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Impact on water depth operating limits of reduced SNAME T&R Bulletin 5-5A environmental load factor γ_3 from 1.25 to 1.15

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EXECUTIVE SUMMARY

SNAME Bulletin 5-5 Guidelines and Bulletin 5-5A Recommended Practice for Site Specific Assessment of Mobile Jack-Up Units adopt the Load and Resistance Factor Design (LRFD) approach. Separate load factors are specified for dead loads, variable loads, environmental loading and dynamic loading. These factors were derived on the basis of assessments of four jack-up units considered in the original Joint Industry Project that led to the development of SNAME T&R Bulletin 5-5A. Recently, however, the SNAME OC-7 Panel North Sea Annex Sub-Committee has proposed that the environmental loading factor (γ_3) presently incorporated in SNAME 5-5A for jack-up assessment be reduced from its current value of 1.25 to 1.15.

The Health and Safety Executive (HSE) sought examination of the effect of reducing γ_3 from 1.25 to 1.15 on a typical assessment, and to quantify this consequence in terms of water depth. PAFA Consulting Engineers has undertaken such an investigation using a LeTourneau 116C jack-up and relevant metocean and soils data for a North Sea site provided by Shell Expro. It is clear that any reduction of the environmental load factor will result in smaller environmental loads and therefore reduced member stresses and overturning moments, which in turn will result in lower maximum utilisation ratios (UR) for the unit. The objective of this study is to quantify the effect of the proposed reduction in γ_3 in terms of the ability of the unit to operate in an increased water depth for the same level of maximum UR.

The following salient conclusions are drawn from the results of this study:

- For a maximum UR of unity and using $\gamma_3 = 1.25$, given a water depth of 59.0 m, the jack-up is able to withstand a maximum wave height of 14.1 m. The controlling parameter for this condition is the reinforced chord section. All other element sections exhibit URs considerably below unity.

- Maximum UR is a function of the location of the lower guide elevation relative to the leg, either at midspan or adjacent to leg chord nodes. Water depth, wave height and airgap requirements dictate the location of the lower guide.

- Plots of maximum UR versus wave height indicate that, although the maximum UR tends to increase with increase in wave height, by far the greatest influence is as a result of re-location of the lower guide due to airgap requirements.

- A reduction in the environmental load factor, γ_3, from 1.25 to the proposed value of 1.15 causes a reduction of 7.8% in the maximum UR, for the lower guide located at leg chord midspan.

- To achieve the same level of maximum UR in the jack-up when $\gamma_3 = 1.15$, the unit is able to operate in a water depth of 62.4 m (3.4 m greater than that possible when $\gamma_3 = 1.25$), all other parameters kept constant. For the water depth under consideration, this represents an increase of 6%. This finding is dependent on the proportion of environmental to gravity load actions and thus can be expected to change should this proportion alter.

1. INTRODUCTION

1.1 BACKGROUND

SNAME Bulletin 5-5 Guidelines and Bulletin 5-5A Recommended Practice for Site Specific Assessment of Mobile Jack-Up Units(1) adopt the Load and Resistance Factor Design (LRFD) approach. Separate load factors are specified for dead loads, variable loads, environmental loading and dynamic loading. These factors were derived on the basis of assessments of four jack-up units considered in the original Joint Industry Project(2) that led to the development of SNAME T&R Bulletin 5-5A. Recently, however, the SNAME OC-7 Panel North Sea Annex Sub-Committee has proposed that the environmental loading factor (γ_3) presently incorporated in SNAME 5-5A for jack-up assessment be reduced from its current value of 1.25 to 1.15. The basis for the proposed reduction appears to stem from two main sources. Firstly, the International Association of Drilling Contractors (IADC) has general concerns regarding the effect of the current magnitude of the environmental load factor in 5-5A on the operating limits of a number of jack-ups. Secondly, a recent study by Global Maritime(3) of the four jack-up units considered in the original jack-up Joint Industry Project has demonstrated that the use of γ_3 of 1.15 in place of 1.25 is justified because grossly under-utilised failure modes which did not govern should not be included in the average betas used to set the target safety factors.

Notwithstanding, it is clear that the 1.25 factor for environmental loads, along with other 5-5A requirements can lead to more strict limitations on jack-up deployment than previous Working Stress Design (WSD) assessments. The reduction of the environmental load factor to 1.15 is seen as one way of relaxing these 5-5A limitations.

The Health and Safety Executive (HSE) sought examination of the effect of reducing γ_3 from 1.25 to 1.15 on a typical assessment, and to quantify this consequence in terms of water depth. PAFA Consulting Engineers has undertaken such an investigation using a LeTourneau 116C jack-up and relevant metocean and soils data for a North Sea site provided by Shell Expro(4). This report presents the study objectives, methodology, results and conclusions of the investigation.

1.2 OBJECTIVES

It is clear that any reduction of the environmental load factor will result in smaller environmental loads and therefore reduced member stresses and overturning moments, which in turn will result in lower maximum utilisation ratios (UR) for the unit. The objective of this study is to quantify the effect of the proposed reduction in γ_3 in terms of the ability of the unit to operate in an increased water depth for the same level of maximum UR. It was agreed with HSE at the outset that this comparison would be performed for the unit operating at or close to its limit, i.e. with a maximum UR at or very near unity.

To achieve the above-noted objective, the following scope of work was undertaken in this study:

- For the selected water depth, soils conditions and metocean data, and using $\gamma_3 = 1.25$, conduct analyses and perform code checks of the unit structural elements in accordance with the requirements of 5-5A. Conduct overturning checks of the unit and determine the controlling maximum UR.

- Vary the wave height until the maximum UR becomes or is very close to unity. The resultant condition is termed the base case.

- Re-assess the base case condition using $\gamma_3 = 1.15$ to determine the maximum controlling UR.

- Conduct further assessments using γ_3 =1.15 for variations in water depth, keeping all other load conditions the same as for the base case, to determine the water depth that results in a maximum UR of the same magnitude as the base case.

1.3 REPORT LAYOUT

The report is formatted as follows. Section 2 contains basic design data for the 116C jack-up, including a general description of the platform and water levels, environmental data and soils data at the selected North Sea location. Design load cases are addressed in Section 3. This section also describes the platform weight and centre of gravity summaries for fixed, variable and live loads. Descriptions of the computer model and the analysis procedure are given in Section 4. All aspects of the leg, hull, the leg-hull connection and the foundation modelling are discussed.

Analysis results, covering natural frequencies, base shears, overturning moments and member utilisation ratios for each assessment are described in Section 5. A number of conclusions have been arrived at, and these are also presented within this section. References are included at the end of the main text followed by tables and figures.

2. BASIC DESIGN DATA

2.1 DESCRIPTION OF THE JACK-UP PLATFORM

The jack-up unit selected was the LeTourneau 116C class, modified for operation in the North Sea. It is an independent 3-leg self-elevating unit with cantilever drilling capability, see Figures 1 and 2. The rig dimensions are as follows: overall hull length of 74.1 m, hull width of 62.8 m and hull depth of 7.9 m. The forward-aft leg spacing is 39.3 m and that between port-starboard legs is 43.3 m.

The legs are of the 4-chord lattice type. Leg rack chords are of the unopposed pinion type on a pitch point spacing of 9.14 m. LeTourneau have confirmed that for operation in the North Sea, the 116C unit would have two rounds of leg removed since the unit is unable to work in water depths that would utilise the full leg length. The total length of the reduced leg including the spudcan is 104.6 m. The “standard” 116C chord cross section is reinforced with 4” x 1” flat bars attached to each side of the rack plate. This reinforcement extends from approximately 33.4 m above tip of can (TOC) to the top of the leg. In addition to this reinforcement, many 116C units operating in the North Sea are also fitted with 12” x 1½” flat bar reinforcement attached to the side plates – see Figure 3. For this project, the chords of the lower sections of leg (from TOC to 33.4 m above TOC) were considered unreinforced, and those in the upper sections of the legs were considered reinforced.

The bay height is 3.4 m and each bay comprises K-bracing from 324 mm diameter x 19.1 mm thickness tubulars. Horizontal bracing and span breakers at each level are 324 mm diameter x 19.1 mm thickness and are 229 mm diameter x 9.5 mm thickness, respectively. In the lower bays of the legs, the wall thickness of the horizontal and diagonal members is increased to 25.4 mm.

The spudcan diameter is 14.0 m across flats.

The jack-up is designed to support the in-service environmental loads and gross maximum drilling condition deck loads under the loading conditions specified in Section 3. Preload condition and temporary loading to which the structure is subjected during transportation were not considered in this study.

2.2 MATERIAL PROPERTIES

All components of the chord are made from steel with a minimum yield strength of 483 MPa, with the exception of the rack plate, which has a minimum yield strength of 586 MPa. The ultimate tensile strengths are 552 MPa and 689 MPa, respectively.

The K-braces, horizontals and span breakers are constructed from steel with a minimum yield strength of 586 MPa. The ultimate tensile strength of the steel is 689 MPa.

Other steel properties were assumed as follows:

Young’s modulus	$E = 200{,}000$ MPa
Shear modulus	$G = 80{,}000$ MPa
Density	$\rho = 7{,}850$ kg/m^3
Poisson’s ratio	$\nu = 0.3$

The density of seawater was taken to be 1025 kg/m^3. For wind load calculations, the density of air was taken as 1.22 kg/m^3.

2.3 WATER LEVELS

Shell Expro provided site-specific data for a site located in the northern sector of the southern North Sea. The water levels used for the determination of the base case are shown in Table 1.

In accordance with the scope of work described in Section 1.2, various water depths were considered subsequent to the initial analysis to determine the condition that resulted in the controlling maximum UR matching that obtained for the base case. To provide the required airgap, it was necessary, in some instances, to locate the hull at a higher elevation due to an increase in water depth. SNAME 5-5A states that the jack-up unit should be checked for two positions of the lower guide: firstly for the lower guide adjacent to the node of the leg chord and secondly, for the lower guide at midspan of the leg chord – see Figure 4. The layout of the lower guide of the 116C jack-up indicated that the lower guide was 1.31 m long. To ensure that load transfer between the leg and the hull was modelled accurately, the computer modelling of the lower guide comprised two springs located 0.656 m either side of the true centre of the lower guide. Figure 4 indicates this detail.

In some instances a change in water depth resulted in a change in the jack-up analysis model, since the hull connection to the leg was required to be at a higher elevation to achieve the airgap and meet the lower guide location criteria.

2.4 ENVIRONMENTAL DATA

Shell Expro provided site-specific metocean data for the selected site. In order to meet the criterion that the maximum UR for the jack-up was unity or very close to unity, 50-year 'summer-only' metocean data were used for this study. An earlier study by PAFA Consulting Engineers(5) showed that use of the 50-year extreme storm condition at this site resulted in maximum URs considerably in excess of unity. The non-directional 50-year 'summer-only' metocean data used in this study are presented in Table 2.

For wind velocity, the 1-minute (individual criteria) value was based on a gust factor of 1.18 applied to the 1-hour value. The values of current velocity were converted into a current profile using the factors given in Table 3. Current blockage factor was calculated in accordance with the requirements of 5-5A. Using the parameters for equivalent leg diameter, equivalent leg drag coefficient and face width of the leg, a current blockage factor of 0.77 was determined and applied to the current velocity.

