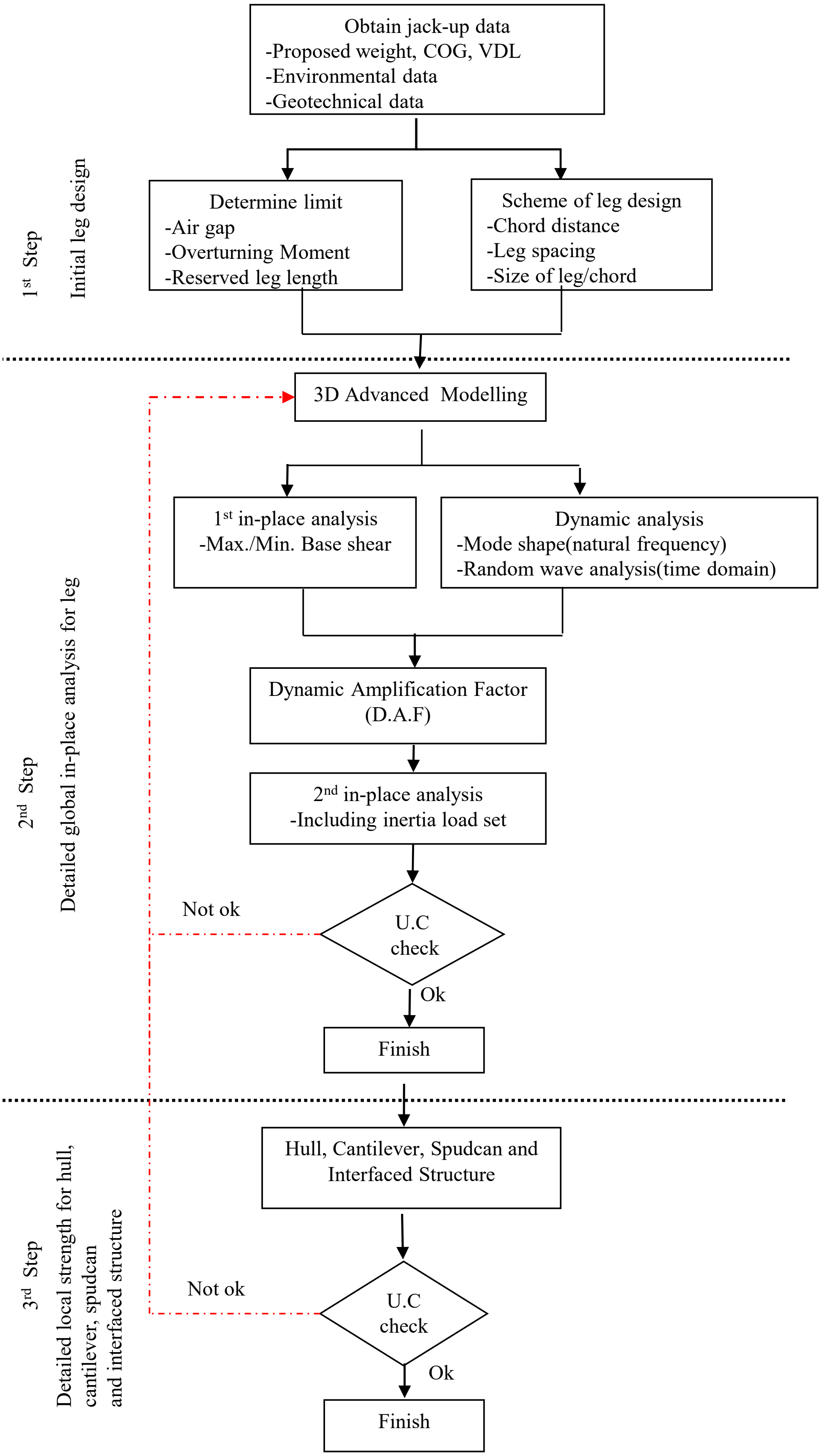


Figure 5. Analysis flow-chart of both global and local structures.

3. Structural Engineering Assessment

3.1. Analysis Model

A simplified hull model was created by using beam and shell elements, as shown in Figure 6. The simplified hull and detailed leg structures were simulated using the SACS IV computer structural analysis program version 11.3, which is developed and maintained by Engineering Dynamics, Inc. Both the material properties and cross-sectional properties of each member and joint can be simulated as mentioned in Table 2. Spudcans were modeled as rigid beams connecting the leg chords to the pin support, which is at half the depth of spudcan penetration and connecting the soil spring to the penetration depth. The leg-to-hull interface was represented with a vertical and rotational spring with a certain stiffness at a vertical position from the base of hull. Chord distance was 18 m and the type was a split-pipe with an opposed teeth rack. The thickness of the leg structure varied from 65 mm to 210 mm. The yield strength of the material was 690 MPa.

