



GUIDANCE NOTES ON

STRUCTURAL ANALYSIS OF SELF-ELEVATING UNITS

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Foreword

The guidance contained herein should be used in conjunction with the *ABS Rules for Building and Classing Mobile Offshore Drilling Units* for the purpose of ABS Classification of a Self-Elevating Unit. The guidance indicates acceptable practice in a typical case for types of designs that have been used successfully over many years of service. The guidance may need to be modified to meet the needs of a particular case, especially when a novel design or application is being assessed. The guidance should not be considered mandatory, and in no case is this guidance to be considered a substitute for the professional judgment of the designer or analyst. In case of any doubt about the application of this guidance ABS should be consulted.

A self-elevating unit is referred to herein as an “SEU”, and the *ABS Rules for Building and Classing Mobile Offshore Drilling Units*, are referred to as the “*MODU Rules*”.

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SECTION 1 Introduction

1 Overview

These Guidance Notes provide suggested practices that can be used in the structural analysis of a self-elevating unit (also referred to herein as an 'SEU' or a 'unit') in the elevated condition. The emphasis is on analyses that are used to assess the structural strength of the unit to resist yielding and buckling failure modes considering the static, and as needed the dynamic, responses of the unit in accordance with the *ABS Rules for Building and Classing Mobile Offshore Drilling Units (MODU Rules)*. As an aid to users of the Rules, these Guidance Notes also provide explanations on the intent and background for some of the related criteria contained in the Rules.

3 General Requirements of Strength Analysis

A unit's modes of operation in an elevated condition should be investigated using anticipated loads, including gravity, functional and environmental loads. The Owner is to specify the environmental conditions for which the plans for the unit are to be approved. Owners or designers are to thoroughly investigate the environmental and loading conditions for each water depth considered in the Classification. It is the Owner's responsibility to ensure that the unit is not exposed to conditions more severe than those for which it has been approved.

A unit with an 'Unrestricted Classification' is designed considering a minimum wind speed of 100 knots in the elevated severe storm condition, and 70 knots in the elevated normal drilling condition. The wave and other conditions that accompany these winds are to be as specified by the Owner. These other conditions, especially those related to waves and currents may not be the maximum values that are expected during the operational life of the unit. Accordingly other sets of environmental and other design parameters are typically specified by the Owner and are included in the scope of the unit's Classification.

5 Information Required for Strength Analysis

Sufficient information needs to be obtained to adequately perform the structural analysis on the unit.

5.1 Unit's Data

Basic information about the unit's configuration is required for the analysis. These data are summarized below.

5.1.1 Structural Information

Most of the structural information is obtained from relevant drawings and reports. These data can be categorized as:

- The primary sizes, scantlings and locations of structural members
- The detailed sections, connections and localized designs of structural members
- The material properties of structural members
- The characteristics of some machinery equipment that affect structural response

In particular, the properties of leg-to-hull connections are of great importance and need special attention:

- The basic configuration and arrangement of connections, which include pinions, chocks (if any), upper/lower guides, jacking case, shock pads (if any), etc.
- The stiffness and capacity of pinions and chocks (if any)
- The gap between leg chords and upper/lower guides
- The detailed structural configuration of jacking case
- The detailed structural configuration of upper/lower guides

5.1.2 Other Information

Other data that are required for the SEU strength analysis include:

- Wind projected areas of the hull, deckhouses, derrick, drilling floor and leg in each direction
- The capacity and moving range of the cantilever
- The capacity of jacking system

5.3 Gravity and Functional Load

The gravity loads include: steel weights, equipment and outfitting weights, the weights of liquid and solid variable quantities; and live loads. The gravity loads should be taken into account for the structural design and stability. The load effects due to operations such as drilling, work over and well servicing (rotary/hook loads and tensioner loads) should also be taken into account as functional loads.

For all modes of operation, the combinations of gravity and functional loads are specified by the Owner for the operations considered in the design. However, maximums (or minimums) of the combinations that produce the most unfavorable load effects on the unit's strength or stability should be used in the design.

Total elevated load defined in 3-1-1/16 of the *MODU Rules* consists of the lightship weight excluding legs and spudcans, all shipboard and drilling equipment and associated piping, the liquid and solid variables and combined drilling (functional) load. The total elevated load is normally used to identify the capacity of an SEU in the elevated mode.

The following information needs to be collected:

- The magnitude and distribution of the lightship weight
- The magnitude and distribution of variable loads
- The magnitude and location of functional loads
- The magnitude and distribution of the total elevated load
- Extreme limits of center of gravity for the whole hull and the corresponding load magnitude
- Weight, center of gravity and buoyancy of the legs including non-structural parts.

5.5 Environmental Data

Environmental loads contribute most of the horizontal forces acting on a unit, which are usually the controlling factors to determine the capacity of the unit. Below, the environmental data requirements as per 3-1-3 of *MODU Rules* are discussed. Each of the following environmental parameters that affect the loads acting on a jack-up unit is discussed:

- Wind
- Wave
- Current
- Water depth

- Airgap and wave clearance
- Geotechnical data

5.5.1 Wind

The *MODU Rules* specify that for unrestricted offshore service, a unit should be designed for an operating wind velocity of at least 36 m/s (70 knots) and at least 51.5 m/s (100 knots) for a severe storm condition.

5.5.1(a) Wind Profile. The wind velocity increases with height above the still water level. The *MODU Rules* specify a profile as given in Section 1, Table 1 to be applied when calculating the wind pressure. This is not a complete listing of the table as given in the Rules, but may be sufficient for most elevated SEU analyses. (A complete listing is given in 3-1-3/Table 2 of the *MODU Rules*.) It is important to note that this is NOT a wind velocity profile. Velocity profile factors are squared during the calculation of wind force. In order to compare the wind pressure coefficients with a wind velocity profile, it is necessary to either square the velocity profile ordinates, or take the square root of the Rules' pressure coefficients.