2.5 SOILS DATA

For the selected site, the stiffness of the footings was based on an assumed G/S_u ratio of 50, where G is the soil shear modulus and S_u is the undrained shear strength of soil beneath the footings (taken as 200 kPa). A reduced value of 60 kPa 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 calculated as 532 MN/m, 106 MN/m and 15684 MNm/rad, respectively.

The soil profile below the mudline was taken from borehole records and is shown in Table 4.

2.6 MARINE GROWTH

In the absence of site-specific data, to allow for extra wave and current loading caused by the presence of marine growth, an increase of 12.5 mm in the radii of tubulars was used for all members below MWL +2 m.

3. LOADING CONDITIONS

3.1 LOAD CASES

This section defines the loads considered for the assessment of the jack-up unit. 50-year 'summer-only' environmental data were considered in this assessment. The full set of loading effects were as follows:

- Dead loads including buoyancy
- Variable loads
- 50-year summer-only wave and current loads
- 50-year summer-only wind loads
- Inertial loads
- P-Δ effects

3.1.1 Dead Loads

LeTourneau supplied data regarding the hull basic weight, stationary fixed weight, cantilever load and leg and spudcan weights as excerpts from a typical 116C Operating Manual. The centre of gravity for each weight component was also provided. These data are reproduced in Table 5. The weights of the legs reflect the fact that two rounds of leg have been removed from the top of each leg section. The cantilever assembly was taken to be in the normal stowed position.

3.1.2 Variable Loads

The maximum variable load is 16.4 MN, taken from excerpts from a typical 116C Operating Manual. Variable load was distributed evenly to the three legs. The longitudinal centre of gravity (LCG) and transverse centre of gravity (TCG) were calculated such that each leg was loaded equally.

3.1.3 50-year Summer-Only Wave and Current Loads

Wave loads on the jack-up were calculated in accordance with Section 4 of 5-5A. An earlier study by P A F A Consulting Engineers demonstrated that at this site, three directions resulted in the critical loading conditions for this unit. Therefore for the present study only these three wave directions were considered, see Figure 5. In order to ensure that maximum loads were captured, each wave was stepped through the structure over a full wave cycle using 15-degree phase angle increments.

To account for reduced wave kinematics in the wave crest, a wave height reduction factor of 1.60/1.86 was applied to the maximum wave height noted in Table 2. This is in accordance with Section 3.5 of SNAME 5-5A. Stream Function wave theory was applicable for the location water depth, maximum wave height and period.

Current loads were applied in conjunction with wave loading. Details of the adopted current velocity and profile are given in Section 2.4. The profile was stretched and compressed, such that the surface component was constant.

Wave and current forces were calculated using Morison's equation, using the vectorial sum of the wave particle velocity and the current velocity, normal to the member axis. Account was taken of the increase in effective diameter due to the presence of marine growth. In accordance with 5-5A, marine growth was not applied to the teeth of the racks and protruding guide surfaces of chords.

3.1.4 50-year Summer-Only Wind Loads

Wind loads on the jack-up were calculated in accordance with Section 4 of 5-5A. Wind areas were calculated for the hull, legs and all major components of the topsides, including the jackhouses, drilling derrick, helideck, living quarters, etc. Calculations were performed for each wave direction considered and due account was taken of appropriate height coefficients and projected areas.

Wind loading on the hull was applied to the model as a series of nodal loads, the direction of loading corresponding to the wave direction under consideration.

In accordance with Section 4.2 of 5-5A, the jack-up legs were converted to equivalent leg sections such that an equivalent drag coefficient, C_D, was determined. The resulting loads per unit length were applied as a series of concentrated loads to every leg node exposed to wind loading. The small inaccuracy of this method of load application was considered acceptable, since sufficient nodes were used to simulate uniformly applied loading.

Wind loading on topside components can be significant due to the large exposed areas and height above the mean water level. In addition, since the topsides are not usually part of the computer model, the effects of wind loading must be correctly simulated. Because computer modelling of the hull ceased at the top of the deck level, the overturning effects of wind loading on the topsides were incorporated to the model by applying appropriate magnitudes of lateral and vertical loads at deck level.

3.1.5 Inertial Loads

The inertial loadset was derived from the recommendations given in Section 7.3.6 of 5-5A. The classical single degree-of-freedom analogy was adopted to determine the magnitude of a point load to be applied to the hull centre of gravity.

Accordingly, the jack-up highest natural periods were determined from analyses to calculate the dynamic amplification factor (DAF). This, together with the amplitude of the quasi-static base shear over one wave cycle, was used to determine the magnitude of the inertial loadset. In accordance with 5-5A, the inertial loads were applied to the model at the centre of the hull.

3.1.6 P-Δ Effects

The USFOS program(7) was used for the analysis. It is a non-linear structural analysis program incorporating large displacement capabilities throughout. Thus, P-Δ effects both global and local were automatically calculated in the analysis routines of this software.

3.2 LOAD COMBINATIONS

Three wave directions and twenty-four phase angles per direction were investigated. Each wave condition was combined with current and wind loading effects to develop environmental loading. The other loading components to be considered were dead loads, variable loads and dynamic loads. Each load component was factored using the 5-5A load factors to prepare factored load combinations for each wave direction and for each phase angle considered. Table 6 shows the load factors for the assessment in accordance with 5-5A.

Overturning moment checks were performed according to Section 8.2 of 5-5A. In Section 3.2.2 of this Practice, it is stated that for checks requiring minimum elevated weight, 50% of the variable load may be applied. For overturning checks the corresponding factor, $\gamma_{2,}$ was therefore set to 0.5.

4. FE MODEL AND ANALYSIS PROCEDURE

4.1 GENERAL APPROACH

A fully detailed finite element (FE) model of legs and hull/leg connections was prepared in accordance with guidance given in 5-5A. The hull was represented in sufficient detail by plate elements to capture the stiffness of the main decks and bulkheads.

The design concept of the 116C unit is such that it has a fixed jacking system and unopposed pinions, but no fixation system. The absence of a fixation system 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 a position offset from the chord neutral axis and will also, therefore, generate local chord bending moments.

The details of the hull/leg connection are critical in ensuring accurate capture of the chord and brace member utilisation ratios in the vicinity of the guides, and appropriate emphasis was placed on this aspect of the modelling.

4.2 DETAILED LEG MODEL

All leg members were modelled using standard USFOS 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 was not required, and was therefore suppressed. The model incorporated all main members in each bay. Members representing the spudcan were also included in the finite element model.

Chord section properties were calculated as a function of the guide plate, rack plate and side plate and were assigned general beam properties. As noted earlier, the standard 116C chord is reinforced with a 4” x 1” flat bar attached to each side of the rack plate extending from approximately 33.4m above tip of can (TOC) to the top of the leg. Many 116C units operating in the North Sea are also fitted with 12 ” x 1½ ” flat bar reinforcement attached to the side plates. This reinforcement was included within the calculation of chord section properties, effectively changing the chord into two separate groups – unreinforced and reinforced.

The braces were modelled as tubular members, their section properties and buoyancy were automatically calculated by USFOS. Horizontal and diagonal bracing of the 116C unit intersect the chord at its neutral axis. Offsets were not modelled because gusset plates to the tubular members were not included in the structural model. However, the effects of gusset plates on the hydrodynamic properties of the leg were included. Figure 6 shows the detailed leg model.

4.3 HULL MODEL

The main decks and bulkheads of the hull were modelled using 4-noded shell elements. An equivalent shell thickness was calculated for the deck of the hull taking into account longitudinal and transverse stiffening. The main bulkheads were identified and an effective shell thickness calculated. Figure 7 shows the layout of the bulkheads isolated from the deck.

4.4 MODELLING OF GUIDES

Non-linear spring elements with a capacity to carry shear were used to model the guides. The elements allowed explicit definition of the force-displacement relationship. By defining “soft” and “stiff” sections on the elements’ P-Δ curve it was possible to accurately model the gaps existing in the upper and lower guide shoes. From Figure 8a it is seen that the leg chord was attached to three non-linear springs in order to allow sliding from front to back and from side to side within the guide shoe. The non-linear springs were in turn connected to coincident stiff beam members, representing the guide shoe that connected to the hull. The chord was free to slide vertically within the guide shoe. The stiff beam members were given an axial stiffness approximately 100 times the stiffness of a chord. This is consistent with the recommended approach in 5-5A that states the guides should be relatively stiff, with freedom introduced by means of gaps. The depth of the upper and lower guides was taken into account by using a double prong connection at both the upper and the lower guide. Figure 8b shows a line diagram of the guide arrangement.

4.5 MODELLING OF THE JACKING SYSTEM

Figure 9 shows a line diagram of the rack, pinion and gear unit case. Each pinion was modelled by two non-linear spring elements. Both elements were given a nominal low stiffness in tension, in order to achieve numerical stability. The upper pinion element was given a linear compressive stiffness of 174 MN/m, based on data received from LeTourneau. Defining a region of low stiffness in the material properties for the lower non-linear spring accounted for backlash of 3 mm. The pinions were inclined at a pressure angle of 25^o, the rack was offset from the chord centroid and the gear unit case was offset from the edge of the yoke. It is important to include these details to correctly capture the line of action of the forces and associated moments. The gear unit case was modelled as a box section with properties based on its construction. Similarly, the associated bracing was modelled as I-sections and orientated in the appropriate direction. Figure 10 shows the gear unit case, bracing and upper guide.

4.6 SPUDCAN AND FOUNDATION MODELLING

Typical soils data from the selected site were used to determine the values for parameters used in modelling the spudcan fixity. Calculations showed that it was reasonable to assume a leg penetration of 3.0 m. The vertical, lateral and rotational stiffnesses of the soil were calculated based on the undrained shear strength of 200 kPa and a G/S_u ratio of 50. By using “spring to ground” elements it was possible to apply vertical, lateral and rotational stiffness values to the node at the tip of each spudcan. The spudcans were modelled as beams, with a stiffness of approximately 100 times the stiffness of the chord.

4.7 AIRGAP

Airgap to the underside of the hull was calculated in accordance with 5-5A Section 3.7.5. It is defined as the sum of the distance of the extreme still water level above LAT, the extreme wave crest height and 1.5 m clearance.

In 5-5A 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 midspan of a leg bay – see Figure 4. For the base case, the jack-up unit was checked for these two locations of the lower guide by altering the FE model in the following manner. In the first instance the minimum airgap was achieved for the centre of the lower guide shoe located at a leg chord node, and secondly for the lower guide located at the midspan of the next bay up, hull was elevated to maintain the required airgap.

4.8 MASS DISTRIBUTION AND HULL SAG

The densities of the leg and the spudcan elements were adjusted such that the required weights and centres of gravity were achieved. However, the hull was modelled with shell elements with element density set to zero. In order to achieve the correct inertial effects it was necessary to distribute nodal masses to the decks and bulkheads. These were distributed such that the total mass and location of centre of gravity for the hull dead and variable loads and for the cantilever loads were in accordance with the values given in Table 5.

The effect of hull sagging due to an accurate distribution of hull masses was determined to be too onerous a condition with respect to bending moments generated at the guides. In 5-5A, it is stated that in practice these effects would not be fully realised due to the details of the jacking system. The Commentary to 5-5A Section 5.3.3 recommends that between 25% and 75% of the hull mass are re-located adjacent to the legs, such that hull sagging is reduced. Accordingly, 50% of nodal mass was re-located adjacent to the connections to the legs.