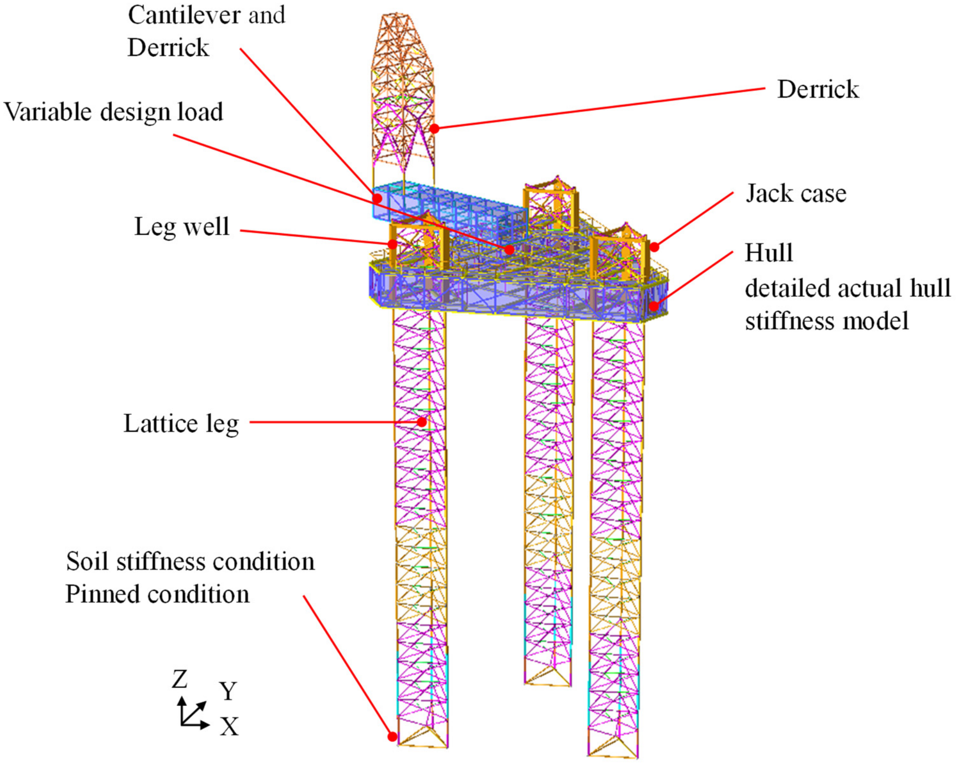


Figure 6. Structural members and analysis modeling.

3.2. Boundary Condition

The boundary condition at the end of the leg applied classical pinned and actual soil conditions as follows.

- **Pinned support**: The model was restrained at the center of leg footings in horizontal and vertical directions and with rotation allowed.
- **Foundation with soil stiffness**: After completion of spudcan penetration, the actual support condition is not a simple support condition, but a clamping condition. However, in most cases of jack-up engineering, simple support conditions are used to obtain conservative results. These factors cause an increase in the weight of both leg and spudcan as resulting in an increase cost.

Pinned support, vertical, horizontal, and rotational spring stiffness at the spudcan location were compared via parametric study. The soil stiffness was identified in accordance with DNV CN.30.4. The authors of [16] calculated the following Equations (4–6) for shear modulus for vertical, horizontal, and rotational loading. From the calculated shear modulus, the soil stiffness of the three components can be obtained by Equations (1–3). These parameters can represent the actual overturning behavior against environmental loads such as waves, wind, and current.

$$K_Z = \frac{4GR}{1-\nu}\left(1+\frac{D}{2R}\right) \quad \text{for vertical direction } (Z) \tag{1}$$

$$K_X = \frac{8GR}{2-\nu}\left(1+\frac{2D}{3R}\right) \quad \text{for horizontal direction } (X) \tag{2}$$

$$K_\theta = \frac{8GR}{3(1-\nu)}\left(1+2\frac{D}{R}\right) \quad \text{for rotational direction } (\theta) \tag{3}$$

$$G_V = 36,600 + 24.9\left(\frac{V_{LO}}{A}\right) \tag{4}$$

$$G_h = 1100 + 5.6\left(\frac{V_{LO}}{A}\right) \tag{5}$$

$$G_r = 4100 + 11.5\left(\frac{V_{LO}}{A}\right) \tag{6}$$

where,

R: Radius of foundation in contact with soil (34);
G_V, G_h, G_r: Initial shear modulus of soil for infinitesimal strains;
ν: Poisson's ratio (0.45);
D: Embedment of the maximum diameter section (3 m);
V_{LO}: Vertical spudcan load during preloading (398 MN);
A: Effective bearing area of spudcan (A=380.1 m^2).

Table 2 lists the calculated soil stiffnesses.

Table 2. Soil stiffness according to soil layer.

Spring Constant	Sand	Dense Sand	Clay
Kz (MN/m)	3359	141	4116
Ky (MN/m)	75	10	3037
Kr (MN·m/deg)	341	51	3723

3.3. Dynamic Amplification Factor (DAF)

The overall design calculations are based on a quasi-static approach. This approach does not directly account for dynamic response of the unit. However, the displacement of the hull due to the dynamic wave loads can amplify the extreme reactions in the legs. In the calculation, the dynamic response effect would be included, resulting in a DAF and inertial loads. The DAF was used to calculate the inertial load factor, which was multiplied by the wave and current loadings to determine the inertial load. The DAF was calculated using the extreme response based on the 3 h time domain simulation. The wave elevation was modeled as a linear random superposition of regular wave components using information from the wave spectra. The statistics of the underlying random process are Gaussian and fully known theoretically. The random wave generation should use at least 200 wave components with divisions of equal wave energy. It is recommended that smaller energy divisions are used in high frequency regions of the spectrum, where the enforcement and cancellation frequencies are located. The generated random sea state must be Gaussian and should be checked for validity as the following data indicate in Table 3.

Table 3. Random wave analysis information.

Components	Criteria
Standard deviation	(Hs/4) ± 1%
Skewness range	±0.03
Kurtosis range	2.9~3.1
Wave period range	<Tz/20, <Tn/20
Simulation time	60 min
Wave spectrum	JONSWAP
Percentage of damping	5%

where:
Hs = significant wave height;
Tz = zero up-crossing period of the wave;
Kurtosis is the sharpness of the peak of a frequency distribution curve;
Skewness is a measure of the asymmetry of the probability distribution of a real-valued random variable about its mean.

$$\text{DAF} = BS_{DYN} \quad / \quad BS_{QUASI-STATIC} \tag{7}$$

where:
BS_{DYN} is the maximum dynamic wave/current base shear;
$BS_{QUASI-STITIC}$ is the maximum quasi-static wave/current base shear.

The calculated DAF is used to estimate an inertial load-set which represented the contribution of dynamics. The inertia load set is calculated using the following formula:

$$F_{in} = (DAF - 1)\frac{(BS_{(Q-S)Max} - BS_{(Q-S)Min})}{2} \tag{8}$$

where:
$BS_{(Q-S)Max}$ is the maximum quasi-static wave/current base shear;
$BS_{(Q-S)Min}$ is the minimum quasi-static wave/current base shear.