TABLE 1
Wind Pressure Height Coefficients

Height (m)	Height (ft)	C_h
0-15.3	0-50	1.0
15.3-30.5	50-100	1.1
30.5-46.0	100-150	1.2
46.0-61.0	150-200	1.3
61.0-76.0	200-250	1.37
76.0-91.5	250-300	1.43
91.5-106.5	300-350	1.48

Section 1, Figure 1 gives a plot of the *MODU Rules* specified height coefficient, C_h in conjunction with various others. The "API 1 min Force Profile" is the wind force profiles as suggested in API RP 2A, but modified from a velocity profile, to a force profile. The basic form of these profiles is:

$$V_h = V_{ref} \left(\frac{h}{h_{ref}} \right)^{\frac{1}{n}}$$

where

V_h = wind velocity at elevation h above the mean sea level

V_{ref} = wind velocity at the reference height

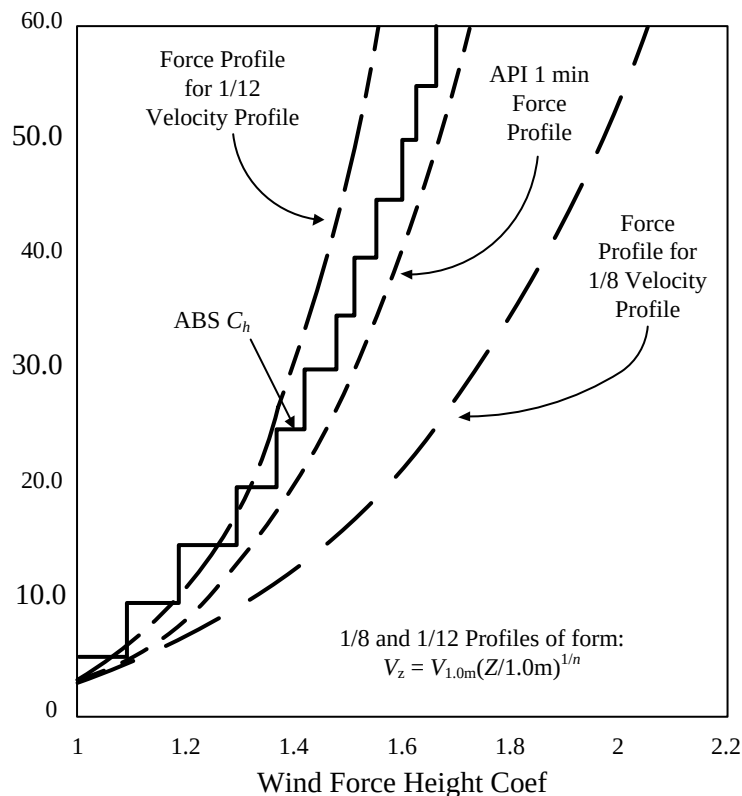
h_{ref} = reference height 10 meters (33 feet)

$1/n$ = exponent of the velocity profile. Note that if the exponent of the velocity profile is $1/n$ the exponent of the force profile will be $2/n$

In older versions of API RP 2A it was suggested that the exponent should range between $1/13$ for gusts, and $1/8$ for sustained winds, but there was no definition of "gusts" or "sustained" winds. The twentieth edition modifies the format and gives an exponent of $1/8$ for a one hour wind, but then gives a more complex conversion to a height profile for the one minute mean wind. It is this modified one minute mean wind speed profile that has been plotted in Section 1, Figure 1.

One of the major causes of difference between different profiles in Section 1, Figure 1 is due to changes in the reference height. The ABS profile is for a wind measured at a reference height of 50 feet, whereas the API profiles are for a wind measured at a reference height of 33 feet. This can be a major cause of the differences between different sets of height coefficients. If the API RP-2A one-minute wind profile were plotted with respect to the same reference height as the ABS C_h profile, the results would be very similar.

FIGURE 1
Plot of Wind Force Height Coefficient vs. Height above Design Water Surface



5.5.2 Wave

The Owner may specify wave criteria as either irregular sea states or deterministic regular waves having shape, size, and period appropriate to the water depth in which the unit is to operate.

In the deterministic design procedure, the design wave is defined as a regular wave described by the maximum wave height (H_{max}) and its associated wave period (T_{ass}) for each water depth in which the unit is to operate.

In the stochastic design procedure, a short-term irregular sea state is defined in terms of a wave energy spectrum characterized by a significant wave height (H_{srp}) and a zero-crossing wave period (T_z). The spectrum should reflect the shape and width of typical spectra appropriate to the depth of water in which the unit is to operate. For a fully developed sea, the Pierson-Moskowitz (P-M) spectrum may be applied. For long swells or locations with a limited “fetch”, a narrower spectrum (e.g., JONSWAP spectrum) should be used. See also 4/3.3 regarding wave parameters. Long-term wave statistics can be described by a family of irregular sea states in a wave scatter diagram.

5.5.2(a) Design Wave Selection. The selected design wave should induce the most unfavorable response of the structure under consideration. Most SEU analyses for Classification are based on a deterministic wave approach, even when dynamics are being included, although appropriate spectral data can be used.

The wave (and current) conditions, which are to be combined with the Rule required minimum wind speeds, are those specified by the Owner. For other wave conditions specified by the Owner for inclusion in the scope of classification, they should be the maximum wave heights appropriate to the depths of water in which the unit is expected to operate.

Where dynamic effects are insignificant, the wave forces on an SEU are not too sensitive to the choice of wave period, except in unusual cases (e.g., where wave force cancellation occurs). It is therefore normally acceptable to use the maximum wave height with a single “Associated Wave Period”, as described below. Where dynamic effects are considered potentially significant, the choice of period can be critical, thus a range of wave periods associated with a range of wave heights are to be investigated.