4.9 HYDRODYNAMIC PROPERTIES

Hydrodynamic coefficients were applied to brace members in accordance with Section 4.7.2 of 5-5A. Values of $C_D = 0.65$ and $C_M = 2.0$ were used for brace members above MWL + 2 m. Below this elevation, C_D was taken as 1.0 and C_M as 1.8. Marine growth of 12.5 mm was applied to the brace members located between MWL +2m and mudline. An allowance was made for the drag force resulting from the gusset plates by calculating an increase to the hydrodynamic diameter of the horizontal bracing.

For the chord section, values of C_D and C_M are dependent on direction. These were calculated according to Section 4.7.5 of 5-5A. Marine growth was not applied to the teeth of the racks and protruding guide surfaces of chords.

4.10 BUOYANCY

Buoyancy was automatically included for all tubular members that were “wet” at the solution time. It was necessary to apply chord buoyancy manually. This was achieved by utilising buoyancy elements. The diameter of the spherical shaped buoyancy elements was calculated to give the same internal dry volume per metre as that of the chord.

5. ANALYSIS RESULTS AND DISCUSSION

5.1 BASE CASE ANALYSIS

In the first instance, the Shell-supplied data for 50-year ‘summer-only’ water levels and environmental data were used to assess the jack-up unit. Table 2 presents the base data used for this analysis. Initially, five separate analyses were undertaken to determine the condition that resulted in maximum UR of unity or very close to unity by varying maximum wave height. Subsequently, two further analyses (Cases 2a and 4a) were conducted to permit the construction of a continuous plot of maximum member UR versus wave height. In particular, the wave height at which the airgap requirements would necessitate the lower guide to be positioned at the next bay up the leg was determined for consideration in the additional analyses. The two additional analyses considered this single wave height, but at two locations of the lower guide.

For the first five cases, Figure 11 shows a diagram and table of values for the jack-up leg elevations, water levels and the location of the hull elevation to satisfy the SNAME 5-5A requirements of airgap and the two required positions of the lower guide.

To establish the final loads on the unit and to perform overturning checks, a number of preliminary analyses were necessary as follows:

- Wave plus current load analysis for each direction over a full wave cycle, to determine the base shear amplitude for use in the calculation of the inertial load set.
- Eigenvalue analysis to determine the natural periods of the unit for use in the calculation of the inertial load set.
- Dead load only analysis with 50% of the variable load, the results of which were required for the calculation of the jack-up unit overturning check.

Member strength checks were performed in accordance with the requirements of 5-5A. The leg members of the unit were separated into groups as follows: reinforced chord, unreinforced chord, horizontal tubular, diagonal tubular, span breaker, horizontal tubular with increased wall thickness and diagonal tubular with increased wall thickness. The last two groups represented members in the lower bays of the legs, where the tube wall thickness for these members was increased from 19.1 mm to 25.4 mm.

Member sizes for each group were as follows:

Reinforced chord	see Figure 3
Unreinforced chord	see Figure 3
Horizontal tubular	324 mm diameter x 19.1 mm wt
Diagonal tubular	324 mm diameter x 19.1 mm wt
Span breaker	229 mm diameter x 9.5 mm wt
Horizontal tubular lower bays	324 mm diameter x 25.4 mm wt
Diagonal tubular lower bays	324 mm diameter x 25.4 mm wt

The structural analysis software used in this study was a non-linear large displacement package, and took into account the global and local P-Δ loads. Therefore in line with the 5-5A practice, the coefficient B, which accounts for the load reduction factor (C_m) and the Euler amplification, was set to unity. In the various checks for compactness, no tube members were classed as ‘slender’.

Chord elastic and plastic section properties were determined using standard techniques. Account was taken of the different yield strength of the rack components. In 5-5A it is stated that all components for a chord may be assumed to be stiffened along both edges. However, this was considered inappropriate for outstands of the guide plate and for the rack component.

For these components slenderness checks were based on b/t limits for a component stiffened along one edge only.

For the reinforced chord, in addition to conducting local buckling checks for each component, for the stiffened side plates it was considered prudent to check the combined section comprising side plate and side plate reinforcement for local buckling. To perform this check, an equivalent plate thickness was calculated on the basis of equivalent second moment of area and the buckling formulations for stiffened plates. This resulted in an equivalent plate thickness of 40.9 mm.

Code check formulations for each assessment were prepared for tube and chord sections. The exponent for biaxial bending, η, was set to unity when checking the chord section. Load and resistance factors were applied in accordance with the practice requirements.

Every leg element was code checked for each combination. Three wave directions were considered together with the phase angles for a full wave cycle. Once the base case parameters had been finalised (i.e. the parameters that resulted in a maximum UR of unity), code checks were made for the position of the lower guide adjacent to the leg node and for the lower guide at midspan of the chord section.

Results of analyses performed to determine the base case plus two additional analyses that were run subsequently are reported in Table 7. The results include natural periods, total factored base shears, overturning check for the jack-up and maximum code check results for each structural element of the leg section.

Loading due to wave, current, wind and inertial loadset gives rise to base shear. Table 7 also presents the total factored base shear magnitude for 60-degree wave direction – the direction used for the determination of the overturning check for the jack-up. Also given in the table are the individual components that make up the total base shear. Not surprisingly, wave + current represent the largest component, although the inertial loadset base shear also increases as the hull elevation is increased. This is so because, in SNAME 5-5A, the formulation used to calculate the inertial loadset, includes a term that considers dynamic amplification factor (DAF) which in turn is based on the natural period of the structure.

Examination of results for element code checks for Case 4 shows that the maximum controlling UR occurs in the reinforced chord. The governing value is 1.05 for a reinforced chord element located in the region of the lower guide. This condition is for the lower guide located at midspan of Bay 21 for a wave height of H_{max} = 14.5 m. Prior to conducting the two additional analyses (Cases 2a and 4a) the maximum UR value of 1.05 was considered to be sufficiently close to unity and this condition was labelled the base case. For the corresponding position of the lower guide adjacent to a leg node, the maximum UR is 0.95 (Case 5). Table 7 results also indicate that all other element groups exhibit maximum URs considerably below unity.

Overturning moment checks indicate that, after application of the appropriate load and resistance factors, the critical overturning moment for the base case is less than the sum of the stabilising moments by a factor of 0.80 and 0.77 for Cases 4 and 5, respectively.

Figure 12 presents a plot of maximum UR versus wave height for the analysis results reported in Table 7. Although based on a limited number of results, it is apparent from Figure 12 that the most prominent parameter that affects the magnitude of the maximum controlling UR is the position of the lower guide. The location of the lower guide relative to the Bay number is dictated by airgap, water depth and wave height. The plot clearly shows a step change in the maximum UR at a wave height of 14.1 m, noting that the water depth used in these analyses was kept constant at 59.0 m. For the conditions under consideration, this is the wave height above which the jack-up hull connection to the leg requires the lower guide to be adjacent to mid Bay 21 to meet the airgap requirements of SNAME 5-5A.

It is also noted from Figure 12 that in addition to the step increase in maximum UR resulting from the need to change the position of the lower guide, there is a steady increase in the maximum UR as the wave height is increased. In fact, the gradient of the slope is near constant either side of the step change (Gradient of line between Cases 1 and 2a is 0.076 and that between Cases 4a and 4 is 0.075).

5.2 ANALYSES WITH γ_3 SET TO 1.15

To investigate the effect of $\gamma_3 = 1.15$, load cases 6 and 7 were prepared to repeat Cases 4 and 5 but using $\gamma_3 = 1.15$ instead of 1.25. The results from Table 8 show that the maximum UR is reduced from 1.05 (Case 4) to 0.97 for the lower guide at midspan, and from 0.95 (Case 5) to 0.91 for the lower guide adjacent to a leg chord node. These are reductions of 7.6% and 4.2%, respectively. It is noted that in each case the location of the lower guide is critical at midspan. This is so because to achieve the airgap requirements, the hull elevation is half a bay higher for the lower guides at midspan than for the lower guide adjacent to a leg chord node.

Cases 8 to 11 were subsequently prepared and analysed to determine the increase in water depth that would result in production of the same UR as for the base case, and to permit the construction of a plot of maximum UR versus water depth. It is seen from Table 9 that water depths of 62.0 m, 62.2 m, 65.0m and 63.7 m were considered, the last being the case that resulted in a maximum UR very close to that of the base case, i.e. Case 4. The basic parameters for each of these cases, together with the results for natural periods, maximum factored base shears, maximum URs for each structural element and maximum overturning check for each case are also given in Table 9.

As for the base case analyses, the controlling URs for all analyses occur in the reinforced chord. A plot has been prepared of the maximum UR versus water depth – see Figure 13. Also annotated on this figure is the location of the lower guide to meet the airgap criterion for the various cases of water depth considered. Examination of this figure reveals that there is a general tendency for the UR to increase by a small amount as the water depth is increased. However, it is clear that this increase is small compared to the increase in UR resulting from the need to locate the lower guide at the next bay up the leg to achieve the required airgap. This pattern of increase in UR is similar to the pattern displayed in Figure 12 when the variable was wave height.

As noted in Section 5.1, additional analyses (Cases 2a, 4a, 8a and 11a) were undertaken during the latter stages of the project. Analysis Cases 1 to 5 were prepared and run initially to determine the base case. From these analyses Case 4 was labelled the base case since it resulted in the maximum UR closest to unity (at 1.05). During the latter stages of the project the scope of work was extended and additional analyses were undertaken so that the plots of maximum UR versus wave height (Figure 12) and maximum UR versus water depth (Figure 13) were continuous. From Figure 12 it is seen that new Case 4a results in a maximum UR closer to unity (1.02) than Case 4. This occurs for a wave height of 14.1 m.

In Figure 13 two plots are presented, one for results obtained from analyses conducted with a wave height of 14.5m and one for predicted results for a wave height of 14.1 m. The plot of predicted results is based on results from Figure 12, which showed that the maximum UR was directly proportional to the maximum wave height. For example, it is shown from Figure 12 that a reduction in maximum wave height from 14.5 m to 14.1 m results in a reduction in maximum UR of 0.03. It was also shown that this reduction is uniform across the range of wave heights. Therefore, it is reasonable to predict the results in Figure 13 for a maximum wave height of 14.1 m drawn at a UR of 0.03 lower than the analysis results for a maximum wave height of 14.5 m.

The water depth at which the predicted plot step occurs was determined on the basis of the wave crest for the reduced wave height of 14.1 m and the predicted plot was adjusted accordingly.

From Figure 12 Case 4a, for which the maximum UR is 1.02 for a wave height of 14.1 m, may be assumed to be the new base case. Considering the predicted plot (for 14.1 m wave height) in Figure 13, at a water depth of 59.0 m, results in a maximum UR of 0.94, i.e. a reduction of 7.8%, compared to 7.6% calculated above, using Case 4 as the base case.

Using Case 4a as the base case and the predicted plot for a maximum wave height of 14.1 m, Figure 13 shows that the same maximum UR of 1.02 is achieved for $\gamma_3 = 1.15$ as for $\gamma_3 = 1.25$ when, in the former case, the water depth is increased to 62.4 m. Noting that for the base case the water depth was 59.0 m, this study has shown that when γ_3 is reduced from 1.25 to 1.15, the unit displays the same magnitude of maximum UR for an increase in water depth of 3.4 m. In simple terms, this is the equivalent of one bay height.