3.4. Stability against Overturning Moment

The design requirement with respect to overturning is:

$$\gamma_s \le \frac{M_s}{M_o} \tag{9}$$

where:
M_o is the overturning moment caused by environmental loads;
M_s is the stability moment caused by functional loads;
γ_s is the safety coefficient against overturning, 1.1.

In order to check the safety against overturning stability, the most conservative conditions are considered, such as highest position, harsh environmental loads, and maximum weight. It is normally assumed that wind, waves, and current are coincident in direction. The stability check against overturning moment is shown at Figure 7.

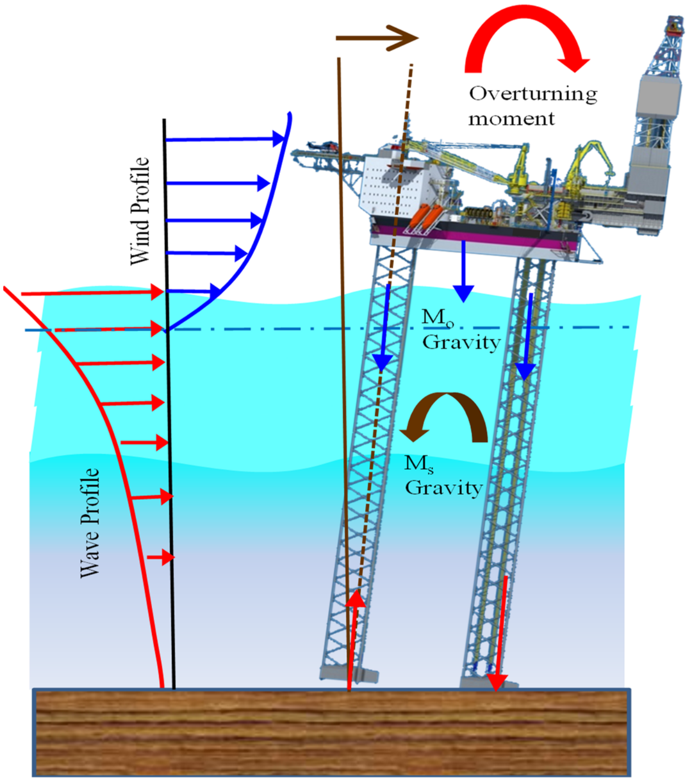


Figure 7. Overturning stability mode against external loads.

3.5. Environmental Condition

The environmental load parameters assumed actual operating conditions in the North Sea, such as wave height (20 m), wave period (10 s), wind speed (30 m/s), and air gap (22 m). The parametric study was performed with varying environmental parameters, which are indicated on Table 4. Current speed was considered to be 0.25 m/s at the sea bottom and 1.25 m/s at surface level. The current load has a smaller effect than other loads. Therefore, current was not considered for parametric study. In order to confirm the structural safety according to magnitude of load, it was composed of five cases at 10% intervals. The size of the variables was determined considering the change in the size of the jack-up rig and the change in environmental load.

Table 4. Design parameters and load cases.

Load Percentage (%)	Wave Height (m)	Wave Period (s)	Wind Speed (m/s)	Air Gap(m)	Remark
100	20	10	30	22.0	Initial design value
110	22	11	33	24.2	Increasing load of 10% compare to initial design
120	24	12	36	26.4	Increasing load of 20% compare to initial design
130	26	13	39	28.6	Increasing load of 30% compare to initial design
140	28	14	42	30.8	Increasing load of 40% compare to initial design
150	30	15	45	33.0	Increasing load of 50% compare to initial design

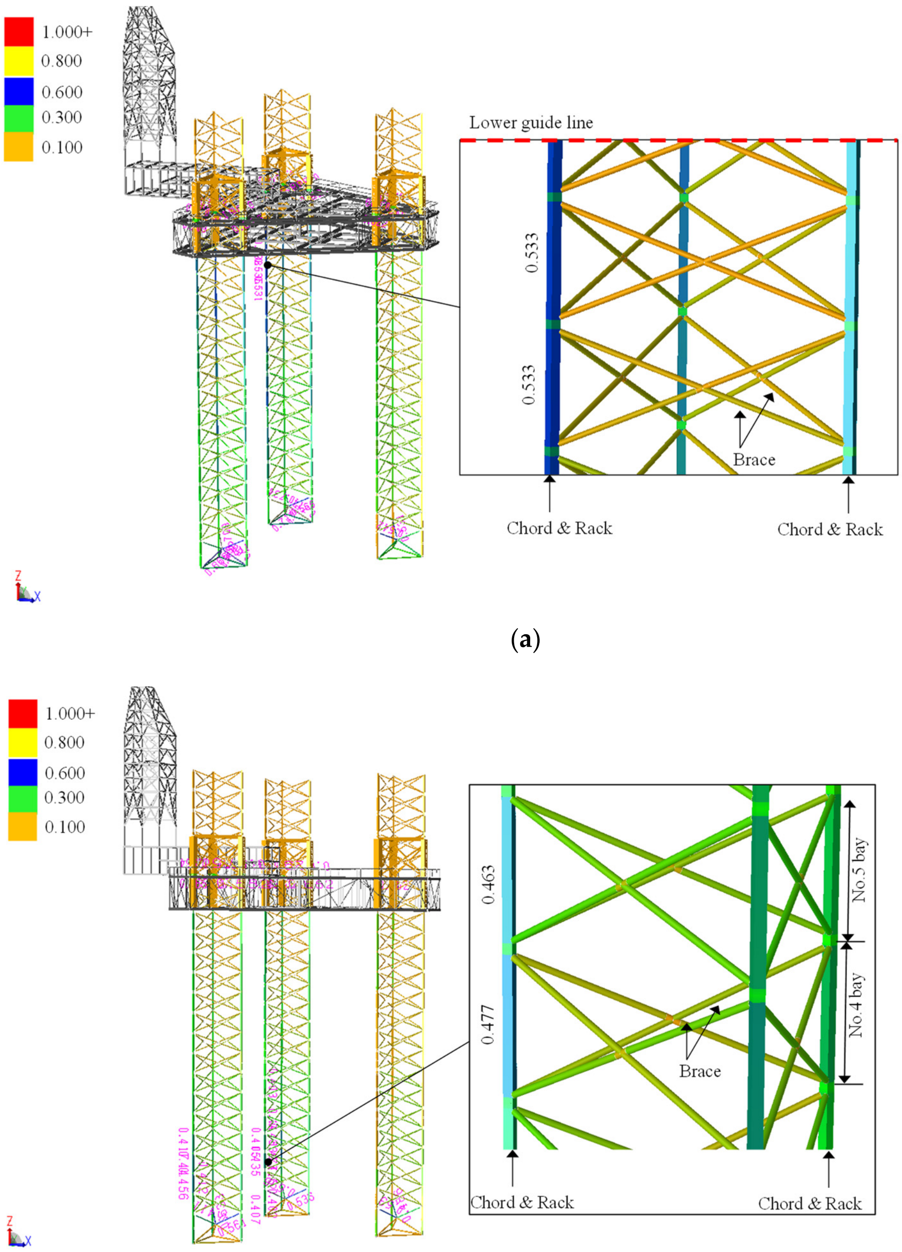
Design loads were considered to be either functional loads or environmental loads. Functional loads included dead load, variable load, and drilling loads such as hook/rotary/set-back. The environmental loads were taken directly from the design conditions. The wave loads, current loads, and wind loads on the legs were considered. In addition, the wind loads on the hull were considered separately following standard wind force calculation methods.