At a certain wave period, the wave forces acting on an SEU will be significantly reduced due to force cancellation. The selected design wave should not be a wave that causes wave force cancellation. This occurs when there is a wave crest at one leg (or a set of legs) and a trough at another. For example, a unit with a leg spacing of 60 meters (200 feet) will experience cancellation in regular waves of approximately 8.8-second period. The length of an 8.8-second wave is 120 meters (400 feet) which is twice the leg spacing. The effect is more severe for four legged units than for three legged units. In the extreme case, the wave force on a four legged unit will be reduced to zero with perfect cancellation, whereas a three legged unit will effectively always have a different number of legs at the crest then at the trough. It is also possible to have wave force reinforcement at shorter wave periods, with wave crests at both sets of legs. Both reinforcement and cancellation can also occur at shorter periods due to harmonic effects. Under certain circumstances, the response to the component of the sea state close to resonance may be significantly reduced if the periods of resonance and cancellation happen to coincide.

5.5.2(b) Variations in Defining Wave Periods

- i) **Peak Period (T_p).** Also known as the “Modal Period”, it is the wave period associated with the “peak” of the wave energy spectrum. It is normally longer than the period associated with the maximum wave.
- ii) **Mean Period (T_m).** The *Mean Period* is the period corresponding to the centroid of the area enclosed under the wave spectrum. The mean period for a Pierson-Moskowitz (P-M) spectrum equals $T_p/1.296$.
- iii) **Mean Zero Crossing Period (T_z).** The *Mean Zero Crossing Period* is the average time between the instances when the instantaneous water surface crosses the mean still water surface, moving in a specific direction (normally the up-crossing period). Normally $0.75T_p < T_z < 0.82T_p$.
- iv) **Associated Period (T_{ass}).** The *Associated Period* is the period associated with the highest wave. Most of the other sea state wave periods are based on statistics for that sea state, but there is only one maximum wave in any given storm, so the associated period is the most probable period of the maximum wave. For this reason it is common to give a range of wave periods for T_{ass} that are independent of T_p . One common range is to have $\sqrt{12H_s} < T_{ass} < \sqrt{20H_s}$, where H_s is the significant wave height in meters.

5.5.2(c) Dynamic Response. When an analysis for dynamic response due to waves, or waves with current, is being pursued, a spectral characterization of selected sea state is needed, refer to 4/3.3 for this topic.

5.5.3 Current

The Owner is to specify the current velocity from water surface to seabed. For Classification, current is normally assumed to act collinearly with wind and wave.

When determining loads due to the simultaneous occurrence of wave and current using Morison's equation, the current velocity is to be added vectorially to the wave particle velocity before the total force is computed. When diffraction methods are used for calculating wave force, the drag force due to current should be calculated in accordance with Section 3-1-3 of the *MODU Rules* and added vectorially to the calculated wave force.

The significance of current loads should not be underestimated, particularly in relatively benign environments. The effects of current are greatest on drag force dominated lattice leg units, but they can still be significant on large tubular legged units. On a drag dominant structure, the force is proportional to the square of the water particle velocity, so even a 10% increase in particle velocity due to current will cause a 20% increase in hydrodynamic load.

5.5.3(a) Current Associated with Waves. The current velocity is to include components due to tidal current, storm surge current and wind driven current. In lieu of a defensible alternative method, the recommended vertical distribution of current velocity in still water and its modification in the presence of waves, is as shown in Section 1, Figure 2 below, where:

$$V_c = V_t + V_s + V_w [(h - z)/h] \quad \text{for } z \leq h$$

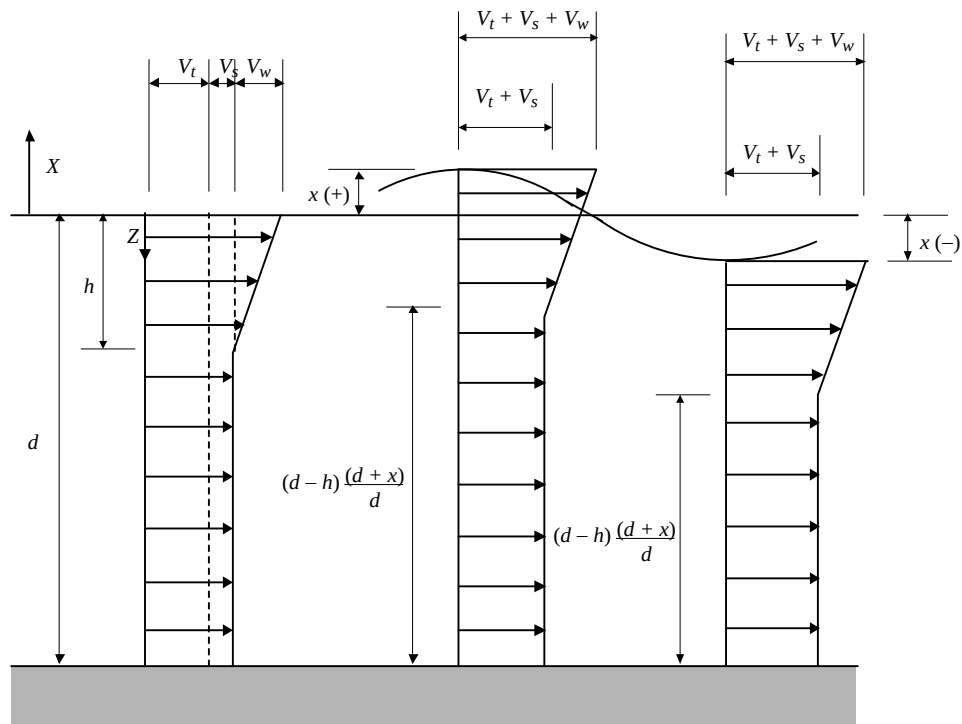
$$V_c = V_t + V_s \quad \text{for } z > h$$

where

- V_c = current velocity, m/s (ft/s)
- V_t = component of tidal current velocity in the direction of the wind, m/s (ft/s)
- V_s = component of storm surge current, m (ft)
- V_w = wind driven current velocity, m/s (ft/s)
- h = reference depth for wind driven current, m (ft). (in the absence of other data, h may be taken as 5 m (16.4 ft).
- z = distance below still water level under consideration, m (ft)
- d = still water depth, m (ft)

In the presence of waves, the current velocity profile is to be modified, as shown in Section 1, Figure 2, such that the current velocity at the instantaneous free surface is a constant.