All other parameters were maintained the same as the base case, so the only variable was water depth. The above has examined variations in water depth only and ignored possible variations in the main metocean parameters with water depth. Wind speed is independent of water depth. With the small variation in water depth considered here, current is judged to demonstrate little variation particularly since its contribution to combined wave plus current loading is secondary. Thus wave height is the only water depth dependent parameter that may influence the results of this study and, therefore, its variation with water depth needs to be determined.

HSE report OTH 89 300(6) discusses metocean parameters and provides a relationship between the 50-year significant wave height and 50-year wind speeds and water depths in waters around the UK, as follows:

$$H_{s50} = 0.7465W_{50} + 8.311(\ln d)^{0.5} - 31.95$$

where H_{s50} is the 50-year return value of significant wave height (m)
W_{50} is the 50-year return value of wind speed (m/s)
d is the water depth (m)

Although this relationship is for extreme storm conditions, it has been used in this study to assess the variation of the 50-year ‘summer-only’ wave height against water depth, assuming a constant wind speed (W_{50}). The accuracy of the formulation for use with 50-year ‘summer-only’ data was checked against the Shell-supplied data. A plot of water depth versus significant wave height for 50-year ‘summer-only’ conditions is presented in Figure 14. Examination of this figure reveals that there is a small increase in wave height (approximately 0.2 m wave height increase for an increase in water depth of 5.0 m) over the range of water depths under consideration. Noting that the plot is based on several original data with a fairly substantial scatter of results and noting that several basic assumptions are used in the formulation, it is concluded that the exclusion of the wave height adjustment was not inappropriate in this study.

5.3 CONCLUSIONS

The following salient conclusions are drawn from the results of this study:

- For a maximum UR of close to unity and using $\gamma_3 = 1.25$, given a water depth of 59.0 m, the jack-up is able to withstand a maximum wave height of 14.1 m.
- The controlling parameter for this condition is the reinforced chord section. All other element sections exhibit URs considerably below unity.
- Maximum UR is a function of the location of the lower guide elevation relative to the leg, either at midspan or adjacent to leg chord nodes. Water depth, wave height and airgap requirements dictate the location of the lower guide. Irrespective, the controlling lower guide position is midspan between leg chord nodes.

- Plots of maximum UR versus wave height indicate that, although the maximum UR tends to increase with increase in wave height, by far the greatest influence is as a result of re-location of the lower guide due to airgap requirements.

- A reduction in the environmental load factor, γ_3, from 1.25 to the proposed value of 1.15 causes a reduction of 7.8% in the maximum UR, for the lower guide located at leg chord midspan.

- To achieve the same level of maximum UR in the jack-up when $\gamma_3 = 1.15$, the unit is able to operate in a water depth 3.4 m greater than that possible when $\gamma_3 = 1.25$, all other parameters kept constant. For water depth and jack-up unit under consideration, this represents an increase of 6%, or in simple terms, one bay height.

- This finding is dependent on the proportion of environmental to gravity load actions and thus can be expected to change should this proportion alter.

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7. SINTEF DIVISION OF STRUCTURAL ENGINEERING
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   Sintef, Trondheim, Norway.

Table 1
Water levels at selected site

	50-year summer-only individual
Nominal LAT (m)	59.0
Max SWL ref. LAT (m)	3.4
Crest elevation (m)	7.2
Total water level	
(max SWL + Crest elevation) (m)	10.6

Table 2
Environmental data for selected site

	50-year summer-only individual
Wind velocity at 10m height	
V (1-hour) (m/s)	24.8
V (1-min) (m/s)	29.3
Wave height and period	
H_s (m)	6.7
T_z (central) (s)	8.8
H_{max} (m)	12.4
T_{max} (central) (s)	11.3
Current velocity	
Depth-mean velocity (m/s)	0.73
Surface current velocity (m/s)	0.79

Table 3
Current velocity profile

Proportional height above sea-bed	Ratio of velocity to depth-mean velocity
1.00d	1.07
0.75d	1.07
0.50d	1.07
0.25d	0.97
0.15d	0.90
0.05d	0.77
0.01d	0.61

Table 4
Soil profile

Depth below mudline	Description
0.0 to 2.7m	very soft CLAY
2.7m to 7.5m	sandy CLAY $S_u = 200$ kPa
> 7.5m	medium dense SAND

Table 5
Dead load summary

Description of Loading	Weight (MN)	LCG (m)	TCG (m)
Hull basic and fixed load	42.7	42.82	0.24
Cantilever assembly	8.1	60.23	-0.29
Bow leg and spudcan	8.7	18.29	0.00
Port leg and spudcan	8.7	57.61	-21.64
Starboard leg and spudcan	8.7	57.61	21.64
Total	76.9	45.23	0.10

LCG is measured aft of hull bow and TCG is measured off the centreline of the hull, taken as positive towards starboard.

Table 6
Load factors for assessment in accordance with 5-5A

Limit State	Dead Loads (D) γ_1	Variable Loads (L) γ_2	Environmental Loads (E) γ_3	Dynamic Loads (Dn) γ_4
ULS	1.0	1.0	1.25	1.0

The factored load vector $Q = \gamma_1 D + \gamma_2 L + \gamma_3 (E + \gamma_4 D_n)$

Table 7
Analysis results for determination of the base cases for $\gamma_3 = 1.25$

	Case 1	Case 2	Case 2a	Case 3	Case 4	Case 4a	Case 5
LAT (m)	59.0	59.0	59.0	59.0	59.0	59.0	59.0
H_{max} (m)	12.4	14.0	14.1	15.0	14.5	14.1	14.5
H_s (m)	6.7	7.5	7.6	8.1	7.8	7.6	7.8
H_{det} (m)[*]	10.7	12.0	12.1	12.9	12.5	12.1	12.5
Surface current (m/s)	0.79	0.79	0.79	0.79	0.79	0.79	0.79
1-min wind speed (m/s)	29.3	29.3	29.3	29.3	29.3	29.3	29.3
SWL (m)	62.4	62.4	62.4	62.4	62.4	62.4	62.4
Crest Elevation (m)	7.2	8.1	8.2	8.7	8.4	8.2	8.4
Location of lower guide	mid	mid	mid	mid	mid	mid	node
Bay number for lower guide	20	20	20	21	21	21	20-21
1st natural period (s)	7.63	7.63	7.63	7.87	7.87	7.87	7.69
2nd natural period (s)	7.52	7.52	7.52	7.75	7.75	7.75	7.58
3rd natural period (s)	6.21	6.21	6.21	6.37	6.37	6.37	6.25
60° inertial base shear (MN)	4.2	5.2	5.3	6.9	6.5	6.2	5.9
60° wind base shear (MN)	1.6	1.6	1.6	1.6	1.6	1.6	1.6
60° wave+curr base shear (MN)	5.8	7.2	7.2	8.2	7.8	7.3	7.8
60° total base shear (MN)	11.6	14.0	14.1	16.7	15.9	15.1	15.3
Max. UR reinforced chord	0.79	0.91	0.92	1.07	1.05	1.02	0.95
Max. UR unreinforced chord	0.45	0.49	0.50	0.54	0.52	0.49	0.52
Max. UR diagonal	0.37	0.43	0.45	0.54	0.52	0.46	0.45
Max. UR horizontal	0.41	0.47	0.48	0.56	0.55	0.49	0.55
Max. UR span breaker	0.08	0.09	0.10	0.12	0.11	0.10	0.10
Max. UR diagonal increased thk.	0.34	0.39	0.40	0.46	0.43	0.40	0.43
Max. UR horizontal increased thk.	0.16	0.25	0.25	0.28	0.28	0.26	0.27
Overturning check UR[**]	0.60	0.67	0.68	0.82	0.80	0.72	0.77
Max. controlling UR	0.79	0.91	0.92	1.07	1.05	1.02	0.95

[*] *H_{det} is the wave height used in the analysis, given as 1.60 H_s*

[**] *UR is defined as disturbing moment divided by stabilising moment*

Table 8
Analysis results for base cases
but with $\gamma_3 = 1.15$

	Case 6	Case 7
LAT (m)	59.0	59.0
H_{max} (m)	14.5	14.5
H_s (m)	7.8	7.8
H_{det} (m)[*]	12.5	12.5
Surface current (m/s)	0.79	0.79
1-min wind speed (m/s)	29.3	29.3
SWL (m)	62.4	62.4
Crest Elevation (m)	8.4	8.4
Location of lower guide	mid	node
Bay number for lower guide	21	20-21
1st natural period (s)	7.87	7.69
2nd natural period (s)	7.75	7.58
3rd natural period (s)	6.37	6.25
60° inertial base shear (MN)	6.0	5.4
60° wind base shear (MN)	1.5	1.5
60° wave+curr base shear (MN)	7.2	7.1
60° total base shear (MN)	14.7	14.0
Max. UR reinforced chord	0.97	0.91
Max. UR unreinforced chord	0.50	0.49
Max. UR diagonal	0.47	0.42
Max. UR horizontal	0.50	0.51
Max. UR span breaker	0.10	0.09
Max. UR diagonal increased thk.	0.41	0.38
Max. UR horizontal increased thk.	0.26	0.25
Overturning check UR[**]	0.67	0.65
Max. controlling UR	0.97	0.91

[*] *H_{det} is the wave height used in the analysis, given as 1.60 H_s*

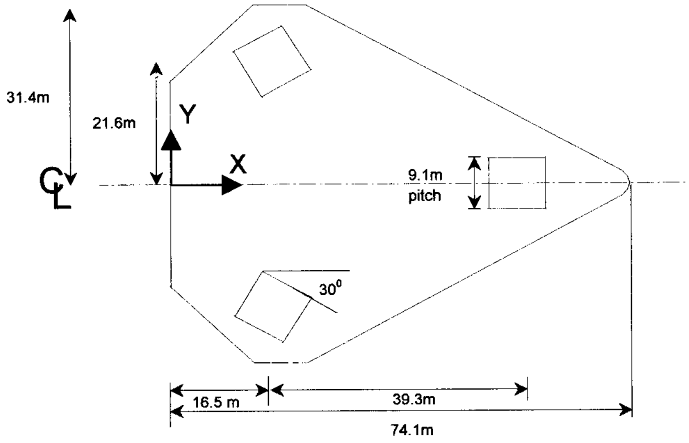
[**] *UR is defined as disturbing moment divided by stabilising moment*