- **Wave loads**: The most significant environmental loads for jack-up rigs are induced by wave action (DNV-RP-C104). The use of a deterministic, regular wave analysis method requires an appropriate wave theory, based on water depth, wave height, and period. The Stokes-V wave theory was applied for the design conditions in accordance with SNAME-RP 5A-5. The Stokes-V is a widely accepted method for determining the kinematics in the Morison equation (SNAME-RP 5A-5). In this paper, the initial design values of wave height and wave period were determined to be 20 m and 10 s, respectively.
- **Wind loads**: The wind load was calculated for three main parts: the hull, legs below the hull base, and legs above the top of the jacking structures. The effective projection area and shape coefficient for wind load on the hull and legs was calculated in accordance with DNV-RP-C104. The reference wind velocity, V_R, was defined as the wind velocity averaged over 10 min, 10 m above the still water level.
- **Air gap**: The air gap is defined as the clear distance between the hull structure and the maximum wave crest elevation. The requirement for the length of the leg is that the distance between the lower part of the deck structure in the operating position and the crest of the maximum design wave, including astronomical and storm tides, is not to be less than 10% of the combined storm tide, astronomical tide, and height of the design wave above the mean low water level, or 1.2 m, whichever is smaller. The air gap should be checked in accordance with DNV OS-C104. In this paper, the air gap initial design value was determined to be 22 m.

4. Comparative Analysis According to Variables

4.1. Result of the Numerical Simulation

The FE analysis is divided into two boundary conditions, namely pinned and soil conditions. As shown in Figure 8, the maximum combined stress and axial stress are both within the yield stress limit, giving a unity check (U.C) of 0.533 and 0.477, respectively. All of the structural members withstood the applied environmental loadings with adequate factors of safety with respect to the failure modes according to both the pinned and soil boundary conditions. The critical loading condition took place at the heading angle of 120 deg under maximum base shear condition owing to the large incensement of the overturning moment. In the case of pinned conditions, the maximum bending moment was higher than under soil conditions at a lower guide since the effective length of the leg was longer than the soil condition resulting in a large dynamic and P-Δ effect. Under the pinned conditions, the maximum U.C occurred at the lower guide at the interfaced joint between the hull and legs. This is also same location where the maximum bending moment occurred, as shown in Figure 8a. In soil conditions, the maximum U.C occurred in the lower part of the leg. The maximum value takes place in the bay Number 4 because it was designed with a lower stiffness compared to other bays in the leg, as shown Figure 8b.



(**a**)

(**b**)

Figure 8. Unit check result according to boundary condition: (**a**) maximum unity check value and location under pinned condition; (**b**) maximum unity check value and location under soil condition.

4.2. Effect of Structural Response According to Wave Height

For parameters of wave height, the summary of the U.Cs are shown in Table 5 and Figure 9. Table 5 shows the results according to various wave heights. In the case of the initial design at 100% of wave height, we found that there was a different critical location between pinned and soil conditions from a structural strength point of view; the maximum U.C value was 0.533 at the lower guide under pinned conditions compared to 0.477 at the bottom of the leg under soil conditions. This means that pinned conditions are subject to large bending moments and soil conditions have smaller bending moments due to a change in the effective length against combined loads.

Table 5. Effect of structural response according to parameters for wave height.

Load Percentage (%)	Unit Check		Unit Check Margin		Location	
	Pinned Model	Soil Model	Pinned Model	Soil Model	Pinned Model	Soil Model
100	0.533	0.477	46.7%	52.3%	Lower Guide	Bottom of Leg
110	0.641	0.630	35.9%	37.0%	Lower Guide	Bottom of Leg
120	0.838	0.833	16.2%	16.7%	Lower Guide	Bottom of Leg
130	1.034	1.036	−3.4%	−3.6%	Brace	Brace
140	1.260	1.261	−26.0%	−26.1%	Brace	Brace
150	1.485	1.486	−48.5%	−48.6%	Brace	Brace

Figure 9 shows the distribution of results of unit check for various wave heights. It can be observed that increasing wave height had a strong effect on the both of them. In other words, the structural margin value decreased linearly with increasing wave height. This is considered to be a governing factor for structural strength in the leg design. The U.C pattern under pinned conditions was quite similar to that under soil conditions. From this result, the primary reinforced area can be known when designing a leg structure under pinned conditions.