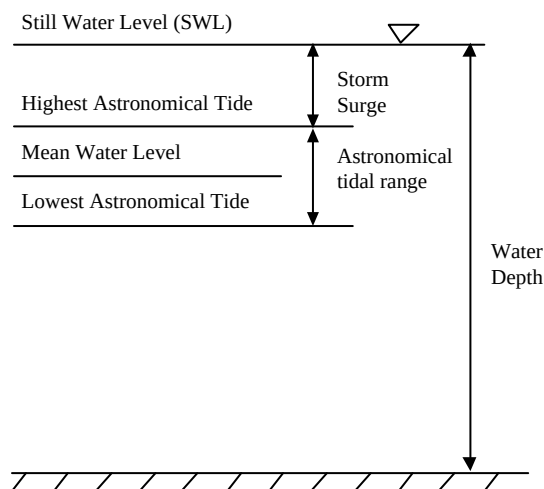
FIGURE 2
Current Velocity Profile



5.5.4 Water Depth

An SEU is to be designed for various water depths in which the unit is to operate. Each water depth for the purposes of Classification is to be specified by the Owner, and should include tidal range and storm surge, see Section 1, Figure 3.

FIGURE 3
Water Depth



Designers should consider shallow water conditions, which could lead to a greater likelihood of the unit experiencing breaking waves, and soil scour around the foundation of the unit.

5.5.5 Wave Clearance and Air Gap

The *MODU Rules* specify in 3-2-3/5.5 that: A crest clearance of either 1.2 m (4 ft) or 10% of the combined storm tide, astronomical tide, and height of the maximum wave crest above the mean low water level, whichever is less, between the underside of the unit in the elevated position and the crest of the wave is to be maintained. This crest elevation is to be measured above the level of the combined astronomical tide and storm tides. Thus, the air gap, which is the distance between the underside of the unit when elevated and the still water line (SWL – see Section 1, Figure 3), should be larger than the total elevation of the required crest clearance and the crest of the maximum wave. This crest elevation is to be measured above the level of the combined astronomical tide and storm tides.

5.5.6 Geotechnical Data

When an SEU is being assessed for Classification, generally there will be no geotechnical data available. Therefore seabed conditions are not considered for Classification. The base of each independent SEU leg is considered pinned at least 3 meters (10 feet) below the seabed. It is the Owner's responsibility to operate the unit within the limits of the Classification approval.

Consideration of "spudcan-soil rotational stiffness" is allowed for cases involving dynamic response. The maximum allowable spudcan fixity K_{rs} is specified in the *MODU Rules*, which is the upper limit of spudcan fixity that can be used.

7 Methods of Analysis

The method of analysis to assess the strength of an SEU's primary structures for Classification in the elevated severe storm, normal operating and preload conditions should consider the SEU's static, and as needed the dynamic responses. The basic approach most commonly used to combine the static and dynamic responses into structural analysis entails a two-step procedure. The first step is to perform a wave dynamic analysis to obtain the inertial loads due to waves on the SEU. In the second step, the inertial loads are imposed, along with all of the other coexisting loads, onto the usual, detailed static structural model that is used to perform the "unity checking" for structural acceptance based on the Rules. This analysis procedure is presented in Section 4 of these Guidance Notes.

7.1 Static Response

The static response of the unit in the elevated condition is usually accomplished using deterministic characterizations of environmentally induced loads and gravity loads. The modeling of the structure should be sufficiently detailed to capture the correct interactions between the loads and the structural elements and between the structural elements themselves. Typically, for computational efficiency the analysis is pursued with a hierarchy of models that start with simplified models that use elements with simplified, equivalent (i.e., 'lumped') properties to establish the equivalent hydrodynamic and stiffness properties themselves. Subsequently a more refined model can be used which combines regions with lumped properties and very detailed portions of the legs where they interact with the hull and elevating machinery. Then detailed models of complete individual legs can be analyzed. Section 3 of these Guidance Notes describes structural analysis modeling procedures and Section 4 of these Guidance Notes describes quasi-static analysis procedure to obtain the static response.

7.3 Dynamic Response

The dynamic response of an SEU in the elevated condition is due to waves because the natural period of an SEU is typically in the range of 5 to 15 seconds, which is in the same range of wave period normally used for design of SEUs. Thus, there will be dynamic amplification (resonance) with waves in this period range. Therefore the dynamic response of the SEU is to be considered for elevated conditions.

The dynamic response of an SEU in the elevated condition is usually obtained by performing a dynamic analysis. The modeling of the structure can be simplified using equivalent legs and hull but should be sufficiently detailed to adequately represent the mass distribution, total mass, leg stiffness, hull stiffness and hull/leg stiffness of the SEU and to capture the dynamic responses. Section 4 of these Guidance Notes describes the dynamic analysis procedure and modeling.



SECTION 2 Loads

1 Overview

The methods of determining the main environmental loads are given in the *MODU Rules* (Section 3-1-3, “Environmental Loadings”). In this Section of these Guidance Notes, a review of environmental and other categories of loads is presented.

It is most important that the methods used to calculate loads are to be compatible with the structural assessment methodology. The emphasis of this section is to give guidance on determining suitable loads for an SEU’s analysis in the elevated mode.

3 Gravity and Functional Loads

The gravity and function loads on the unit comprise:

- Hull lightship weight
- Variable load
- Leg and spudcan weight (including spudcan ballast and any marine growth if applicable)
- Buoyancy of the legs and footings
- Hook or conductor tension load

In general, the loads should always be considered conservatively, but realistically. For example, when the unit is being assessed for overturning resistance, a low variable load should be assumed. When footing reactions, or leg stresses are being assessed, a high variable load should be assumed.