Table 9
Analysis results for water depth variation with $\gamma_3 = 1.15$

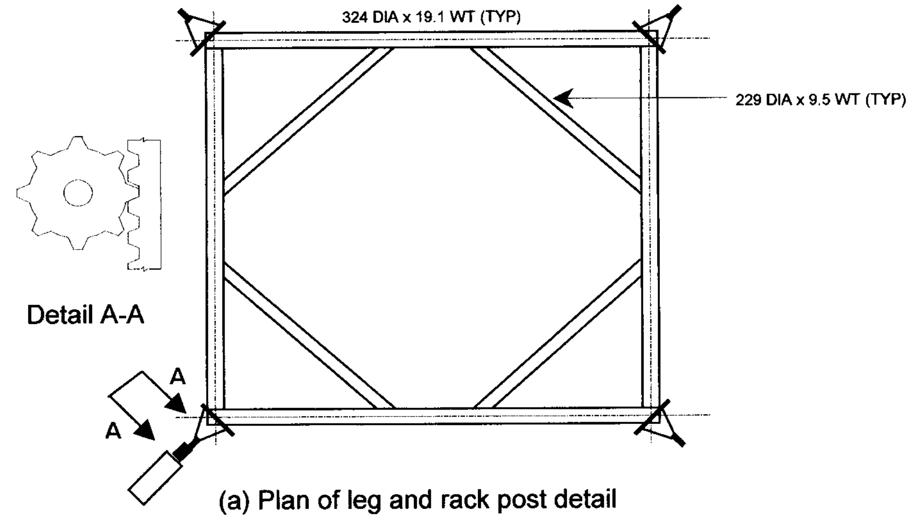
	Case 8	Case 8a	Case 9	Case 10	Case 11	Case 11a
LAT (m)	62.0	62.2	62.0	65.0	63.7	62.2
H_{max} (m)	14.5	14.5	14.5	14.5	14.5	14.5
H_s (m)	7.8	7.8	7.8	7.8	7.8	7.8
H_{det} (m)*	12.5	12.5	12.5	12.5	12.5	12.5
Surface current (m/s)	0.79	0.79	0.79	0.79	0.79	0.79
1-min wind speed (m/s)	29.3	29.3	29.3	29.3	29.3	29.3
SWL (m)	65.4	65.6	65.4	68.4	67.1	65.6
Crest Elevation (m)	8.4	8.4	8.4	8.4	8.4	8.4
Location of lower guide	mid	mid	nod	mid	mid	mid
Bay number for lower guide	21	21	21-22	22	22	22
1st natural period (s)	7.87	7.87	8.00	8.20	8.20	8.20
2nd natural period (s)	7.75	7.75	7.87	8.06	8.06	8.06
3rd natural period (s)	6.37	6.37	6.49	6.62	6.62	6.62
60□ inertial base shear (MN)	5.9	5.9	6.5	7.1	7.1	7.2
60□ wind base shear (MN)	1.5	1.5	1.5	1.5	1.5	1.5
60□ wave+curr base shear (MN)	6.9	6.9	7.0	6.8	6.8	6.8
60□ total base shear (MN)	14.3	14.3	15.0	15.4	15.4	15.5
Max. UR reinforced chord	1.01	1.02	0.98	1.11	1.07	1.06
Max. UR unreinforced chord	0.49	0.49	0.51	0.51	0.51	0.50
Max. UR diagonal	0.48	0.48	0.48	0.57	0.53	0.54
Max. UR horizontal	0.51	0.51	0.58	0.60	0.56	0.56
Max. UR span breaker	0.11	0.11	0.11	0.12	0.12	0.12
Max. UR diagonal increased thk.	0.41	0.41	0.42	0.44	0.42	0.44
Max. UR horizontal increased thk.	0.26	0.26	0.27	0.29	0.27	0.27
Overturning check UR**	0.73	0.73	0.78	0.85	0.86	0.85
Max. controlling UR	1.01	1.02	0.98	1.11	1.07	1.06

* *H_{det} is the wave height used in the analysis, given as 1.60 H_s*

** *UR is defined as disturbing moment divided by stabilising moment*



(a) Rig layout



(a) Plan of leg and rack post detail

All dimensions are in mm

Figure 1
Jack-up layout

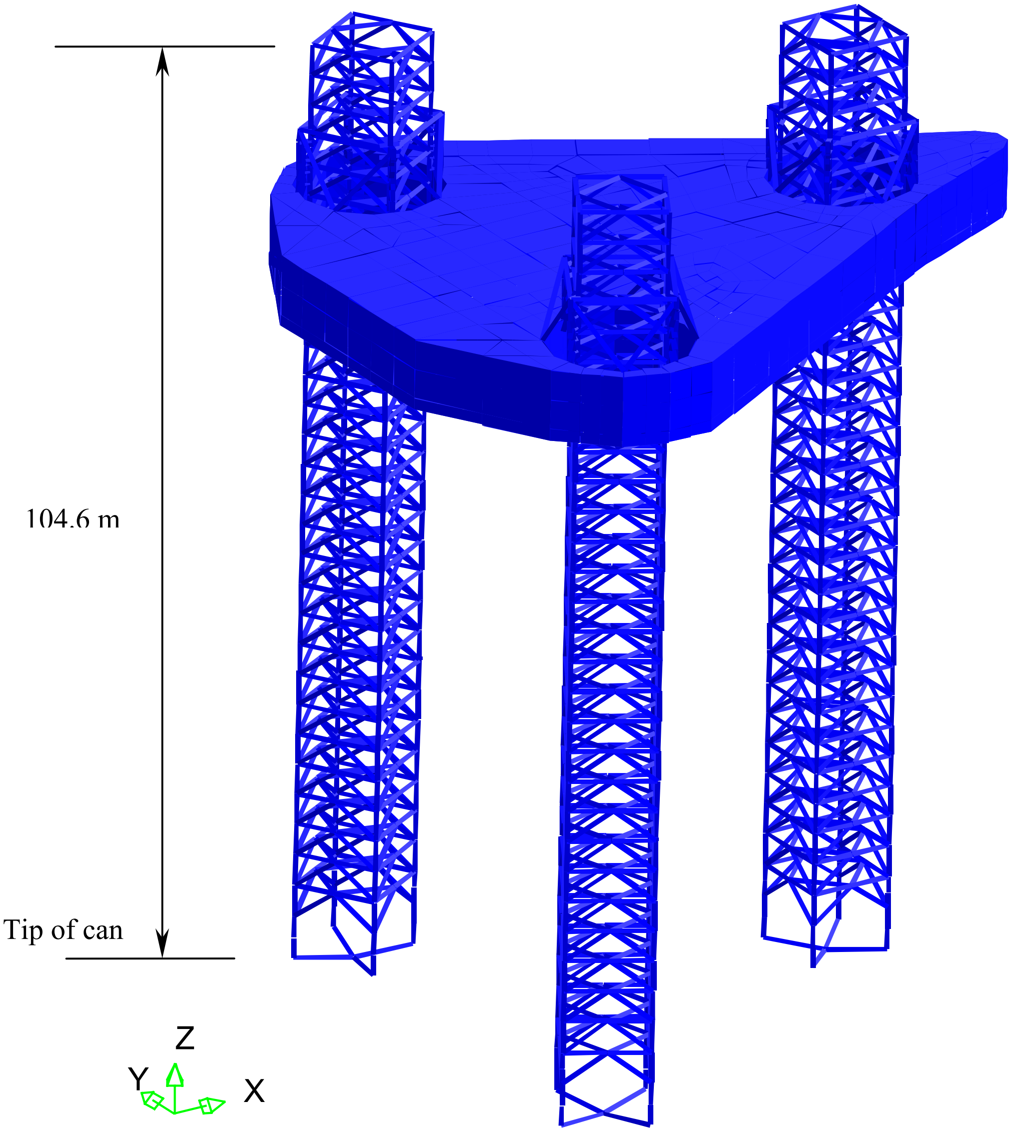
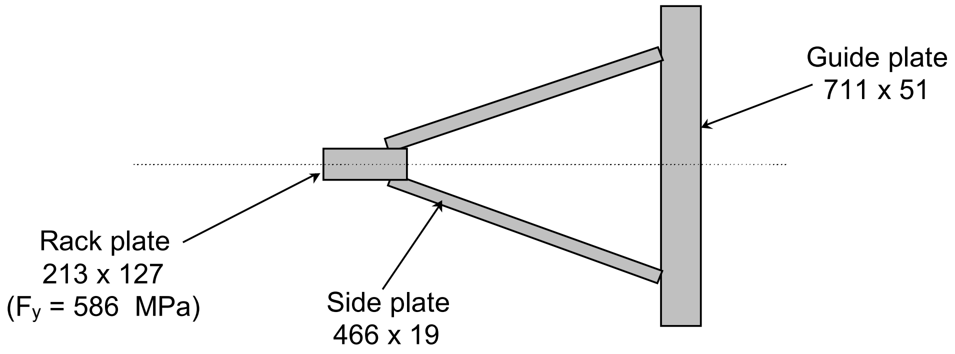
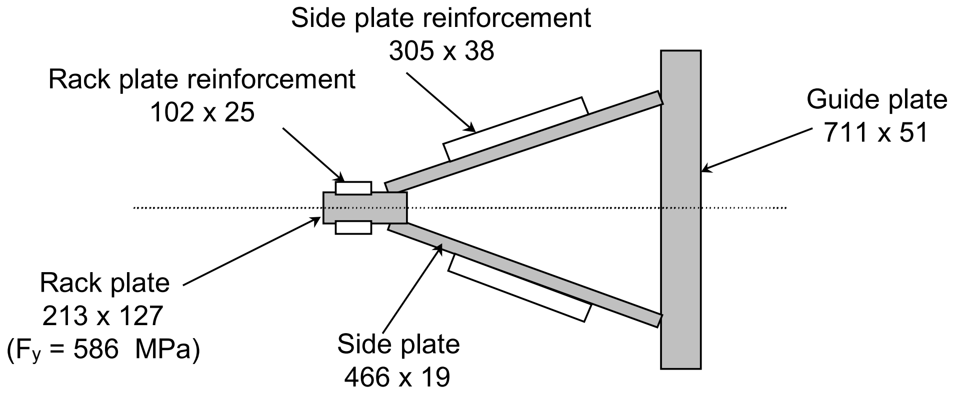