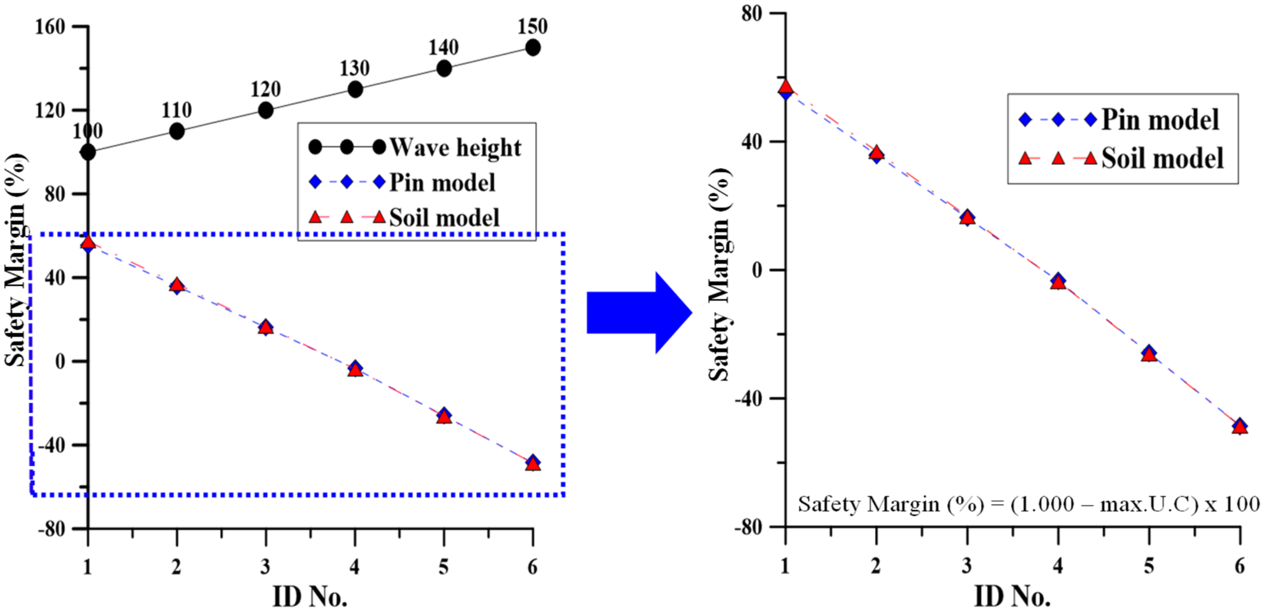


Figure 9. Comparative unit check margin with varying wave height.

4.3. Effect of Structural Response According to Wave Periods

For the wave period parameter, the summary of the U.Cs is shown in Table 6 and Figure 10.

Figure 10 shows the result of the U.C with varying wave periods. As the wave period increased, the structural strength margin of the leg decreased linearly. The main reason for this pattern is that the wave energy increases with length of the wave. The structural strength of the leg showed a small difference of about 1% according to boundary conditions (pinned and soil condition).

Table 6. Effect of structural response according to parameters for wave period.

Load Percentage (%)	Unit Check		Unit Check Margin		Location	
	Pinned Model	**Soil Model**	**Pinned Model**	**Soil Model**	**Pinned Model**	**Soil Model**
100	0.445	0.427	55.5%	57.3 %	Lower Guide	Bottom of Leg
110	0.441	0.424	55.9%	57.6%	Lower Guide	Bottom of Leg
120	0.436	0.420	56.4%	58.0%	Lower Guide	Bottom of Leg
130	0.432	0.417	56.8%	58.3%	Lower Guide	Bottom of Leg
140	0.434	0.418	56.6%	58.2%	Lower Guide	Bottom of Leg
150	0.436	0.419	56.4%	58.1%	Lower Guide	Bottom of Leg

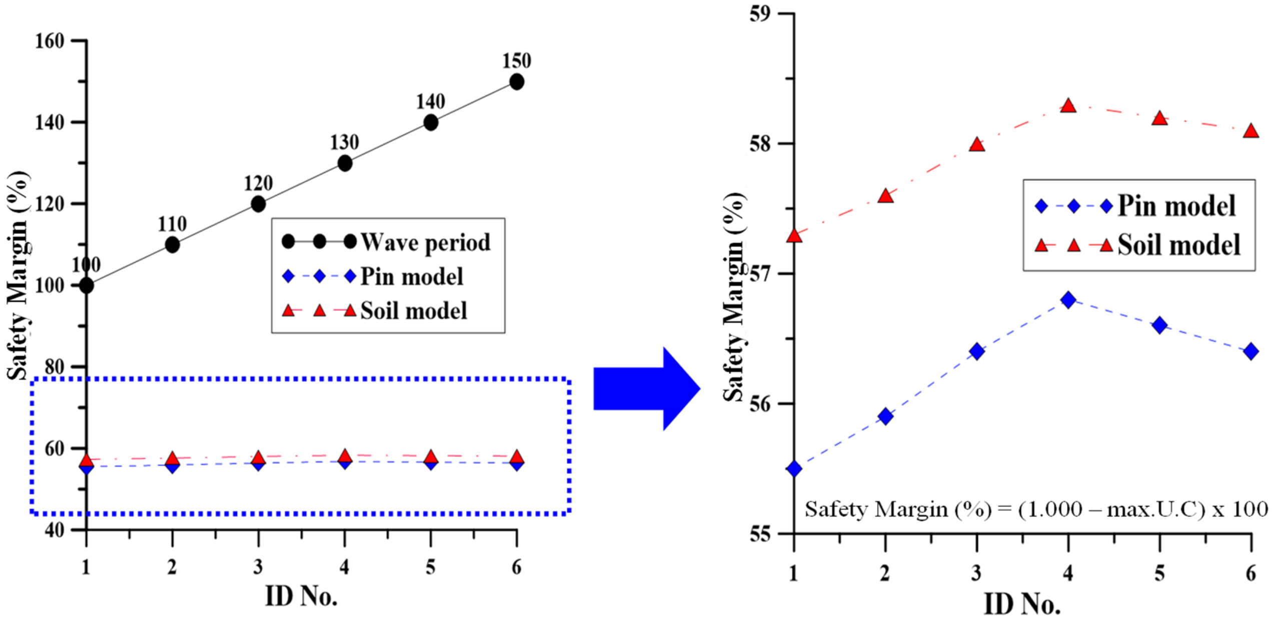


Figure 10. Comparative unit check margin with varying wave period.