The *MODU Rules* specify that when checking overturning safety in the operating condition, the unit should be assessed with minimum design variable load and the cantilever in most unfavorable condition. From a practical standpoint this means that, in most cases, the cantilever is at its maximum extension with full drilling/set back load, and the hull has approximately one half the maximum variable load on board in a realistically unfavorable arrangement. On larger units, with particularly high variable loads, it may be necessary to use less than half the variable load, and on a smaller unit, it may be acceptable to use more than half. The calculated center of gravity should then be used in the overturning assessment. If the operating manual sets limits on the location or magnitude of the operating variable loads, then it must be a demonstrably possible arrangement.

In the severe storm condition, the overturning safety of the unit should be assessed with the minimum design variable load, and the center of gravity in the most onerous design condition. This allows the designer to specify that the cantilever/drill floor is retracted in preparation for a storm, and that the center of gravity is maintained at a specific location.

It is important to differentiate a load associated with mass (gravity load), or a load that is not associated with a mass (functional loads, such as hook load). The mass related load will affect the dynamic response of a unit while functional loads will not. Specially, buoyancy is not associated with mass; while “added mass” is a kind of hydrodynamic load, which plays its role in a totally different manner than the buoyancy force.

5 Wind Load

The wind force, in its simplest form, is calculated as the product of the projected area and the wind pressure:

$$F = P \cdot A \dots\dots\dots (2.1)$$

where

$$\begin{aligned} F &= \text{wind force} \\ P &= \text{wind pressure} \\ A &= \text{projected area of all the exposed surfaces} \end{aligned}$$

The wind pressure is a function of air density, the shape and height coefficient, and the square of the wind velocity:

$$P = 0.5\rho V_k^2 C_h C_s \dots\dots\dots (2.2)$$

where

$$\begin{aligned} V_k &= \text{wind velocity} \\ C_h &= \text{height coefficient (dimensionless) as given in } MODU \text{ Rules} \\ C_s &= \text{shape coefficient (dimensionless) as given in } MODU \text{ Rules} \\ \rho &= \text{air density, } 1.22 \text{ kg/m}^3 \text{ (0.0024 slugs/ft}^3\text{)} \end{aligned}$$

The form of this equation is slightly different from that given in the Rules where the “0.5ρ” is replaced by a dimensional factor that also takes into account the conversion from knots to feet per second for the case of U.S. Customary units.

Increased projected areas due to the accumulated ice/snow should be considered for wind force calculation.

It is important to divide the vertical extents of the structure into sections less than approximately 50 feet (15 m) in height when calculating wind force. Some calculations for tall structures (e.g., a unit with a large leg reserve operating in shallow water) take height coefficients at the average height of the structure under consideration. Because the value of the height coefficient is not constantly changing with height, the force tends to be overestimated by this approach, and the overturning moment underestimated. The resulting errors may be surprisingly large.

The simplest method of calculating the wind force on most jack-ups hull body is to calculate the hull wind loads based on a block-projected area above the main deck using an appropriate shape factor of 1.1. The normal extent of the block area would be to around the top of the jack houses, and then the extra items that are not included in this (the main hull, leg reserve, derrick, and helideck, etc.) would be added in later.

5.1 Wind Load on Open Truss

Open truss work commonly used for derricks, crane booms, and certain types of mast, may be approximated by taking 30% of the block projected area of each side/face that is perpendicular to the wind. For example, take a conventional derrick that is fabricated out of angles. The effective exposed area, excluding the effects of height coefficients, could be approximated as:

$$\begin{aligned} \text{Effective Area} &= \text{block projected area perpendicular to the wind} \times 2 \text{ (number of faces)} \\ &\quad \times 0.3 \text{ (open truss)} \times 1.25 \text{ (shape coefficient)} \\ &= 0.75 \times \text{block projected area perpendicular to the wind} \end{aligned}$$

If the wind direction is not directly perpendicular to a face, the same relationship can be used based on the diagonal projected area, but still only considering two faces on a four-sided derrick.

5.3 Wind Load on Leg

The lattice legs of an SEU should not be treated as open trusses when calculating the wind loads. In general, the same drag coefficient should be used for the calculation of wind loads as hydrodynamic loads, although it is generally acceptable to assume that any tubular member in the reserve of the leg is smooth, with a drag coefficient of 0.5. Drag coefficients of other members should be based on wind tunnel tests, or recognized sources.

5.5 Dynamic Effects and Vortex Induced Vibration

The effects of wind spectra and other short-term variation in wind velocity on the response of SEU need not normally be considered, except in special cases of particularly flexible or sensitive structures.

Most of the members in a lattice leg are sufficiently stiff so that vortex-induced-vibration (VIV) generated by wind will not to be an issue. However, there have been cases in which the internal horizontal diagonals are slender enough to be excited in steady winds. The same phenomenon has been noted on some slender helideck bracing members. There is also a potential for VIV on some braces of the newer designs that feature slender “X” braces. The checks for VIV can be complex, but there are a number of simple checks that will give an indication of the propensity for VIV. If the propensity exists, a more detailed analysis may be warranted.

If VIV is found to be an issue, it is important to use the correct level of damping when undertaking an assessment. Generally, low displacement structural damping is extremely small, but it is possible that joint flexibility may increase damping.

7 Wave and Current Loads

This Subsection will address direct calculation of wave loads for a conventional quasi-static analysis. Dynamic effects and their determination are discussed in Section 4 of these Guidance Notes.

7.1 Validity and Application of the Morison's Equation

Most SEUs can be adequately assessed using the Morison equation, which is generally considered viable in the analysis of members/legs in which the member diameter is no greater than 20% of the wave length. For SEUs with lattice legs, in which there is normally relatively little shielding, virtually all waves can be assessed using Morison's equation, although it may be necessary to use a rather detailed equivalent leg model for very short period waves.