Figure 2
Isometric of jack-up



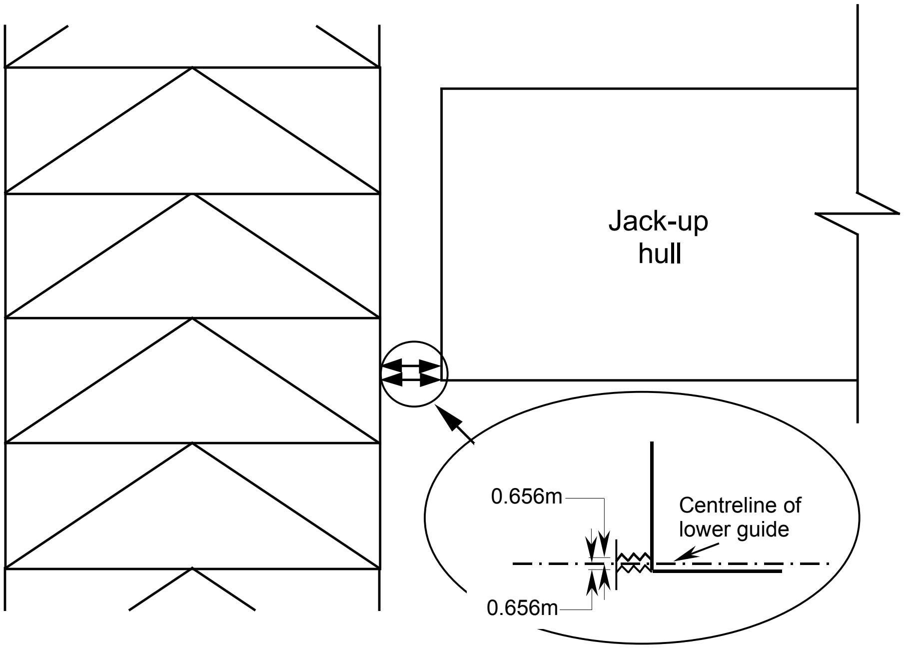
(a) Unreinforced



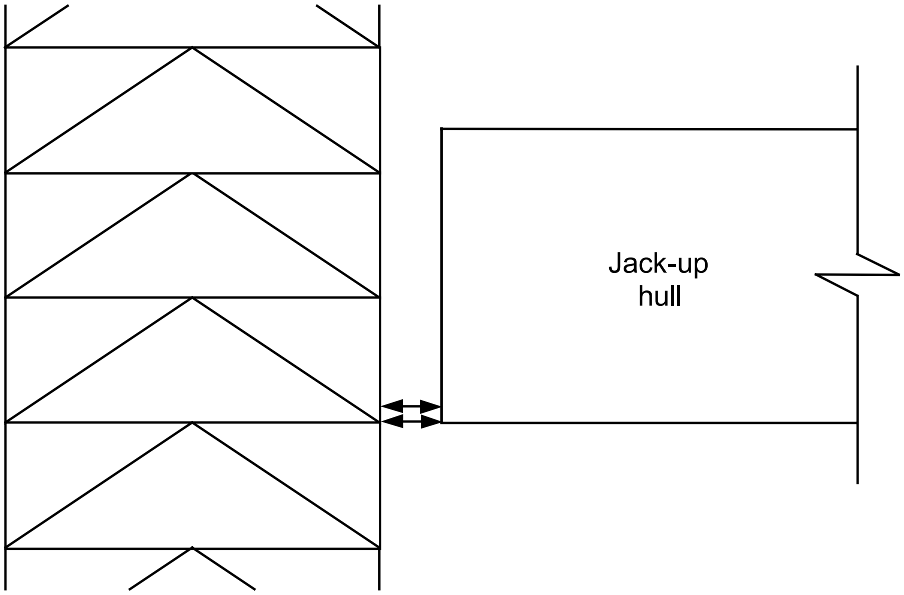
(b) Reinforced

Notes:
1. All dimensions in mm
2. F_y = 483 MPa, unless noted

Figure 3
Reinforced and unreinforced chord



Lower guide at
midspan of leg chord



Lower guide
adjacent to node of
leg chord

Figure 4
Location of lower guides relative to leg chord

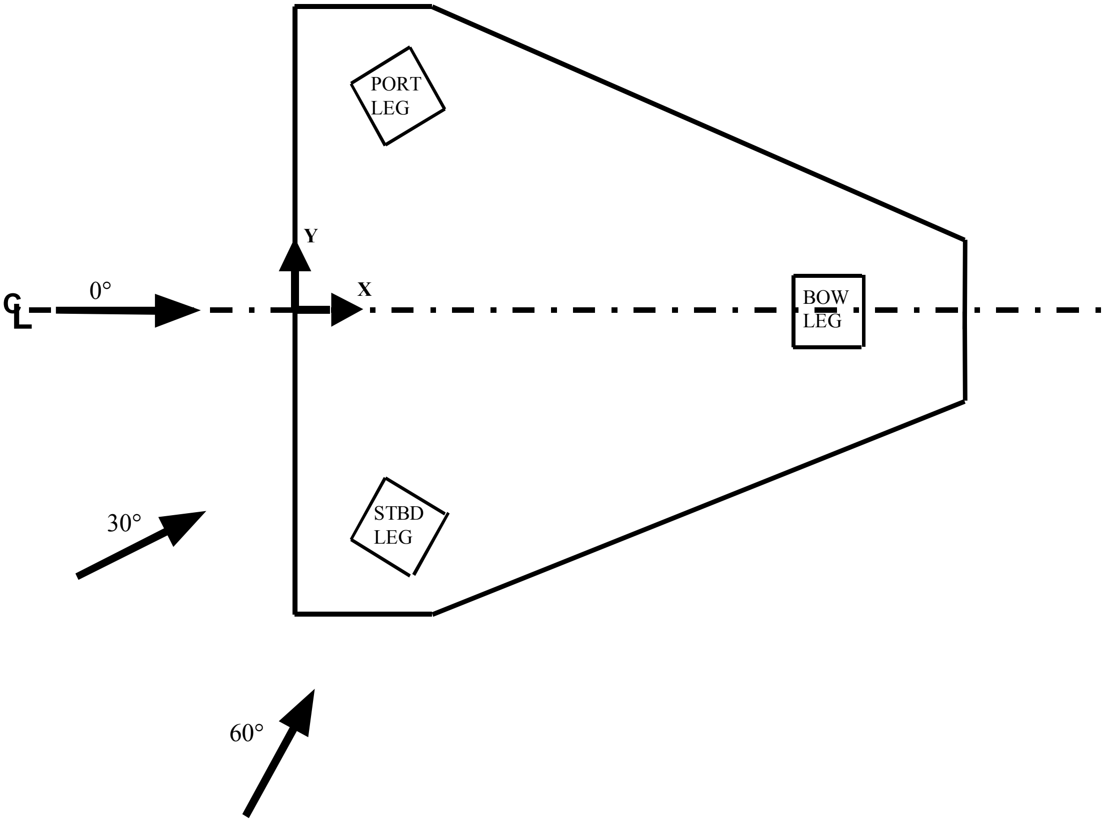


Figure 5
Wave directions used in analysis

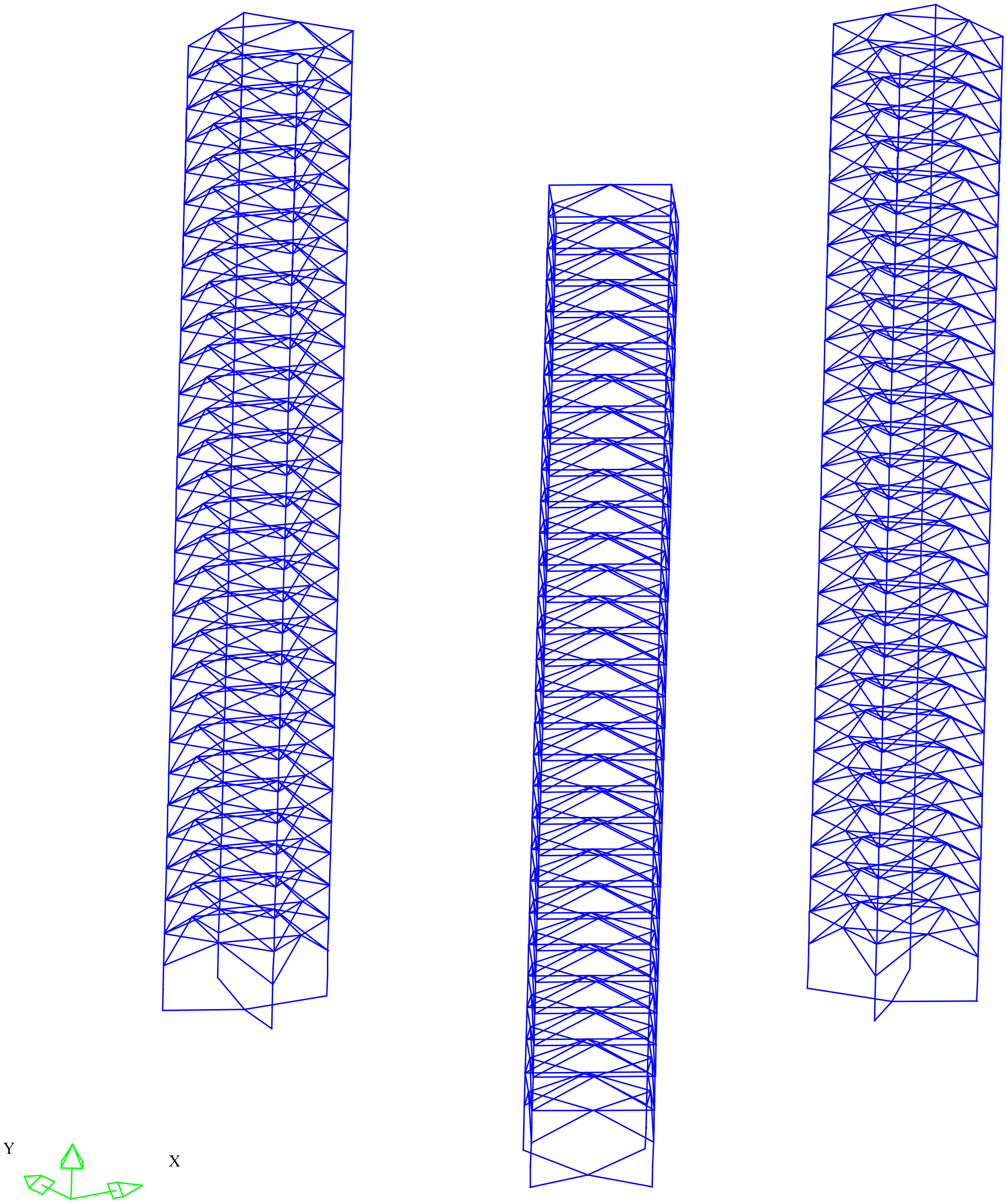


Figure 6
Detailed leg model

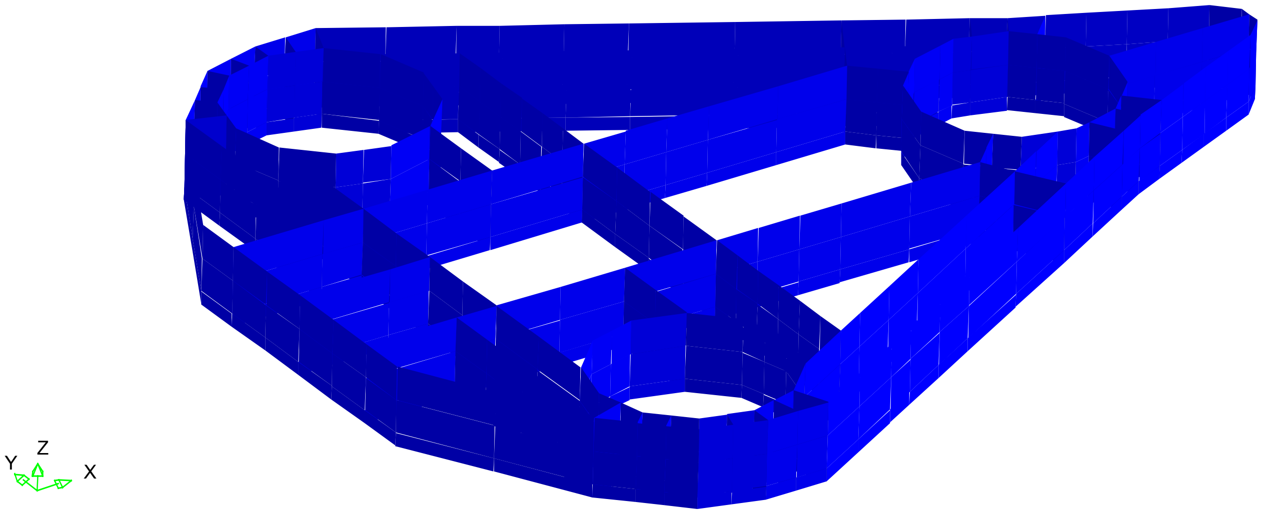


Figure 7
Deck bulkheads

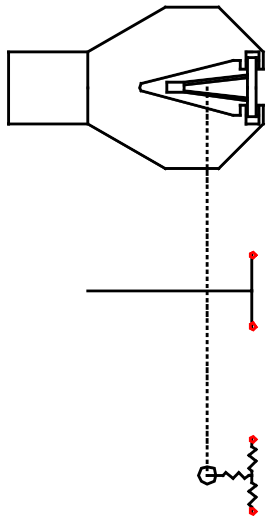