4.4. Effect of Structural Response According to Wind Speed

The summary of U.Cs is shown in Table 7 and Figure 11 according to varying wind speeds.

Table 7. Effect of structural response according to parameters for wind speed.

Load Percentage (%)	Unit Check		Unit Check Margin		Location	
	Pinned Model	**Soil Model**	**Pinned Model**	**Soil Model**	**Pinned Model**	**Soil Model**
100	0.445	0.427	55.5%	57.3%	Lower Guide	Bottom of Leg
110	0.459	0.436	54.1%	56.4%	Lower Guide	Bottom of Leg
120	0.472	0.444	52.8%	55.6%	Lower Guide	Bottom of Leg
130	0.486	0.453	51.4%	54.7%	Lower Guide	Bottom of Leg
140	0.528	0.474	47.3%	52.6%	Lower Guide	Bottom of Leg
150	0.569	0.495	43.1%	50.5%	Lower Guide	Bottom of Leg

Figure 11 shows the distribution of results of unit check with varying wind speed. It can be observed that as the wind speed increased, the structural strength margin of the leg linearly decreased. This is because the wind load increases in proportion to the square of the wind speed. The structural strength of the leg showed a small difference of about 1% according to boundary conditions (pinned and soil conditions). The leg U.C under soil conditions was lower than that under pinned conditions because the bending moment became small due to the effect of the soil.

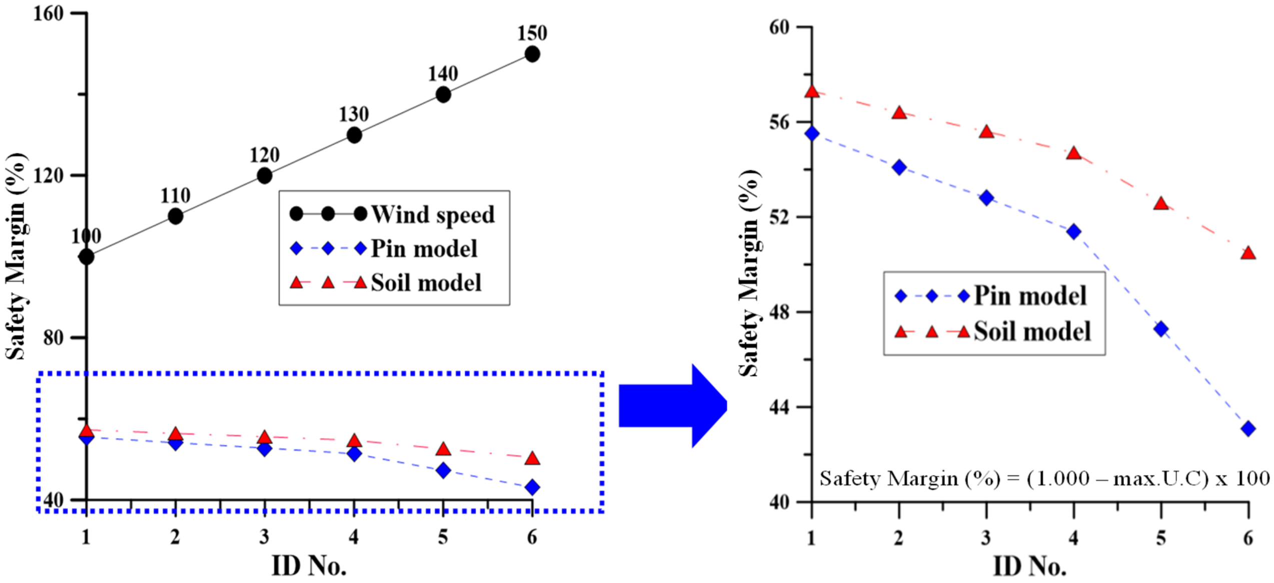


Figure 11. Comparative unit check margin with varying wave speed.

4.5. Effect of Structural Response According to Air Gap

The main U.C results while varying parameter of the air gap are shown in Table 8 and Figure 12. The safety margin is the percentage of the remaining values, excluding the maximum U.C of 1.0 according to API and AISC requirements, as indicated in Figure 12. As the distance of the air gap increased, the structural strength margin of the leg decreased linearly. This is because the air gap increases overturning moment as well as increases the maximum displacement of the leg structure. In the soil conditions, the maximum U.C occurred at the bottom of the leg, while under pinned conditions it showed around the lower guide in the hull bottom, same as the pattern in Figure 8.

Table 8. Effect of structural response according to parameters for air gap.

Load Percentage (%)	Unit Check		Unit Check Margin		Location	
	Pinned Model	Soil Model	Pinned Model	Soil Model	Pinned Model	Soil Model
100	0.445	0.427	55.5%	57.3%	Lower Guide	Bottom of Leg
110	0.446	0.428	55.4%	57.2%	Lower Guide	Bottom of Leg
120	0.448	0.429	55.2%	57.1%	Lower Guide	Bottom of Leg
130	0.449	0.430	55.1%	57.0%	Lower Guide	Bottom of Leg
140	0.451	0.431	54.9%	56.9%	Lower Guide	Bottom of Leg
150	0.453	0.435	54.7%	56.5%	Lower Guide	Bottom of Leg

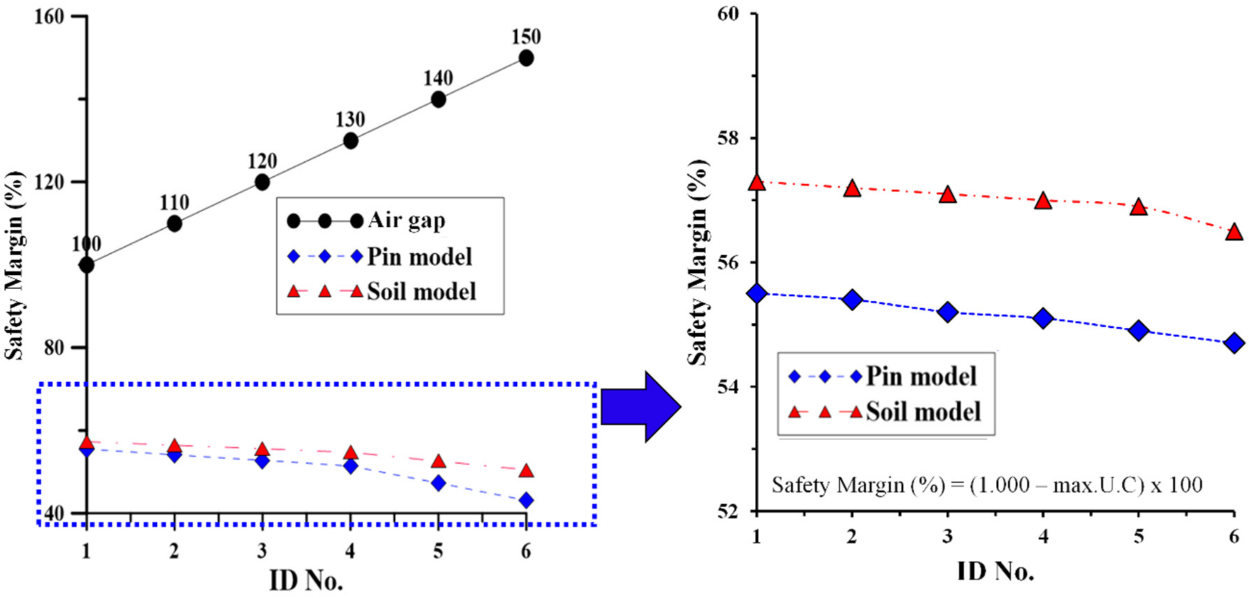
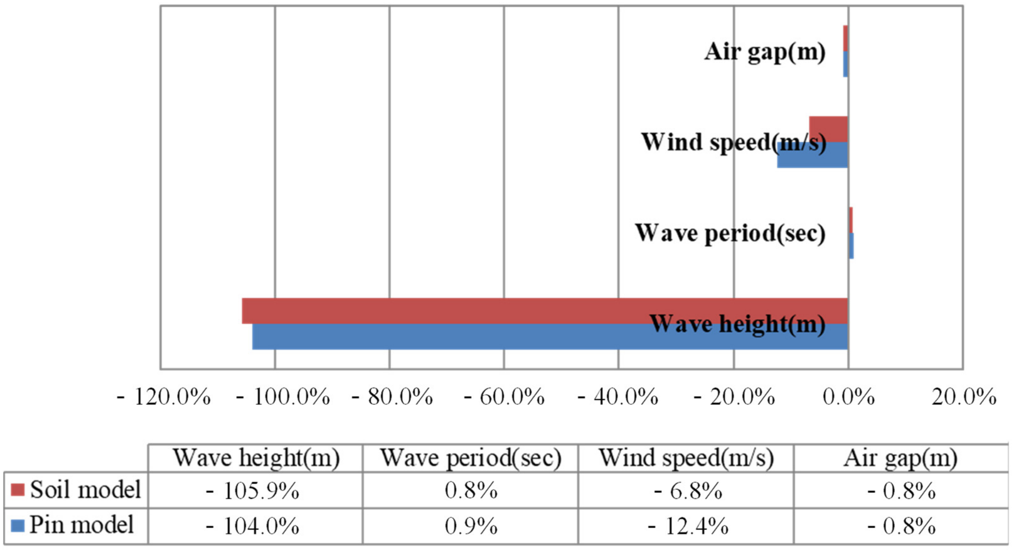


Figure 12. Comparative unit check margin with varying air gap.

The summarized results of the structural response with varying parameters are shown in Figure 13. It can be observed that the wave height is the most significant factor for structural strength in the leg design. Secondly, wind speed is an important considering factor among varying environmental loadings. Air gap and wave period are minor factors from a structural strength point of view. From the above results, it is necessary to determine the realistic wave load when building technical specifications with the project owner. The leg design is greatly changed according to the wave load change, and has a great influence on the construction cost and time.

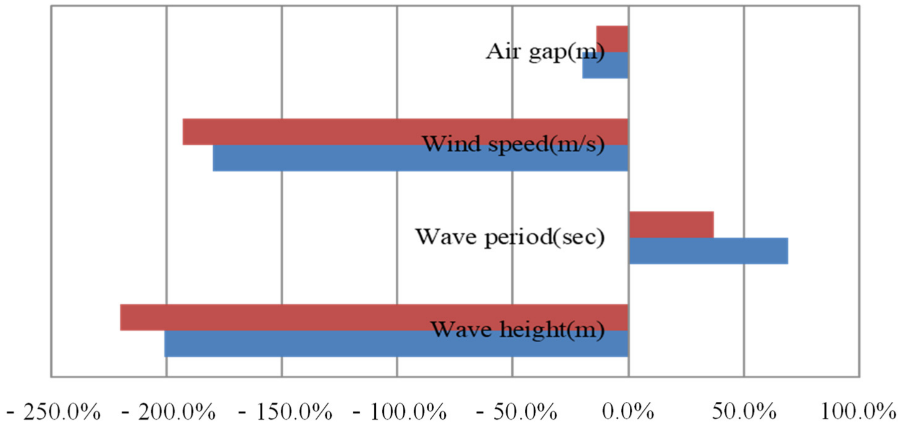


	Wave height(m)	Wave period(sec)	Wind speed(m/s)	Air gap(m)
🟥 Soil model	- 105.9%	0.8%	- 6.8%	- 0.8%
🟦 Pin model	- 104.0%	0.9%	- 12.4%	- 0.8%

Figure 13. Summary of effect of structural response according to parameters.