The Morison's equation models the wave force as two components:

$$F_w = F_D + F_I \dots\dots\dots (2.3)$$

The first component is the drag force F_D , which is proportional to the square of the water particle's velocity:

$$F_D = 0.5\rho \cdot C_D \cdot D \cdot u_n \cdot |u_n| \dots\dots\dots (2.4)$$

where

ρ	=	density of fluid surrounding the member
u_n	=	water particle velocity normal to the structural member
$ u_n $	=	absolute value for water particle velocity normal to the structural member
C_D	=	drag coefficient
D	=	projected width (diameter for a tubular member)

The second component is the mass or inertia force, F_I , which is proportional to the water particle's acceleration.

$$F_I = \rho \cdot C_M \cdot (\pi \cdot D^2/4) D \cdot a_n \dots \dots \dots (2.5)$$

where

a_n = water particle acceleration normal to the structural member

C_M = mass coefficient

The general form of the drag and inertia forces, including the effects of structural motions, is given below. In the case of a rigid structure, the structural velocity and acceleration are set to zero.

$$F_W = 0.5 \rho D C_D (u_n - u'_n) |u_n - u'_n| + \rho (\pi D^2/4) [C_M a_n - (C_M - 1) a'_n] \dots \dots \dots (2.6)$$

where

u_n = component of wave and current induced water particle velocity vector normal to the axis of the member

u'_n = component of the velocity vector of the structural member normal to its axis and in the plane of the water particle velocity of interest

a_n = component of wave and current induced water particle acceleration vector normal to the axis of the member

a'_n = component of the acceleration vector of the structural member normal to its axis and in the plane of the water particle acceleration of interest

Because the drag force is proportional to the square of the water particle velocity, the superposition method is not applicable. Therefore when calculating the hydrodynamic loads it is important to vectorially combine the water particle velocities due to both wave and current.

7.3 Hydrodynamic Coefficients

7.3.1 General

It is evident from Morison's equation that the values of C_D and C_M are significant to the determination of wave and current load.

Drag and inertia coefficients vary considerably with cross-section shape, Reynolds number, Keulegan-Carpenter number and surface roughness and should be based on reliable data obtained from literature, model tests or full-scale tests. As such, it should be noted that the drag and inertia coefficients discussed below are appropriate only for the brace (tubular) and chord members used to construct the lattice legs of a jack-up. As stated at the start of Section 2, the parameters given in this section have been chosen as part of a complete system for calculating the deterministic loads on an SEU, and as part of an allowable stress design (ASD) approach. They may not be appropriate for use in other analyses, particularly if undertaking a stochastic dynamic analysis.

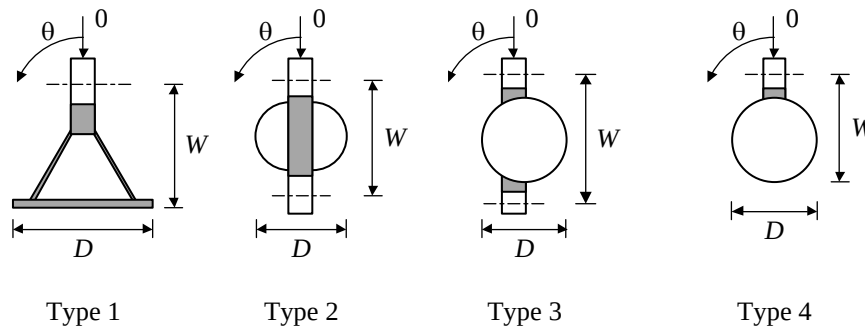
7.3.2 Drag Coefficient C_D

For circular cylindrical members the *MODU Rules* give specific recommendations for the drag coefficients, C_D (i.e., 0.62 if smooth).

Apart from cylinders, non-tubular members are often used as the chords of an SEU's legs; some types found in practice are as follows:

- Approximately triangular, with a single rack at the apex of the triangle.
- Double sided rack plate with a half round (or similar) welded on each side of the rack creating a cylindrical chord with a rack through the middle
- Cylindrical with a pair of racks welded to the chord, but offset from the center.
- Cylindrical with non-opposing rack on one side.

FIGURE 1
Non-cylindrical Chords



It needs to be emphasized that there are two kinds of designs for Type 2:

- Double-sided rack plate with a half round welded on each side of the rack creating a cylindrical like chord with a rack through the middle (“split tube” type, D = diameter of tube + Rack Thickness).
- Double-sided rack plate with a less than a half round welded on each side of the rack creating a circular chord with a rack through the middle (“circular” type, D = diameter of tube)

Most of these chords are of the order of 1 meter or less in overall dimension. It is not the intent of this document to give detailed values for each of these leg chord shapes, but to help the analyst decide what an appropriate value to use in the load analysis is.

The drag coefficients of most of the irregular shapes are not dependent on the Reynolds number, and are largely unaffected by surface roughness (although increases in diameter due to marine growth should be considered). The drag coefficient depends more on width and depth of the member and changes with the change of flow angle. Section 2, Figure 2 provides the definition of flow angle, θ .

For cylindrical based members (Types 2 to 4), the drag coefficient is similar to that used for a cylinder when flow angle, θ is small. When the flow is perpendicular to the teeth (90° in Section 2, Figure 2) the drag coefficient will be dependent on the size of the rack, but will not be as dependent on whether the tube is smooth or rough. Section 2, Figure 2A shows the shape of curve that could be used to determine the drag coefficient of such a shaped chord. In effect, the drag coefficient is similar to that used for a cylinder for θ is between 0° and 30° , accounting for surface roughness (i.e., 0.62 if smooth, 0.75 if rough). Between 30° and 80° it linearly increases to a plateau level to be used between 80° and 90° . The value at the plateau would vary between 1.5 if the racks do not appreciably increase the overall size of the member, and 2.0 for very large racks. For large diameter tubular legs (as opposed to chords) with attached racks, the upper plateau level could be reduced to 1.2. All the values suggested incorporate a reduction factor to account for the over-prediction of particle kinematics inherent in a deterministic analysis using Stokes fifth order wave theory, or similar. Larger values would need to be used for a stochastic analysis.