Figure 8a
Connection point for guide arrangement

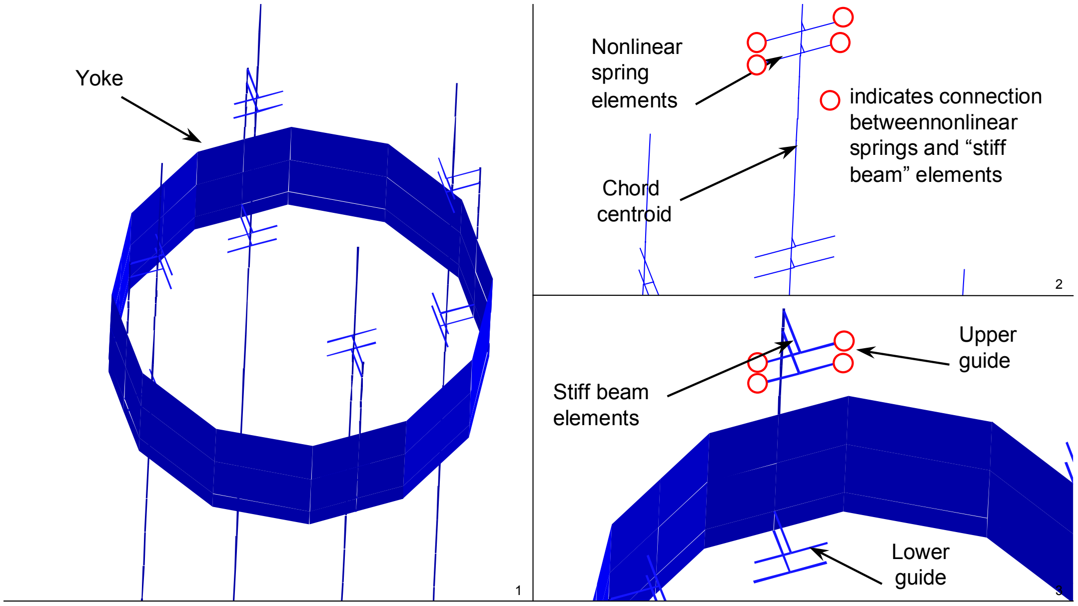


Figure 8b
Connection point for guide arrangement

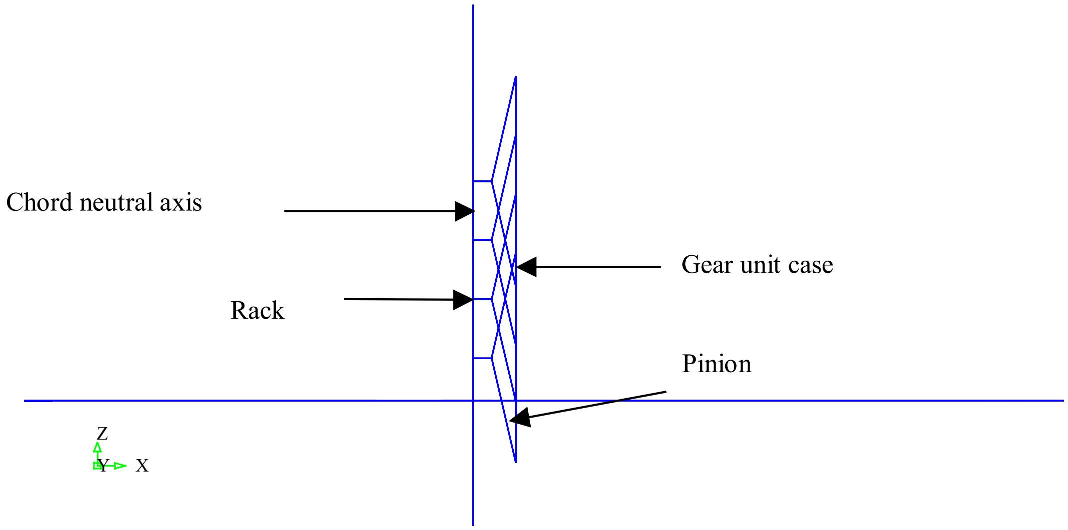


Figure 9
Line diagram of rack and pinion

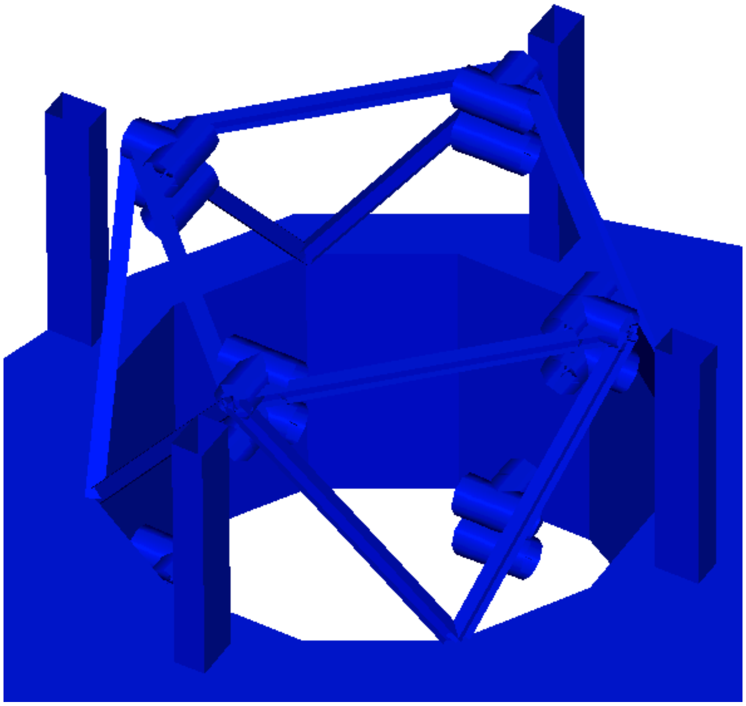
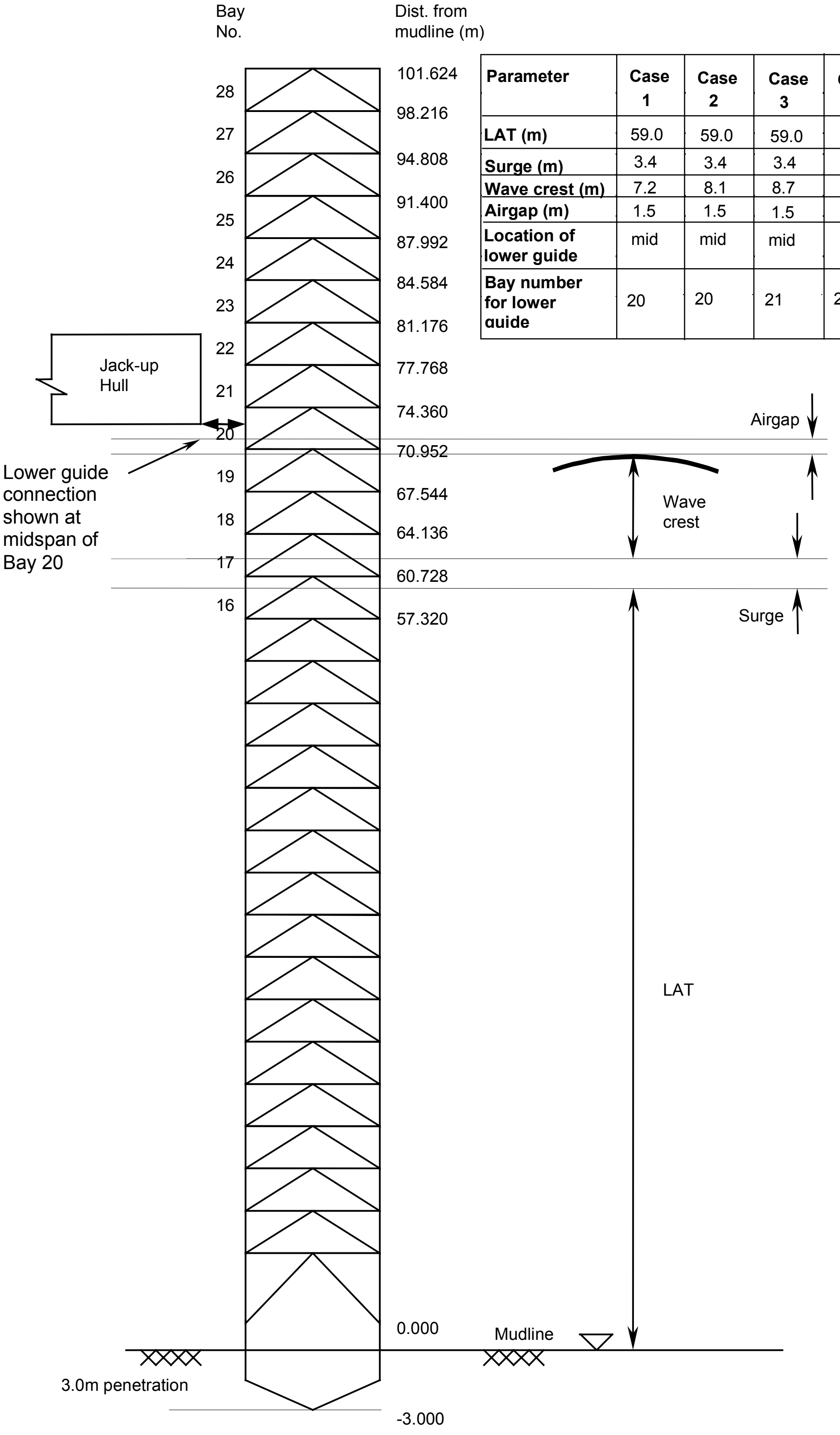


Figure 10
Gear unit case, bracing and upper guide



Parameter	Case 1	Case 2	Case 3	Case 4	Case 5
LAT (m)	59.0	59.0	59.0	59.0	59.0
Surge (m)	3.4	3.4	3.4	3.4	3.4
Wave crest (m)	7.2	8.1	8.7	8.4	8.4
Airgap (m)	1.5	1.5	1.5	1.5	1.5
Location of lower guide	mid	mid	mid	mid	node
Bay number for lower guide	20	20	21	21	20-21