4.6. Effect of Structural Response According to Overturning Stability

The summary of U.Cs based on the overturning stability with varying design parameters is shown in Figure 14. It can be also observed that the wave height is the most significant factor for overturning stability in the leg design. Secondly, wind speed is also an important considering factor among varying environmental loadings, and wave period is also significant factor for overturning stability. Pinned condition is more conservative than soil condition against changes in wave period. It means that the maximum displacement depends on the rotational degree of freedom at the end of the leg.



	Wave height(m)	Wave period(sec)	Wind speed(m/s)	Air gap(m)
🟥 Soil model	- 220.0%	37.0%	- 193.0%	- 14.0%
🟦 Pin model	- 201.0%	69.0%	- 180.0%	- 20.0%

Figure 14. Summary on effect of overturning stability response according to parameters.

5. Conclusions

In the present study, an engineering procedure is proposed to review the structural strength of legs, hulls, and cantilevers, in which different models and analyses can be configured so that they are solved within unit flow-chart. Through this process, we can expect that engineering time and cost can be greatly reduced. From various references and engineering data, it was possible to determine the governing inputs to examine the effects of parameters under extreme environmental conditions. The numerical parameters consisted of a combined set of variables including wave height (20 m), wave period (10 s), wind speed (30 m/s), and air gap (22 m). The parametric study was performed with varying environmental parameters. For the parametric study, the influence of each factor on the leg boundary conditions increased by 10% from the initial design value up to 50%. Through sensitivity analysis for varying environmental characteristics, wave height and wind speed were significant factors for structural strength and overturning stability in the leg design. From the meaningful results, it could be very useful guidance about the effect of parameters during the conceptual design stage of jack-up rigs. The following conclusions were drawn from this study:

(1) The unified engineering procedures can save time and cost by evaluating legs, hulls, and cantilevers step-by-step using the detailed model;
(2) Considering soil conditions enables a more lightweight leg design;
(3) The wave height is the most significant factor for structural strength and overturning stability in the leg design;
(4) Wave height and wind speed are significant factors for structural strength and overturning stability in the leg design;
(5) Pinned condition is more conservative than soil condition in response to wave period;
(6) The comparative results in this paper would be very helpful for leg design of jack-up rigs;
(7) The critical loading condition takes place at around 120 deg under maximum base shear condition owing to big incensement of overturning moment.
(8) The lower guide and bottom of the leg should be reinforced against wave loading in the basic design stage.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Emren, V. Three Dimensional Finite Element Modeling for the Spudcan Penetration into Clayed Seabed. Master's Thesis, Middle East Technical University, Ankara, Turkey, July 2015.
2. Noble Denton Europe and Oxford University. *The Calibration of SNAME Spudcan Footing Equations with Field Data*; Report No. L19073/NDE/mjrh; Noble Denton Europe and Oxford University: Oxford, UK, 2005; Volume 5.
3. Health and Safety Executive (HSE). *Guidelines for Jack-Up Rigs with Particular Reference to Foundation Integrity*; HSE Research Report 289; Health and Safety Executive (HSE): Bootle, UK, 2004.
4. Tan, X.M.; Li, J.; Lu, C. Structural behaviour prediction for jack-up units during jacking operations. *Comput. Struct.* **2003**, *81*, 2409–2416. [CrossRef]
5. Zhang, Y.; Bienen, B.; Cassidy, M.J. Development of a combined VHM loading apparatus for a geotechnical drum centrifuge. *Int. J. Phys. Model. Geotech.* **2013**, *13*, 13–30. [CrossRef]
6. Hu, P.; Cassidy, M.J. Predicting jack-up spudcan installation in sand overlying stiff clay. *Ocean Eng.* **2013**, *146*, 246–256. [CrossRef]
7. Jun, M.J.; Kim, Y.H.; Hossain, M.S.; Cassidy, M.J.; Hu, Y.; Sim, J.W. Numerical investigation of novel spudcan shapes for easing spudcan-footprint interactions. *J. Geotech. Geoenviron. Eng.* **2018**, *144*, 144–154. [CrossRef]
8. Pisanò, F.; Schipper, R.; Schreppers, G.J. Input of fully 3D FE soil-structure modeling to the operational analysis of jack-up structures. *Mar. Struct.* **2019**, *63*, 269–288. [CrossRef]
9. Kim, Y.H.; Hossain, M.S.; Edwards, D.; Wang, P.C. Penetration response of spudcans in layered sands. *Appl. Ocean Res.* **2019**, *82*, 236–244. [CrossRef]
10. Pisanò, F. Input of advanced geotechnical modelling to the design of offshore wind turbine foundations. In Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavik, Iceland, 1–6 September 2019; pp. 1–26.
11. Park, J.S.; Ha, Y.S.; Koo, J.B.; Jang, K.B. Parametric study of allowable stress design and load & resistance factor design for jack-up rig. In Proceedings of the The Twenty-fourth International Ocean and Polar Engineering, Busan, Republic of Korea, 15–20 June 2014.
12. American Petroleum Institute (API). *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms-Load and Resistance Factor Design*; American Petroleum Institute (API): Washington, DC, USA, 1993.
13. American Institute of Steel Construction. *Specification for Structural Steel Buildings Load and Resistance Factor Design*, 13th ed.; American Institute of Steel Construction: Chicago, IL, USA, 2005.
14. Det Norske Veritas (DNV). *Environmental Conditions and Environmental Loads*; DNV-RP-C205; DNV: Oslo, Norway, 2014.
15. The Society of Naval Architects and Marine Engineers (SNAME). *Guidelines for Site Specific Assessment of Mobile Jack-Up Units*; Technical Research Bulletin 5-5A; SNAME: Alexandria, VA, USA, 2002.
16. Det Norske Veritas (DNV). *Classification Notes–No. 30.4*; DNV: Oslo, Norway, 1992.