The drag coefficient of a simple triangle (Type 1), excluding the kinematics reduction, is often given as approximately 1.3 for flow towards the apex, and 1.8 for flow towards the base. These can be used as the basis for the basic triangular chord, but some other factors need to be taken into account. Flow towards the apex (0° in Section 2, Figure 2) initially confronts a blunt rack in the actual chord, which will tend to increase the drag coefficient. In addition, the shape at the back plate is not as clean as that of a simple triangle. The net result is that, after the inclusion of the kinematics factor, the drag coefficient for flow towards the apex should be taken as 1.2, based on a diameter equal to the width of the back plate.

As θ increases, initially the coefficient remains flat for approximately 20° , but then it starts to increase. At around 70° (depending on the details of the shape) the maximum projected face is exposed. The shape is also reentrant, so the drag coefficient will increase to a maximum value of approximately 1.75. It will then start to decrease again until the back of the back plate becomes the apex of the triangle. Finally, the coefficient for flow towards the back plate will be 1.5. These values are shown in Section 2, Figure 2B. It must be borne in mind that these are generalized numbers that will not be appropriate for all triangular chord shapes, and the real shape of the graph will be rounded, without abrupt changes of angle at the various change points.

FIGURE 2A
Drag Coefficient of Tubular Chord with Rack: Deterministic Analysis

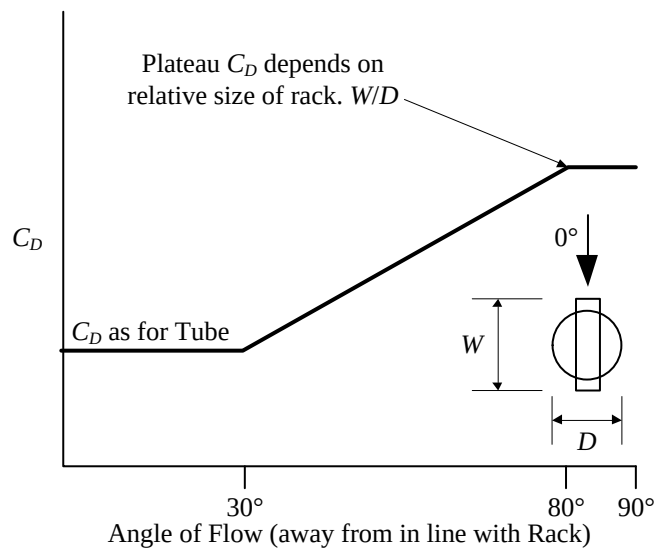
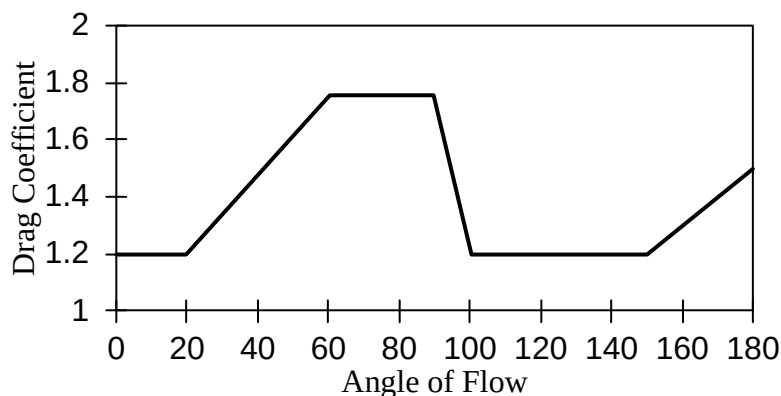


FIGURE 2B
Drag Coefficient of Triangular Chords: Deterministic Analysis



Typically, the sections of a leg chord are non-tubular, but they are often modeled as a tubular member in analysis having the product of an equivalent diameter and direction dependent hydrodynamic coefficients for various flow directions. Formulas (2.9) thru (2.12) below are for calculating the hydrodynamic coefficients of the equivalent tubular. Several comments about these formulas are as follows.

- The wave/current approach angle plays an important role; angle selection should cover all possibilities.
- There are two kinds of tubular-like chords; one is “split-tube” and the other is “circular” one. This will lead to different C_D values.
- The most reliable hydrodynamic coefficients for these non-cylindrical members will be obtained from verified model testing.

7.3.3 Inertia Coefficient C_M

The Rules specify that the inertia coefficient, C_M , for a tubular should be taken as 1.8. It is of note that, unlike the drag coefficient, the inertia coefficient for tubes decreases as the roughness increases, but similar to drag, both coefficients decrease with increasing Keulegan Carpenter number. This explains the difference between the value given in the Rules, and the theoretical value of 2.

For other shapes, a C_M of 2.0 should be used, based on an effective diameter of tubular that creates the same volume per unit length as the member.

The inertia coefficient does not normally have a significant impact on the loads of a lattice leg SEU, particularly in the severe storm condition. The times that it can be important are in fatigue analyses, on units with large diameter tubular legs, and on units operating in relatively shallow water when the spudcan takes up a significant portion of the water depth.

If it transpires that the inertia coefficient is significant for a specific unit, or area of operations, then consideration will be given to evidence of changed values from those given above.

7.3.4 Appurtenances

There are a number of appurtenances that are often attached to the legs of an SEU. The most common are anodes, ladders, jetting lines, gusset plates, and raw water towers. Many of these are small, and can be incorporated through the use of minor conservatism in the calculation, but other items can be of significant size.

Anodes, ladders, and jetting lines, as long as none of them is too large, can normally be incorporated implicitly by using node-to-node length for members, rather than allowing for the reduction in length due to the joint sizes, when creating the hydrodynamic model of the leg.

Gusset plates can have a significant impact on the effective drag coefficient of a leg, and should be considered carefully. Unless they are very small, it is advisable to calculate their effect on the hydrodynamic coefficients of the leg. The drag coefficient recommended for gusset plates is 2.0, but shielding effect can be taken into account. This is particularly significant for legs with high drag chords. These chords severely disrupt fluid flow, so gusset plates often get heavily shielded. Care should be taken when considering the effects of gusset plates on legs with tubular chords as it is possible for a gusset plate to locally increase the effective drag coefficient of the chord by a factor of three. Rarely would there be such an increase on a triangular chord because the initial drag coefficient is already high.