Figure 11
Water levels, leg dimensions and lower guide locations

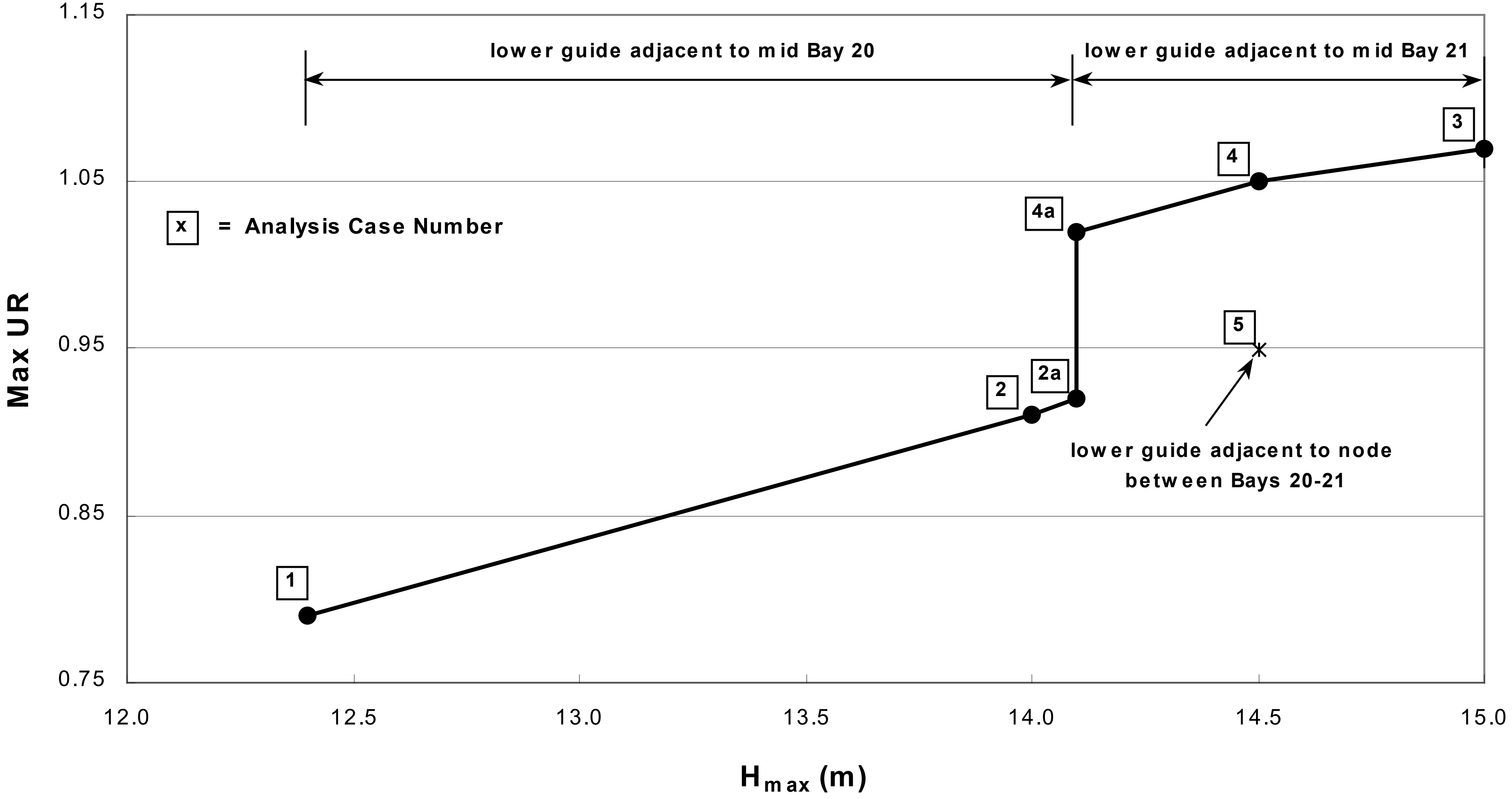


Figure 12
Plot of H_{max} vs. max UR for $\gamma_3 = 1.25$ and a water depth of 59.0 m

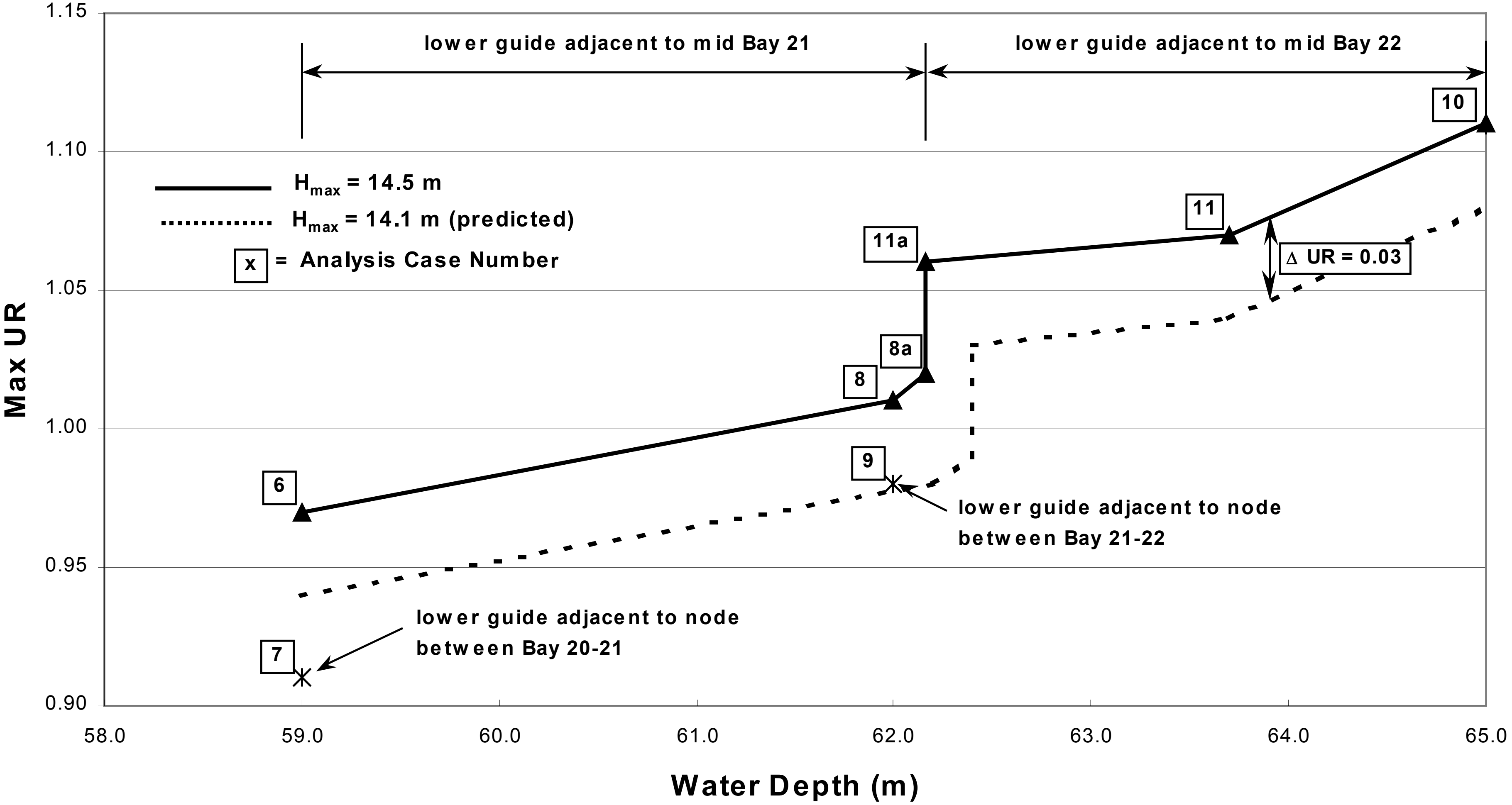


Figure 13
Plot of water depth vs. max UR for γ_3 = 1.15 for wave height of 14.5 m and 14.1 m

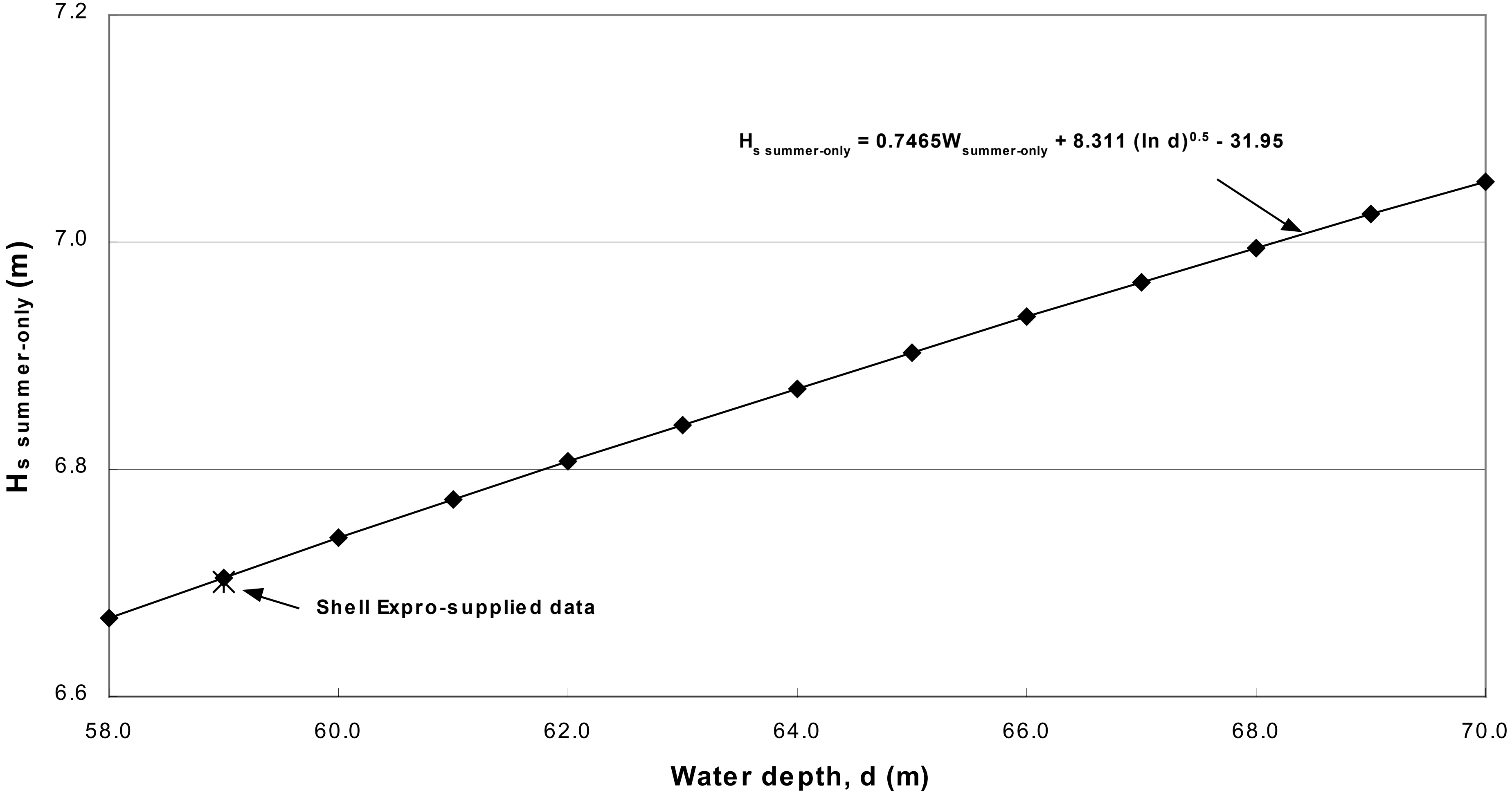


Figure 14
Approximate relationship between water depth
and significant wave height, taken from OTH 89 300

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