Another item that can significantly affect leg forces is the raw water tower. In the past these were normally independent structures that were cantilevered from the hull down to below the water surface. As such, they attracted some wave load, but in many cases it was not too significant because of the spatial separation from the legs, and because they were relatively small. However many modern units incorporate the tower into the leg. Therefore considerable care should therefore be taken in ensuring that the pipes and guides are properly accounted for when calculating the hydrodynamic loads. Usually it is not the raw water piping itself that attracts the majority of the load, but the guide system, which runs the full extent of the leg.

7.3.5 The Hydrodynamic Leg Model – Detailed and Equivalent Leg

Total wave loads can be calculated using a detailed or equivalent hydrodynamic leg model. The hydrodynamic coefficients (C_D and C_M) of individual tubular and non-tubular members that comprise the leg were discussed in 2/7.3.1 and 2/7.3.2. Detailed model is required for the SEU analysis in step 2 of the quasi-static analysis for performing the “unity checks”. Since the member elements used to represent the legs in most software have structural and hydrodynamic properties, thus, the detailed leg model is normally used for hydrodynamic and structural calculations at the same time.

However, it is common practice to use an equivalent leg in analysis to reduce computational effort, especially for the nonlinear time domain dynamic analysis, which can be very time-consuming. It will be necessary to determine the hydrodynamic properties of the equivalent leg. This can be done by using a wave force program to analyze an entire leg bay in a uniform current. Alternatively, manual calculation as described below may be used.

The hydrodynamic properties of a lattice leg in the “equivalent model” can be represented by an equivalent drag coefficient C_{De} , an equivalent mass coefficient C_{Me} , and an equivalent diameter D_e . The following items can be used to determine these equivalent hydrodynamic parameters.

7.3.5(a) Equivalent Diameter. The equivalent diameter, D_e , of a lattice leg shown in Section 2, Figure 3, can be determined as:

$$D_e = \sqrt{\sum (D_i^2 \ell_i) / s} \dots\dots\dots (2.7)$$

where

- D_e = equivalent diameter of the lattice leg
- D_i = reference diameter of member i
- ℓ_i = reference length of member i (node to node)
- s = height of one bay, or part of bay being considered.

7.3.5(b) Equivalent Drag Coefficient. The equivalent drag coefficient, C_{De} , of the lattice leg can be determined as:

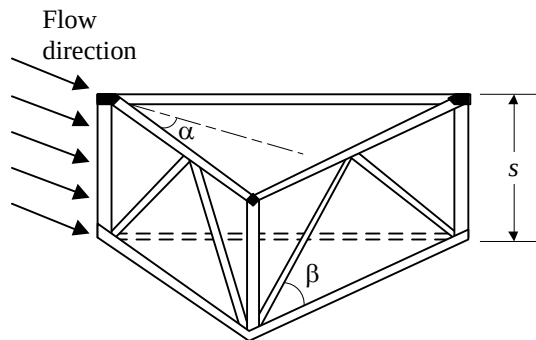
$$C_{De} = \sum C_{Dei} \dots\dots\dots (2.8)$$

where

- C_{Dei} = equivalent drag coefficient of each individual member
- $C_{Dei} = [\sin^2 \beta_i + \cos^2 \beta_i \sin^2 \alpha_i]^{3/2} C_{Di} \frac{D_i \ell_i}{D_e s}$
- C_{Di} = drag coefficient of an individual member i , related to reference dimension D_i
- α_i = angle between flow direction and member axis projected onto a horizontal plane (see Section 2, Figure 3 below)
- β_i = angle defining the member inclination from the horizontal plane (see Section 2, Figure 3 below)

Note: “ Σ ” indicates summation over all members in one leg bay.

FIGURE 3
One Bay of Lattice Leg



For a split tube chord as shown in Section 2, Figure 4, the drag coefficient C_{Di} , related to the reference dimension D_i , may be taken as:

$$C_{Di} = \begin{cases} C_{D0} & ; 0^\circ < \theta \leq 20^\circ \\ C_{D0} + (C_{D1}W/D_i - C_{D0})\sin^2[\theta - 20^\circ]9/7 & ; 20^\circ < \theta \leq 90^\circ \end{cases} \quad (2.9)$$

where

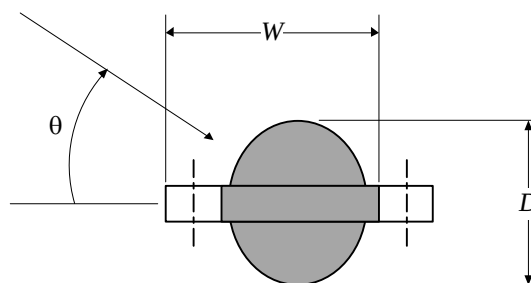
θ = angle in degrees, Section 2, Figure 4

C_{D0} = drag coefficient for a tubular

C_{D1} = drag coefficient for flow normal to the rack ($\theta = 90^\circ$), related to projected diameter, W

$$= \begin{cases} 1.8 & ; W/D_i < 1.2 \\ 1.4 + 1/3(W/D_i) & ; 1.2 < W/D_i < 1.8 \\ 2.0 & ; 1.8 < W/D_i \end{cases} \quad (2.10)$$

FIGURE 4
Split-Tube Chord Section



For a triangular chord as shown in Section 2, Figure 5, the drag coefficient, C_{Di} , related to the reference dimension $D_i = D$, the back plate width, may be taken as:

$$C_{Di} = C_{Dpr}(\theta) \cdot D_{pr}(\theta)/D_i \quad (2.11)$$

where the drag coefficient related to the projected diameter, C_{Dpr} , is determined from equation below with linear interpolation applicable for intermediate headings: