TECHNICAL REPORT

ISO/TR 19905-2

First edition
2012-~~##-##~~

Petroleum and natural gas industries — Site-specific assessment of mobile offshore units —

Part 2: Jack-ups commentary and detailed sample calculation

Industries du pétrole et du gaz naturel — Évaluation liée au site des unités marines mobiles —

Partie 2: Compléments sur les plates-formes auto-élévatrices

PROOF/ÉPREUVE

Reference number
ISO/TR 19905-2:2012(E)

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Contents

Page

Foreword v
Introduction vii
1 Scope 1
2 References 1
3 Terms and definitions 1
4 Symbols 1
4.1 Symbols for Clause 6 1
4.2 Symbols for Clause 7 3
4.3 Symbols for Clause 8 5
4.4 Symbols for Clause 9 6
4.5 Symbols for Clause 10 6
4.6 Symbols for Clause 12 8
5 Commentary on ISO 19905-1:2012, Clauses 5 and A.5 8
6 Commentary on ISO 19905-1:2012, Clauses 6 and A.6 8
TR.6.4.1 Metocean data — General 8
TR.6.4.2 Waves 8
TR.6.4.3 Current 20
TR.6.4.4 Water depths 20
TR.6.4.5 Wind 21
7 Commentary to ISO 19905-1:2012, Clauses 7 and A.7 24
TR.7.1 Scope 24
TR.7.3.2 Hydrodynamic model 24
TR.7.3.2.1.1 Length of members 24
TR.7.3.2.1.2 Spudcan 24
TR.7.3.2.1.3 Shielding and solidification 24
TR.7.3.2.2 “Detailed” leg model 25
TR.7.3.2.3 “Equivalent” leg model 25
TR.7.3.2.3.1 Equivalent drag coefficient 25
TR.7.3.2.3.2 Equivalent inertia coefficient 26
TR.7.3.3 Wave and current actions 48
TR.7.3.4 Wind actions 56
TR.7.8 Other considerations 56
APPENDIX TR.7.A : Example of equivalent model computations 57
APPENDIX TR.7.B: Comparison cases to assess implications of the ISO 19905-1 formulation 62
APPENDIX TR.7.C: Comparison of test results for chords 66
8 Commentary to ISO 19905-1:2012, Clauses 8 and A.8 69
TR A.8.8.6 Derivation of the alternative simplified negative stiffness correction term for P-Δ effects 69
9 Commentary to ISO 19905-1:2012, Clauses 9 and A.9 76
TR.9.3.6.2 Derivation of the limiting horizontal reaction given in ISO 19905-1:2012, Table A.9.3.7 76
10 Commentary to ISO 19905-1:2012, Clauses 10 and A.10 78
TR.10.4.2.1 Natural period — General 78
TR.10.4.2.2 Derivation of K_e, effective stiffness used to calculate the jack-up natural period 81
TR.10.4.3.3 Hysteretic damping 94
TR.10.4.3.4 Vertical radiation damping in earthquake analysis 95
TR.10.5.3.4 / C.2.4 Guidance on the fourth method of ISO 19905-1:2012, Table A.10.5.1 — Application of the drag-inertia method 95

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Full document details: ISO TR 19905 WG -2_2012

11 Commentary to ISO 19905-1:2012, Clauses 11 and A.11 95

12 Commentary to ISO 19905-1:2012, Clauses 12 and A.12 95
TR.12.6.2.2 Nominal bending strength 95
TR.12.6.2.2.1 Example 95
TR.12.6.3.2 Background for η in interaction equation approach 96

13 Commentary to ISO 19905-1:2012, Annex C 97
TR.C.2.4 Guidance on the fourth method of ISO 19905-1:2012, Table A.10.5.1 — Application of the drag-inertia method 97

Annex A (informative) **Detailed example calculation 98**

Annex B (informative) **SIPM "drag-inertia method" for dynamic analysis and estimation of extreme response for jack-ups 265**

Bibliography 295

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Full document details: ISO TR 19905 WG -2_2012

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 19905-2 was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 7, *Offshore structures*.

ISO 19905 consists of the following parts, under the general title *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units*:

— *Part 1: Jack-ups*

— *Part 2: Jack-ups commentary and detailed sample calculation* [Technical Report]

The following part is under preparation:

— *Part 3: Floating units*

ISO 19905 is one of a series of International Standards for offshore structures. The full series consists of the following International Standards:

— ISO 19900, *Petroleum and natural gas industries — General requirements for offshore structures*

— ISO 19901-1, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 1: Metocean design and operating considerations*

— ISO 19901-2, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 2: Seismic design procedures and criteria*

— ISO 19901-3, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 3: Topsides structure*

— ISO 19901-4, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 4: Geotechnical and foundation design considerations*

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— ISO 19901-5, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 5: Weight control during engineering and construction*

— ISO 19901-6, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 6: Marine operations*

— ISO 19901-7, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units*

— ISO 19901-8[1)], *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 8: Marine soil investigations*

— ISO 19902, *Petroleum and natural gas industries — Fixed steel offshore structures*

— ISO 19903, *Petroleum and natural gas industries — Fixed concrete offshore structures*

— ISO 19904-1, *Petroleum and natural gas industries — Floating offshore structures — Part 1: Monohulls, semi-submersibles and spars*

— ISO 19905-1, *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 1: Jack-ups*

— ISO/TR 19905-2, *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 2: Jack-ups commentary and detailed sample calculation*

— ISO/TR 19905-3[1)], *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 3: Floating units*

— ISO 19906, *Petroleum and natural gas industries — Arctic offshore structures*

1) Under preparation.

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Introduction

The series of International Standards applicable to types of offshore structures, ISO 19900 to ISO 19906, addresses design requirements and assessments for all offshore structures used by the petroleum and natural gas industries worldwide. Through their application, the intention is to achieve reliability levels appropriate for manned and unmanned offshore structures, whatever the type of structure and the nature or combination of the materials used.

It is important to recognize that structural integrity is an overall concept comprising models for describing actions, structural analyses, design or assessment rules, safety elements, workmanship, quality control procedures and national requirements, all of which are mutually dependent. The modification of one aspect of the design or assessment in isolation can disturb the balance of reliability inherent in the overall concept or structural system. The implications involved in modifications, therefore, need to be considered in relation to the overall reliability of offshore structural systems.

The series of International Standards applicable to the various types of offshore structure is intended to provide a wide latitude in the choice of structural configurations, materials and techniques without hindering innovation. Sound engineering judgement is therefore necessary in the use of these International Standards.

ISO 19905-1 was developed from SNAME T&R Bulletin 5-5A[5], but has been considerably altered from that original document. Some of the alterations have involved a restructuring and modification of terminology, but there have been additional changes of greater technical consequence. New material has been added based on studies undertaken since the original development of SNAME T&R 5-5A; new calculation techniques have been addressed because of improved computational capabilities allowing more complex assessments; gaps that existed in the original SNAME T&R 5-5A have been filled, thereby ensuring a more thorough assessment; and changes have been made to align ISO 19905-1 with other standards within the 19900 series. A description of the more important changes, along with the reasoning for the changes, can be found in a series of papers published in 2012 by Offshore Technology Conference. These papers can be of considerable value in helping the analyst, particularly those who are familiar with SNAME T&R 5-5A, in understanding ISO 19905-1. The papers, part of the Technical Session *ISO 19905-1: A Site-Specific Assessment of Mobile Jack-Up Units* are listed in the Bibliography:

— Reference [6], *Background to the ISO 19905-Series and an Overview of the New ISO 19905-1 for the Site-Specific Assessment of Mobile Jack-Up Units*

— Reference [7], *Environmental Actions in the New ISO for the Site-Specific Assessment of Mobile Jack-Up Units*

— Reference [8], *Structural Modeling and Response Analysis in the New ISO Standard for the Site-Specific Assessment of Mobile Jack-Up Units*

— Reference [9], *Foundation Modeling and Assessment in the New ISO Standard 19905-1*

— Reference [10], *Long-Term Applications in the ISO Standard for Site Specific Assessment of Mobile Jack-Up Units and the Use of Skirted Spudcans*

— Reference [11], *Structural Acceptance Criteria in the New ISO for the Site-Specific Assessment of Mobile Jack-Up Units*

— Reference [12], *The Benchmarking of the New ISO for the Site-Specific Assessment of Mobile Jack-Up Units*

This part of ISO 19905, which has been developed from SNAME T&R Bulletin 5-5A, provides a commentary to some clauses of ISO 19905-1 including background information, supporting documentation, and additional or alternative calculation methods as applicable and also provides a detailed sample “go-by” calculation in Annex A. The reader is advised that the information presented herein is intended for use in conjunction with ISO 19905-1 and that the cautions and limitations discussed in ISO 19905-1 apply.

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Petroleum and natural gas industries — Site-specific assessment of mobile offshore units —

Part 2: Jack-ups commentary and detailed sample calculation

1 Scope

This part of ISO 19905 provides a commentary to some clauses of ISO 19905-1 including background information, supporting documentation, and additional or alternative calculation methods as applicable and also provides a detailed sample 'go-by' calculation. ISO 19905-1 specifies requirements and guidance for the site-specific assessment of independent leg jack-up units for use in the petroleum and natural gas industries.

2 References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 19905-1:2012, *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 1: Jack-ups*

3 Terms and definitions

For the purposes of this document the terms and definitions given in ISO 19905-1 apply.

4 Symbols

4.1 Symbols for Clause 6

C_D	drag coefficient
$C_{De}D_e$	equivalent drag coefficient times effective diameter
d	water depth
D_2	depth attenuation
$D(\theta)$	directional spreading function from ISO 19901-1
$F(\alpha)$	directional spreading function from SNAME
f	frequency (Hz)
g	acceleration due to gravity

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H	wave height
H_{det}	reduced wave height which may be used in deterministic/regular wave force calculations
H_{max}	maximum wave height for a given return period; used for airgap calculations
H_{mpm}	wave height associated with H_{srp}, equivalent to the height between the extreme crest and the following trough
H_{mo}	estimate of H_s significant wave height (meters)
H_s	scaled significant wave height to be used in irregular seas simulation (meters)
H_{srp}	significant wave height for assessment return period
k	wave number
m	power constant in the $\left[\cos(\alpha)\right]^{2m}$ spreading function
$S_{nn}(f)$	power density of wave surface elevation as a function of wave frequency
T	wave period (seconds)
T	wind averaging tome (seconds)
T_0	standard reference time averaging interval for wind speed of 1 hr = 3600 s
T_p	peak period in wave spectrum (seconds)
T_z	zero-upcrossing period of wave spectrum (seconds)
U	wind speed
$U_{w,T}(10)$	is the sustained wind speed at 10 m height above mean sea level
U_{w0}	is the 1 h sustained wind speed at the reference elevation 10 m above mean sea level
u	the computed velocity for long crested waves
u_{red}	the reduced horizontal velocity
V	current velocity
α	equilibrium range parameter
α_3	skewness
α_4	kurtosis
γ	peak enhancement factor
γ_d	scaling of drag forces
κ	kinematics reduction factor
η	crest elevation by Airy theory

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η_s crest elevation by Stokes

ϕ directional spreading factor defined in ISO 19901-1

σ spectral peakwidth parameter

4.2 Symbols for Clause 7

A cross-sectional area of member

A_e equivalent area of leg per unit height

A_i equivalent area of element

A_s sum of projected areas for all members in the considered plane

A_t total projected envelope area of the considered plane

C_A added mass coefficient

C_D drag coefficient

C_{Do} drag coefficient for chord at direction $\theta = 0°$

C_{D1} drag coefficient for flow normal to the rack, $\theta = 90°$

C_{De} equivalent drag coefficient

C_{Dei} equivalent drag coefficient of member i

C_{Di} drag coefficient of an individual member, related to D_i

$C_{Dpr}(\theta)$ drag coefficient to the projected diameter

C_{Drough} drag coefficient for a rough member

$C_{Dsmooth}$ drag coefficient for a smooth member

C_M inertia coefficient

C_{Me} equivalent inertia coefficient

C_{Mei} equivalent inertia coefficient of member i

C_{Mi} inertia coefficient of a member, related to D_i

d mean, undisturbed water depth (positive)

D member diameter

D_e equivalent diameter of leg bay

D_F face width of leg, outside dimensions

D_i reference dimension of individual leg members

$D_{pr}(\theta)$ projected diameter of the chord

f_i fundamental vibration frequencies of the member

H_s significant wave height

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k	roughness height
k/D	relative roughness
KC	Keulegan-Carpenter number
l_i	length of member "i" node to node
m_a	added mass contribution (per unit length) for the member
N	constant in wind velocity power law
$\dot{r}_n$	velocity of the considered member, normal to the member axis and in the direction of the combined particle velocity
$\ddot{r}_n$	acceleration of the considered member, normal to the member axis and in the direction of the combined particle velocity
Re	Reynolds number
s	length of one bay, or part of bay considered
S	Strouhal number
S	average wave steepness
S	outer diameter of an array of tubulars
T	wave period
T_n	first natural period of sway motion
T_z	zero-upcrossing period
u	particle velocity
u_n	particle velocity normal to the member
$\dot{u}_n$	particle acceleration normal to the member
$u_x, \dot{u}_x$	horizontal water particle velocity and acceleration
U	flow velocity at the depth of the considered element
U_C	current particle velocity
U_m	maximum orbital particle velocity
U_{red}	reduced particle velocity for regular waves
U_W	representative wave particle velocity
v_n	total flow velocity normal to the member
V_C	reduced current velocity for use in the hydrodynamic model; V_C should not be taken as less than $0{,}7V_f$
V_{Cn}	current velocity normal to member used in the hydrodynamic model
V_f	far field (undisturbed) current

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W dimension from backplate to pitch point of triangular chord or dimension from root of one rack to tip of other rack of split tubular chord

W width of the structure

z coordinate measured vertically upward from the mean water surface

z' modified coordinate to be used in particle velocity formulation

α indicator for relative velocity, 0 or 1

α_i angle defining flow direction relative to member

β ratio of Re/KC, a parameter to describe the test environment

β_i angle defining the member inclination

ΔF_{drag} drag force per unit length

$\Delta F_{inertia}$ inertia force per unit length

$\Delta F_{inertiaH}$ horizontal inertia force per unit length

λ wave length

ν kinematic viscosity

θ angle in degrees for waves relative to the chord orientation

θ_o angle where half the backplate is hidden behind the rackplate

ρ mass density of water or air

ζ instantaneous water surface elevation (same axis system as z)

ζ_o wave crest elevation (same axis system as z)

4.3 Symbols for Clause 8

K_o lateral stiffness without axial load

K_1 lateral stiffness with axial load

K_E sum of individual leg stiffnesses

L distance from the spudcan point of rotation to the hull centre of gravity

P axial load in one leg

P_G total gravity load only

P_g effective hull gravity load; includes hull weight and weight of the legs above the hull

y_0 deflection without axial load P

y_1 additional lateral deflection due to axial load P

y_{max} total lateral deflection

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4.4 Symbols for Clause 9

a depth interpolation parameter

B_S soil buoyancy of spudcan below bearing area, i.e. the submerged weight of soil displaced by the spudcan below D, the greatest depth of maximum cross-sectional spudcan bearing area below the sea floor

F_H horizontal force applied to the spudcan due to the assessment load case

F_V gross vertical force acting on the soil beneath the spudcan due to the assessment load case

Q_V gross ultimate vertical foundation capacity

V_{Lo} maximum vertical reaction under the spudcan considered required to support the in-water weight of the jack-up during the entire preloading operation (this is not the soil capacity)

W_{BF} submerged weight of the backfill

$\gamma_{R,PRE}$ preload resistance factor

4.5 Symbols for Clause 10

A axial area of one leg (equals sum of effective chord areas, including a contribution from rack teeth; see ISO 19905-1:2012, A.8.3.3, Note)

A_s effective shear area of one leg

d distance between upper and lower guides

D_{hyst} hysteretic damping

E Young's modulus

F shear transmitted from the hull

F_g geometric factor; = 1,125 (three-leg jack-up), 1,0 (four-leg jack-up)

F_h factor to account for horizontal soil stiffness, K_{hs}, and horizontal leg-hull connection stiffness, K_{hh}

F_h modification factor to be applied to the leg lateral deformation stiffness

F_n factor to account for the number of chords; = 0,5 (three-chord leg), 1,0 (four-chord leg)

F_r modification factor to be applied to the leg-hull connection stiffness

F_v factor to account for vertical soil stiffness, K_{vs}, and vertical leg-hull connection stiffness, K_{vh}

g acceleration due to gravity

h distance between chord centres (opposed pinion chords) or pinion pitch points (single rack chords)

I second moment of area of leg

I_H representative second moment of area of the hull girder joining two legs about a horizontal axis normal to the line of environmental action

K_A effective horizontal stiffness due to axial deformation

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K_B	effective bending stiffness
K_e	effective stiffness associated with one leg
k_f	combined vertical stiffness of all fixation system components on one chord
K_{hh}	horizontal leg-hull connection stiffness
K_{hull}	hull rotational stiffness
k_j	combined vertical stiffness of all jacking system components on one chord
K_{rh}	leg-hull connection rotational stiffness
K_{rs}	leg-soil connection rotational stiffness
k_u	total lateral stiffness of upper guides with respect to lower guides
K_{vh}	effective stiffness due to the series combination of all vertical pinion or fixation system stiffnesses, allowing for combined action with shock-pads, where fitted
L	length of leg considered
M_e	effective mass associated with one leg
M_h	moment on leg-hull spring
M_{hull}	full mass of hull including maximum variable load
M_{la}	mass of leg above lower guide (in the absence of a clamping mechanism) or above the centre of the clamping mechanism
M_{lb}	mass of leg below the point described for M_{la}, including added mass for the submerged part of the leg ignoring spudcan
M_s	moment on leg-soil spring
N	number of legs
P	axial load in leg
P	mean force due to vertical fixed load and variable load acting on one leg
P_E	Euler buckling force of one leg
T_n	highest (or first mode) natural period
x_h	hull deflection
Y	distance between centre of one leg and line joining centres of the other two legs (three-leg jack-up), or distance between windward and leeward leg rows for direction under consideration (four-leg jack-up)
ν	Poisson's ratio
δ_{axial}	axial deflection
Δ_{horz}	horizontal hull deflection
θ_{hull}	hull rotation

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4.6 Symbols for Clause 12

F_y yield strength, in stress units, taken as the minimum of the yield strength and 90 % of the ultimate tensile strength (UTS; see ISO 19905-1:2012, A.12.2.2)

M_p nominal bending strength

Z plastic section modulus

5 Commentary on ISO 19905-1:2012, Clauses 5 and A.5

No commentary is offered.

6 Commentary on ISO 19905-1:2012, Clauses 6 and A.6

TR.6.4.1 Metocean data — General

ISO 19905-1 permits the use of either 50-year return period individual extremes or 100-year joint probability environmental data with associated and different load factors; see ISO 19905-1:2012, 6.4. For these alternative environmental formulations, adjustments for season and directionality are permitted as given below:

— Seasonally adjusted data may be used if appropriate (ISO 19905-1:2012, 6.4).

NOTE When seasonal data are specified, the data should not be divided into periods of less than one month and the values so calculated should generally be factored such that the extreme for the most severe period equals the all-year value for the required assessment return period.

— Where directional data are available, these may be considered (ISO 19905-1:2012, 6.4).

NOTE When directional data are specified, the data should normally not be divided into sectors of less than 30° and the directional values so calculated should generally be factored such that the extreme for the most severe sector equals the omni-directional value for the required assessment return period and season where applicable. In certain areas 30° sectors may be inappropriate; caution should be exercised if an assessment heading falls marginally outside a sector with higher data or if data is highly directional.

— The downwind (vector) component of the maximum surface flow of the mean spring tidal current is specified rather than the maximum spring tidal current (ISO 19905-1:2012, A.6.4.3).

— Site-specific information may be used to determine an appropriate combination of wind-driven and surge currents (ISO 19905-1:2012, A.6.4.3).

TR.6.4.2 Waves

TR.6.4.2.2 Extreme wave height

The wave heights utilized by ISO 19905-1 for wave load calculations are related to the return period significant wave height for a three-hour storm, H_{srp}. ISO 19905-1 however recognizes that this data may not always be available to the assessor and therefore provides relationships between H_{srp} and H_{max}, the individual extreme wave height for the assessment return period with an annual probability of exceedance of 1/(return period). If the assessment return period is taken as 50 years, $H_{max(50)}$ is the wave height with a 2 % annual probability of exceedance.

H_{srp} and the associated period are normally determined through a direct extrapolation of measured or hindcast site-specific significant wave heights. H_{max} may be determined either from an extrapolation of the distribution of individual wave heights over the assessment return period or by the application of a multiplication factor to H_{srp}.

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It is noted that the "extreme wave height" of a regular wave, H_{mpm}, determined from a three-hour storm segment is the most probable maximum (MPM) wave height, defined as the distance from the extreme crest to the following trough. Using this definition, the MPM wave height from the three-hour storm segment is given by:

$$H_{mpm} = 1{,}68\ H_{srp} \qquad \text{(TR.6.4-1)}$$

This relationship is confirmed by the data of Reference [6-1] for individual storms. However, H_{mpm} must not be confused with H_{max} and must not be used to determine the value of H_{srp} on which an assessment is based. This is because H_{max} includes site-specific considerations of potentially longer durations of storms (including build up and decay) and the additional probability contributions of other return period storms (i.e. 20-, 30-, 40-, 100-year, etc. return period storms). Consequently, the ratio H_{max}/H_{srp} is larger than the ratio H_{mpm}/H_{srp}.

A consequence of the site-specific nature of the derivation of H_{max} is that there is no unique relationship between H_{max} and H_{srp} applicable to all areas of the world. Thus, if a specified return period maximum wave height is given at a particular location there is no consistent way to derive H_{srp} without knowledge of how the maximum H_{max} wave height was derived originally.

Average factors between H_{srp} and H_{max} have been derived for a North Sea and a Gulf of Mexico location for a 50-year return period. Without further information, the North Sea factors can be generalized to any non-tropical revolving storm area and the Gulf of Mexico factors can be generalized to tropical revolving storm areas. These factors are:

Environmental conditions	H_{max}/H_{srp}
Tropical revolving storms	1,75
Non-tropical storms	1,86

TR.6.4.2.3 Deterministic waves

The selection of wave height to be applied in a particular analysis approach (regular or irregular waves) is recommended based on matching the loads resulting from the combination of the wave height and kinematics models, as recommended in ISO 19905-1:2012, A.7.3.3.3.1. The scaling of wave heights is introduced as an alternative to the scaling of drag coefficients.

For regular wave analyses using an appropriate wave theory, the wave asymmetry is properly accounted for, but the irregularity of the sea surface and the wave spreading may not be modelled properly.

Considering that the computations with regular waves are made with a kinematics model that has been documented in Reference [6-4] to be somewhat conservative, a reduction factor is appropriate to arrive at realistic force estimates.

As indicated in Tables TR.6.4.2.2-1 and TR.6.4.2.2-2, a reduction factor is required to give similar forces as predicted by an irregular seas simulation if $H_{max} = 1{,}86H_s$. There are a few ways that the reduction factor could be realized in the assessment. In Reference [6-2] a reduction of the drag coefficient by a factor of 0,7 is chosen and in Reference [6-3] a reduction of wave kinematics is chosen. Some classification societies may specify lower C_D values than specified in ISO 19905-1:2012, A.7.3.4, and these apply to regular wave analyses.

Accepting that a scaling factor on kinematics is applicable, the kinematics reduction factor κ is introduced in ISO 19905-1:2012, A.6.4.2.3 for application to the kinematics obtained from H_{max} (preferred) or, alternatively, to scale the wave height, but not both.

In the development of the SNAME T&R Bulletin 5-5A[5] it was chosen to follow a practical way of implementing the reduction in the Practice by reducing the wave height to be used for force computations in regular wave analyses. This was found to be more practical than using a factor on kinematics, as most software on the market did not allow such a scaling factor to be used. Equivalent wave heights are suggested as:

$$H_{det} = 1{,}60H_{srp} \qquad \text{(TR.6.4-2)}$$

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The scaling factors on kinematics could be implemented assuming that the load effect is proportional to wave height to the power 2,2, remembering that drag coefficients (C_D) should not be scaled. As a comparison with previous practices, the relationship $H_{det} \approx 1{,}60 H_{srp}$ can also be compared with the reduction of C_D by a factor of 0,7 as recommended in Reference [6-2] in combination with the wave height $H_{max} = 1{,}86 H_s$. By assuming that load effects are proportional to the ratio of wave heights to the power 2,2, the scaling becomes $(1{,}60/1{,}86)^{2,2} = (0{,}86)^{2,2} = 0{,}72$, indicating that this is not lower than current practice. The computational results of Table TR.6.4.2.2-2 indicate also that scaling of 0,66 would give similar static forces as the irregular seas simulation at large water depths. See also Appendix TR.7.B for a comparison of the computational results, related to other practices. In effect, in the SNAME T&R Bulletin 5-5A, the above resulted in a kinematic reduction factor of 0,86 (= 1,60/1,86).

In the course of developing ISO 19905-1, new technology was introduced (see ISO 19905-1:2012, Reference [A.6.4-1]), replacing the above definition of equivalent wave height H_{det}. The directional spreading factor defined in ISO 19901-1 was taken as the basis. This factor ϕ may be applied directly as a kinematics reduction factor κ. Depending on the type of storm region (see TR.6.4.2.2 above) and the latitude, ϕ may vary between 0,87 and 0,94.

In short-crested waves, the wave energy propagates in different directions around the main wave direction. The peak particle velocities under waves become smaller as the waves become more spread. As a result, the directional spreading of waves tends to result in peak loading that is somewhat smaller than that predicted for uni-directional seas. Design codes and practices have accounted for spreading by introducing a factor on horizontal kinematics (either directly or via the wave height) in conjunction with the regular wave approach. The reduction factor reflects the reduced kinematics under the highest point of the wave crest and is thus appropriate for the calculation of quasi-static loads on a single pile. However, it does not account for all the effects of spreading. The loads on offshore structures are reduced further due to the spatial distribution of the wave-loaded structural components.

Thorough inclusion of both 3D and nonlinear effects of waves can reduce the extreme loads computed for a jack-up. In the study reported in ISO 19905-1:2012, Reference [A.6.4-1], a systematic study of a variety of jack-ups (LeTourneau 82SDC, LeTourneau 116C, F&G Mod V, LeTourneau Super 300 and MSC CJ70) in different water depths and environments was performed to generalize the applicability of results. A formula was developed which can robustly represent the above effects in an assessment context, without having to perform the more complex and time consuming direct evaluation. The formulation is given in ISO 19905-1:2012, A.6.4.2.3 in Equations (A.6.4-4) through (A.6.4-7).

The development of the formula was based on fitting the total wave actions on the legs of a typical jack-up by regular wave analysis to the most probable maximum extreme (MPME) results from a stochastic wave analysis. The fitting was done by a kinematic reduction factor. The stochastic wave analyses were performed using the ISO directional spreading factor as the basis and a second order directional wave theory for the irregular extreme wave kinematics coupled with an analysis model which simulates jack-up quasi-static loading. The response quantities assessed were the base shear and the overturning moment. Using the formulae given in ISO 19905-1:2012, A.6.4.2.3, the accuracy of the fit compared to the stochastic loads is within ± 5 %. For the majority of the cases analysed, the resulting κ was between 0,70 and 0,85, but there were cases that produced higher wave loads than the original SNAME ($\kappa = 0{,}86$), so with $\kappa > 0{,}86$.

Caution should be exercised if the above formulation is applied to cases other than three-legged drag-dominated (truss legs) jack-ups in extreme storm conditions. The main reason for this is that only these typical jack-up designs in ultimate limit state (ULS) conditions have been considered in the calculations that form the basis of the formulation. For these jack-up types and conditions, the results are valid; for others, caution is necessary.

TR.6.4.2.3.1 Comparison of wave loads obtained using different wave theories for regular and irregular wave analyses

The Dean's stream function/Stokes' fifth order theories predict higher peak than trough amplitudes, increasing the maximum velocities and the wetted surface compared with the Airy theory. In Figure TR.7.3.3.3-2 the difference in the profiles is illustrated. Using the same specified wave height, this difference can be seen in terms of the overturning moment, base shear and/or deck displacement.

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A number of computations were performed to determine the differences due to wave kinematics on selected jack-up designs. Some results are summarized in Tables TR.6.4.2.2-1 and TR.6.4.2.2-2. See also Appendix TR.7.B.

Table TR.6.4.2.2-1 — Regular wave analysis normalized results, $C_{De}D_e$ = 5,13 over the full water depth

Theory	Water depth m	Wave H_{max} & T m/s	Crest amp. m	Base shear MN	Overturning. moment MNm	Dean's overturning/ other
Airy Const.	30	15/14	7,5	3,577	91,607	1,74
Airy Wheeler		15/14	7,5	3,266	82,782	1,93
Stokes' fifth		15/14	10,22	5,211	156,16	1,02
Dean's stream		15/14	10,42	5,243	159,45	1,0
Airy Const.	70	15/14 28/16	7,5 14,0	2,916 14,121	160,83 677,69	1,12 1,44
Airy Wheeler		15/15 28/16	7,5 14,0	2,563 13,446	138,80 636,53	1,30 1,53
Stokes' fifth		15/14 28.16	8,41 19,17	3,171 18,264	180,80 976,62	1,00 1,00
Dean's stream		15/14 28/16	8,41 19,33	3,161 18,136	180,30 972,54	1,0 1,0

In Table TR.6.4.2.2-2 the deterministic analysis is based on application of various H_{max} to H_s relationships. The stochastic analysis refers to extreme values determined from time domain analyses by fitting a three-parameter Weibull distribution to the response peaks and reading the extreme as the 0,999 fractile, approximating a three-hour storm extreme.

The results show dependence on the choice of wave kinematics differing with wave height.

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Table TR.6.4.2.2-2 — Scaling factor χ_d on loads to comply with Airy Wheeler in irregular seas[6-10]

		Airy Wheeler	Airy No stretch	Airy Constant	Stokes' Fifth
BASE SHEAR					
Stochastic irregular seas		1,00	1,03	0,83	-
Deterministic regular waves	a	0,79	0,84	0,69	0,66
	b	0,66	0,69	0,56	0,66
	c	0,71	0,75	0,61	0,66
	d	—	—	—	0,92
OVERTURNING MOMENT					
Stochastic irregular seas		1,00	1,10	0,79	—
Deterministic regular waves	a	0,81	0,93	0,69	0,66
	b	0,67	0,76	0,56	0,66
	c	0,72	0,83	0,61	0,66
	d	—	—	—	0,93

Water depth 110 m, H_s = 13,0m, T_p = T_{ass} = 17,0 s, uniform current V = 0,4 m/s.

Wheeler stretching basis for normalized results, i.e. Airy Wheeler stochastic load = χ_d (other load).

a H_{max} = 1,86H_s.

b Crest as Stokes.

c H_{max} = 1,86H_s × 1,07 except Stokes.

d H_{max} = 1,60H_s (see Reference [5]).

TR.6.4.2.4 Wave crest elevation

Wave crest elevations are specified in ISO 19905-1 with the intention of determining minimum hull elevation and airgap to avoid storm waves impinging on the jack-up hull; see ISO 19905-1:2012, A.6.4.2.4 and 13.6.

TR.6.4.2.5 Wave spectrum

In Reference [5] the wave spectrum is represented by the power density of wave surface elevation $S_{\eta\eta}$(f) as a function of wave frequency by:

$$S_{\eta\eta}(f) = [16I_0(\gamma)]^{-1}H_s^2T_p(T_pf)^{-5}\exp[-1{,}25/(T_pf)^4]\gamma^q \qquad \text{(TR.6.4-3)}$$

where

q = $\exp[-(T_pf - 1)^2/2\sigma^2]$ with:

σ = 0,07 for T_pf <= 1,0;

σ = 0,09 for T_pf > 1,0; (Carter 1982, ISO 19905-1:2012, Reference [A.6.4-4])

and

H_s is the significant wave height (meters), including depth correction, according to TR.6.4.2.6;

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T_p is the peak period (seconds);

f is the frequency (hertz);

γ is the peak enhancement factor;

$I_0(\gamma)$ is discussed below.

The above definition yields a single-parameter Pierson-Moskowitz spectrum when γ = 1 and $T_p = 5\sqrt{(H_s)}$, with H_s in meters. In this case an appropriate T_p/T_z ratio is 1,406 (see below).

When considering a JONSWAP spectrum, the peak enhancement factor γ varies between 1 and 7 with a most probable average value of 3,3. There is no firm relationship between γ, H_s and T_p. Relationships between variables for different values of γ according to Carter (1982), ISO 19905-1:2012, Reference [A.6.4-4], are as follows (see also ISO 19905-1:2012, A.6.4.2.7):

γ	$I_0(\gamma)$	T_p/T_z
1	0,200	1,406
2	0,249	1,339
3	0,293	1,295
3,3	0,305	1,286
4	0,334	1,260
5	0,372	1,241
6	0,410	1,221
7	0,446	1,205

Alternatively:

$$\left[I_0(\gamma) = \frac{0{,}2}{1 - 0{,}287\,\mathrm{Ln}\ (\gamma)} \right]$$

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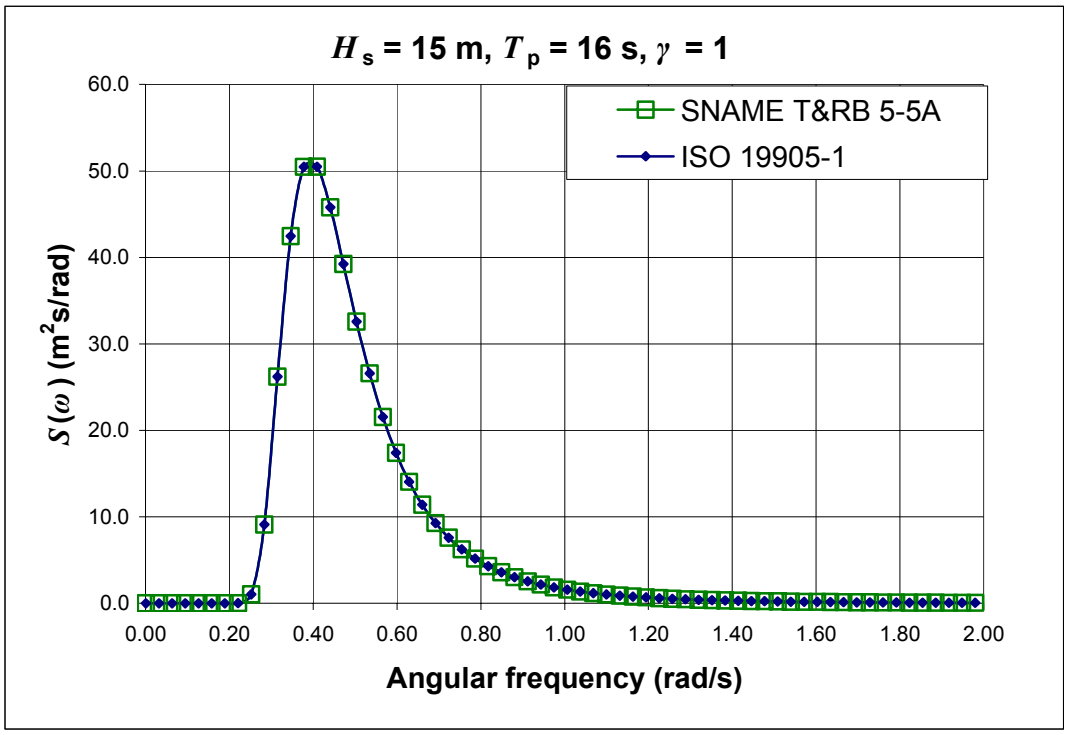
A comparison wave of spectra calculated according to ISO 19901-1:2005, A.8.6, and those calculated according to the SNAME T&R Bulletin 5-5A formulation is shown in Figure TR.6.4.2.5-1. The comparison shows equivalence between the calculated spectra.



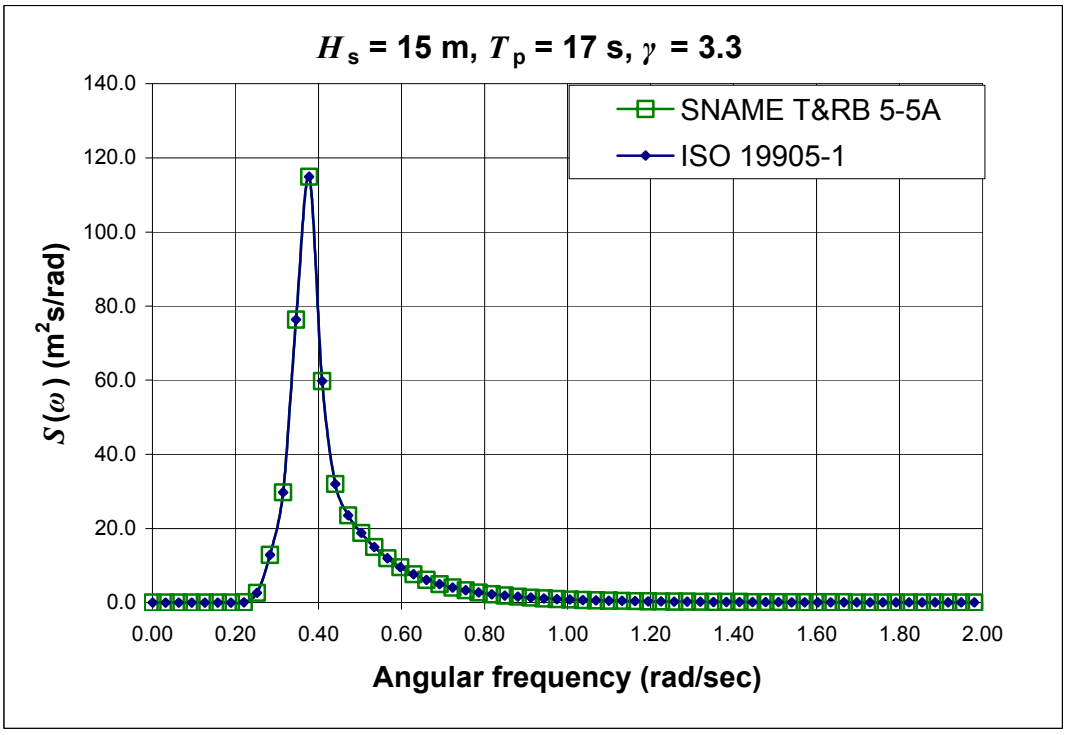


Figure TR.6.4.2.5-1 — Comparison of ISO 19901-1 and SNAME T&R 5-5A wave spectrum formulations

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The following alternative, and rather restrictive, representation of the wave spectrum by the power density of wave surface elevation $S_{\eta\eta}(f)$ as a function of wave frequency may be used:

$$S_{\eta\eta}(f) = \alpha g^2(2\pi)^{-4}(f)^{-5}\exp[-1{,}25/(T_p f)^4]\gamma^q \qquad \text{(TR.6.4-4)}$$

where

α is the equilibrium range parameter = 0,036 – 0,005 6$T_p/\sqrt{H_{m0}^2}$

g is the acceleration due to gravity

q = $\exp[-(T_p f - 1)^2/2\sigma^2]$

σ is the spectral peakwidth parameter = 0,07 for $T_p f \leq 1$

= 0,09 for $T_p f > 1$

H_{m0} is the estimate of H_s significant wave height (m)

T_p is the spectral peak period (s)

f is the frequency (Hz)

γ is the peak enhancement factor

= $\exp[1/0{,}287(1-0{,}197\ 5\alpha T_p^4/H_{m0}^2)]$

The above definition yields a Pierson-Moskowitz spectrum when γ = 1,0 and T_p = 5$\sqrt{(H_s)}$, with T_p in seconds and H_s in meters.

TR.6.4.2.6 Airy wave height correction for stochastic analysis

Airy theory may be applicable together with a stochastic irregular seas analysis, and in ISO 19905-1:2012, A.7.3.3.3.2, the Wheeler stretching is recommended for describing the kinematics to the instantaneous surface.

It is accepted that the increasing asymmetry described by higher order theories such as Stokes is appropriate. The asymmetry can also be seen in recorded data as skewness of the waves, as shown in Figure TR.6.4.2.6-1. Since Airy theory has certain limitations, a practical way to compensate for the asymmetry is to increase the significant wave height used as input to the force computations. In order to show that a scaling of significant wave height is appropriate, and to determine the absolute values of the scaling factors, one needs to decide which theory is correct at a given wave condition. Based on the good fit to test results in wave tank measurements[6-5], the Wheeler stretching is found to be a best fit. However, due to the asymmetry of wind-generated ocean waves in shallow water, this agreement is judged to be valid only for large water depths. In Reference [6-6] it is also indicated that a higher peak than trough is appropriate.

Here it is assumed that the significant wave height should have a scaling factor close to 1,0 for Wheeler stretching at water depths equal to or greater than 110 m using irregular wave analysis. At shallower water depths a scaling factor in excess of 1,0 should be due to the wave asymmetry.

In Reference [6-7], a scaling of wave crests is suggested based on the Stokes wave profiles. Comparisons are made both with data for North Sea conditions (d = 70 m) (see also Figure TR.6.4.2.6-1) and shallow waters ($d \approx$ 5,0 m) in the Baltic Sea, implying that this may be a general model. A correction proportional to wave steepness is deduced which shows fair agreement with the data.

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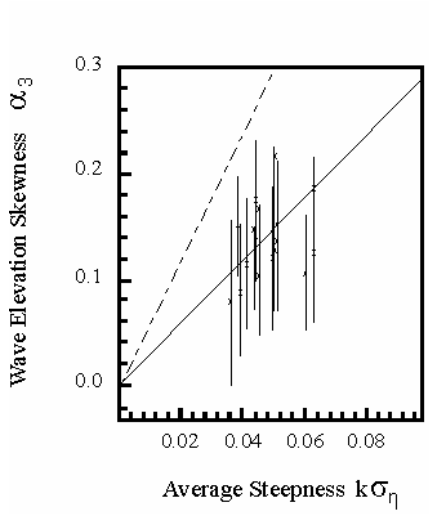

Tp(s)	<1	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15
Hs (m) <2	0.076 2.996 1021								
2-3	0.105 2.974 194	0.102 2.966 61	0.107 2.671 1						
3-4		0.121 3.001 43	0.118 3.007 59	0.088 2.912 11					
4-5			0.184 2.991 3	0.147 3.001 33	0.111 2.912 11				
5-6				0.194 2.674 1	0.135 3.021 20	0.148 2.934 9			
6-7						0.126 2.936 3	0.174 2.978 7	0.148 3.018 2	
7-8							0.209 2.875 2	0.141 3.086 3	
8-9								0.168 3.096 1	
9-10									0.256 2.548 1

Figure TR.6.4.2.6-1 — Comparison of wave crest elevation predicted skewness and observed data at 70 m in the North Sea[6-7]

The crest height correction formula may be simplified, neglecting the higher order terms[6-7], to be:

$$\eta_s/\eta \approx 1{,}0 + 0{,}6\alpha_3 + 0{,}5(\alpha_4 - 3) \qquad \text{(TR.6.4-5)}$$

where

η_s is the crest elevation by Stokes

η is the crest elevation by Airy

α_3 = $2{,}5D_2\, H_s / T_p^2$, $\alpha_4 - 3 \approx (1{,}6\alpha_3)^2$: Skewness & kurtosis relations

D_2 = $\coth(kd)\,[1 + 3/(2\sinh^2(kd)]$: Depth attenuation

k = $(2\pi/T)^2/g$: Wave number

The data and the model indicate that the skewness, α_3, is about 0,08 to 0,2 for large seastates at 70 m water depths giving a correction of 1,05 to 1,12 on the crest height compared with a linear model. The forces on a jack-up structure increase proportionally as the square (or more) of the elevation. Applying a correction for the square of the bias in wave crest, the correction for 70m should be in the range 1,10 to 1,25, depending on wave steepness.

By combining the above suggested formulae, a correction for the Wheeler stretching in a stochastic analysis may be deduced as:

$$H_s = 1{,}0 + 1{,}5D_2\, H_{srp} / T_p^2 \qquad \text{(TR.6.4-6)}$$

The D_2 factor includes a dependence on the wave number for individual waves. This is not suitable for the purpose of inclusion in ISO 19905-1, since there is no unique wave number for a seastate.

The elevation is not the only parameter to be considered; others are as follows:

— the depth attenuation over water depth;

— the profiles are not similar in horizontal directions;

— forces at some distance lose correlation.

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This gives a different scaling to that deduced from the wave crest height only.

Based on the above a significant wave height for stochastic/irregular wave analysis using Airy waves and Wheeler stretching is recommended as:

$$H_s = [1 + (10H_s/T_p^2)e^{(-d/25)}]H_{srp} \quad \text{(TR.6.4-7)}$$

This removes the direct link to the Stokes profile as suggested in Reference [6-7], but contains the linear dependence on steepness and a depth dependence with an exponential decay.

A similar scaling on wave height for Airy/Wheeler stretching is currently being applied indirectly in design specifications[6-8] where it is stated that the wave heights according to Airy should be two times the peak amplitude predicted by the Stokes wave profile.

The above scaling is an approximation. It would be more correct to account for the wave asymmetry directly in the generation of the sea surface elevation by, for example, the methods indicated in Reference [6-7]. The significant wave height H_{srp} could then be applied directly.

Scaling for other stretching techniques combined with Airy waves may be deduced for stochastic, irregular waves and based on computational comparisons for different wave heights and water depths. However, this will not give exactly the same force profile over the leg and discrepancies in force prediction will occur. Such scaling is therefore not included in ISO 19905-1.

For computational comparisons using this wave height scaling, see also Appendix TR.7.B.

TR.6.4.2.8 Short-crested stochastic waves

TR.6.4.2.8.1 Directional spreading functions according to SNAME

According to SNAME T&R Bulletin 5-5A, subclause 3.5.4, the directional spreading may, in the absence of more reliable data, be taken as

$$F(\alpha) = C \cdot \left[\cos(\alpha)\right]^{2m} \quad \text{for } -\frac{\pi}{2} \le \alpha \le \frac{\alpha}{2} \quad \text{(TR.6.4-9)}$$

where

m is the power constant

C is a constant chosen such that $\int_{-\pi/2}^{\pi/2} F(\alpha) \cdot d\alpha = 1{,}0$

The power constant should normally not be taken as less than

m = 2,0 for fatigue analysis

m = 4,0 for extreme analysis

The above provides a formulation which may be used to incorporate the effects of wave spreading in the analysis. The power constants recommended[6-9] imply that the extreme seastate is close to long-crested, and that there is therefore little angular distribution of wave energy about the mean direction.

It should be noted that where significant spreading exists, it may be non-conservative to assume a long-crested sea.

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In Reference [6-3] a reduction formula is suggested which reduces the velocity by a factor "primarily accounting for wave spreading":

$$u_{red}/u = \sqrt{[(2m + 1)/(2m + 2)]} \qquad \text{(TR.6.4-10)}$$

where

u_{red} is the reduced horizontal velocity;

u is the computed velocity for long-crested waves;

m is the exponent in the $\cos^{2m}\theta$ spreading function at T_p.

For a range of the spreading exponent, $2 < m < 3$, the range of the scaling is:

$$0{,}91 < u_{red} / u < 0{,}94$$

This corresponds to a reduction of the forces by a factor ranging from 0,833 to 0,875. To use such a spreading factor in reducing overall forces on a structure is debatable, and especially so for jack-up structures. There may be cases where the inclusion of the spreading in irregular seas results in higher forces for some headings. If the leg spacing corresponds to a wave period, inducing opposing wave forces for different legs coinciding with the first resonance period, the forces will in fact be amplified when spreading is included. For jack-ups where the resonance period may often be as high as 4 s to 7 s, the effect of wave spreading is believed to reduce forces. However, the size of the reduction is dependent on the structure. See ISO 19905-1:2012, Reference [A.6.4-1], for a thorough discussion on inclusion of wave spreading and resulting effects on wave loads and dynamics of jack-ups.

TR.6.4.2.8.2 Directional spreading functions according to ISO 19901-1

In ISO 19901-1:2005, A.8.7.1, the directional spreading function $D(\theta)$ is described with alternative symmetric functions around the mean direction $\bar{\theta}$. In the absence of information to the contrary, the mean wave direction can be assumed to coincide with the mean wind direction. The three expressions for $D(\theta)$ are:

$$D_1(\theta) = C_1(n)\cdot\left[\cos\left(\theta-\bar{\theta}\right)\right]^n \qquad \text{for } -\frac{1}{2}\pi \le \left(\theta-\bar{\theta}\right) \le +\frac{1}{2}\pi \qquad \text{(TR.6.4-11)}$$

$$D_2(\theta) = C_2(s)\cdot\left[\cos\left(\frac{\theta-\bar{\theta}}{2}\right)\right]^{2s} \qquad \text{for } -\pi \le \left(\theta-\bar{\theta}\right) \le +\pi \qquad \text{(TR.6.4-12)}$$

$$D_3(\theta) = C_3(\sigma)\cdot\frac{1}{\sigma\sqrt{2\pi}}\cdot\exp\left[-\frac{\left(\theta-\bar{\theta}\right)^2}{2\sigma^2}\right] \qquad \text{for } -\frac{1}{2}\pi \le \left(\theta-\bar{\theta}\right) \le +\frac{1}{2}\pi \qquad \text{(TR.6.4-13)}$$

$$D_1(\theta) = D_2(\theta) = D_3(\theta) = 0 \qquad \text{for all other } \left(\theta-\bar{\theta}\right) \qquad \text{(TR.6.4-14)}$$

where

$$C_1(n) = \frac{\Gamma(n/2+1)}{\sqrt{\pi}\,\Gamma(n/2+1/2)}$$

$$C_2(s) = \frac{\Gamma(s+1)}{2\sqrt{\pi}\,\Gamma(s+1/2)}$$

$$C_3(\sigma) = 1$$

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The functions all have a peak at $\theta = \bar{\theta}$, the sharpness of which depends on the exponent n in $D_1(\theta)$ or s in $D_2(\theta)$, or the standard deviation of the normal distribution $D_3(\theta)$. The coefficients C are normalizing factors dependent on n, s or σ, which are determined such that the integral of $D(\theta)$ over all θ is equal to 1,0.

In engineering applications,

$D_1(\theta)$ is often used with n = 2 to n = 4 for wind seas, and n = 6 or higher for swells,

$D_2(\theta)$ may be used with typical values s = 6 to 15 for wind seas, and s = 15 to 75 for swells.

TR.6.4.2.8.3 Comparison of directional spreading functions in SNAME T&R Bulletin 5-5A and ISO 19901-1

The curves in Figure TR.6.4.2.8.3-1 show parameter values in the directional spreading functions in ISO 19901-1 giving a directional spreading function that is equivalent to the SNAME formulation, with values of the parameter m along the horizontal axis.

Directional spreading functions for $F(\alpha)$ with m = 4, $D_1(\theta)$ with n = 8, $D_2(\theta)$ with s = 15, and $D_3(\theta)$ with σ = 0,34 are shown in Figure TR.6.4.2.8.3-2.

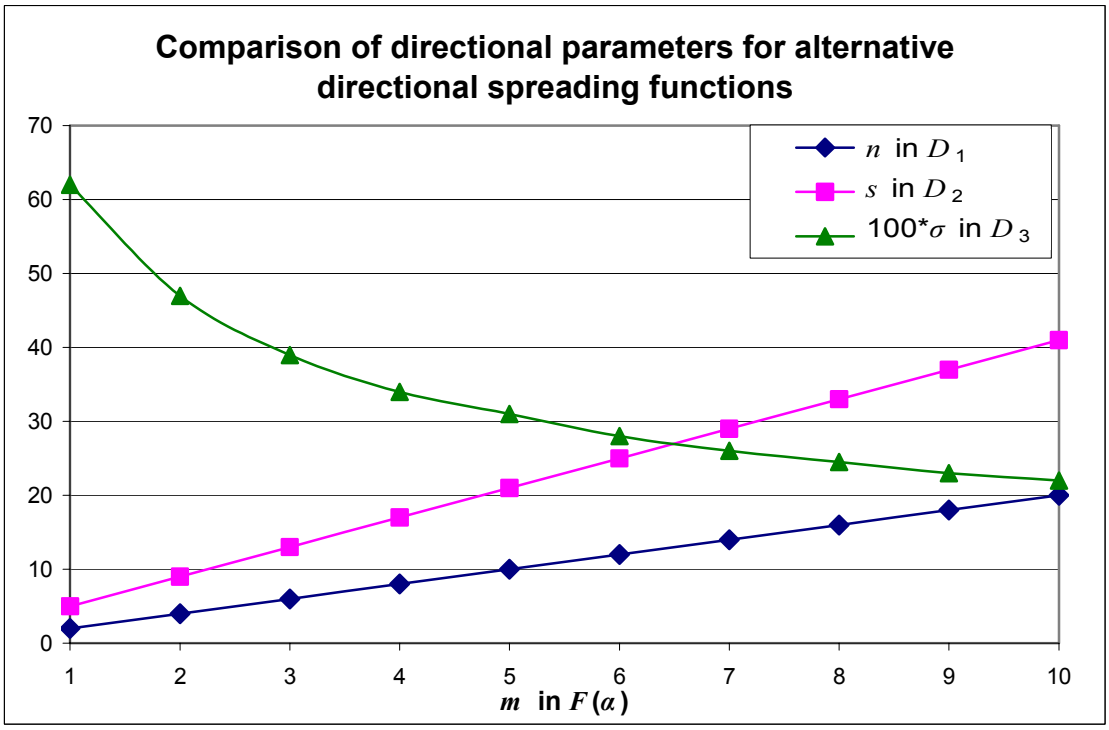

Figure TR.6.4.2.8.3-1 — Comparison of parameters for ISO 19901-1 and SNAME T&R Bulletin 5-5A directional spreading functions

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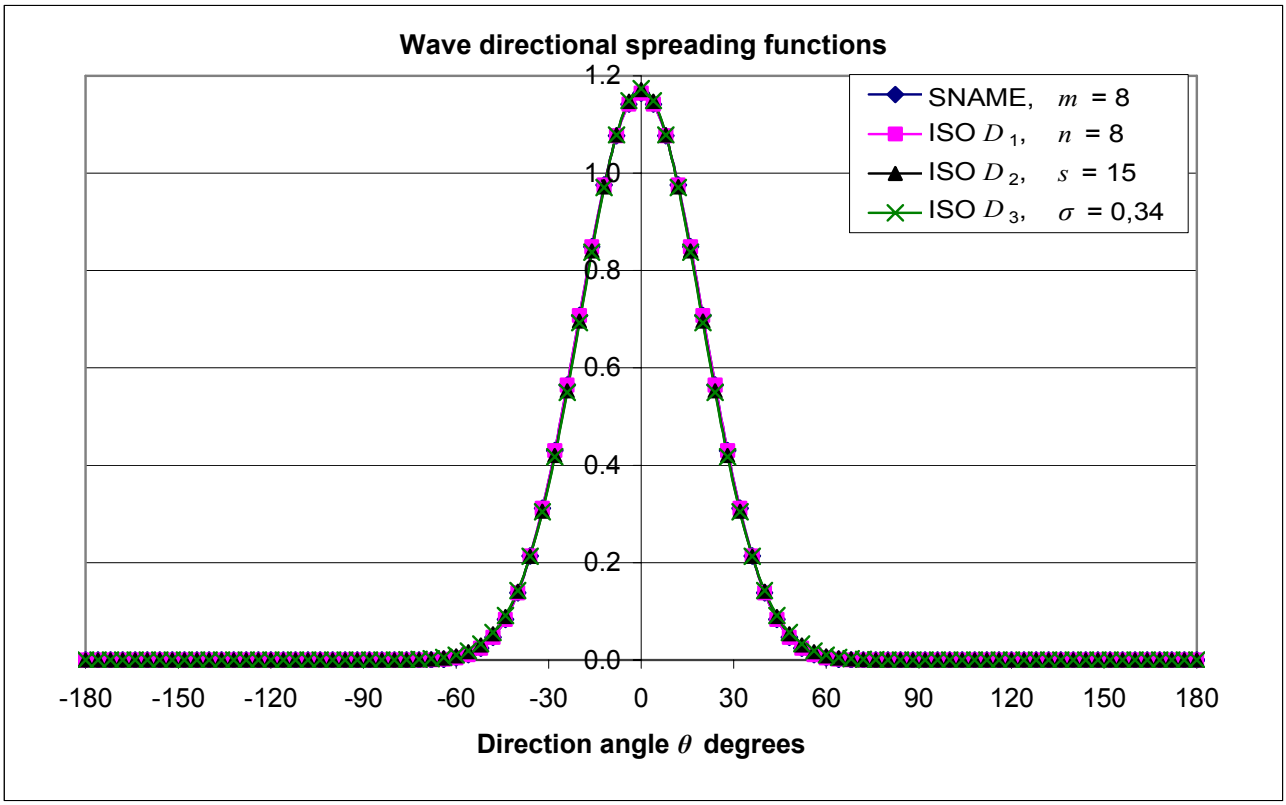

Figure TR.6.4.2.8.3-2 — Comparison of directional spreading functions

TR.6.4.3 Current

According to ISO 19901-1:2005, A.9.3, a power law current profile can be used where appropriate, e.g. in areas dominated by tidal current in shallow waters such as the southern North Sea. The power law exponent is typically 1/7, and stretching of the current profile to the wave crests and troughs when combining with waves is advised.

The profile in ISO 19905-1:2012, A.6.4.3, with constant tidal and surge current speed profile, with addition of linear varying wind-driven current can be applied as a simple and slightly conservative estimate of the current profile. This profile is used as part of the SNAME recipe for jack-up site assessment.

The base shear and overturning moment calculated using the ISO 19901-1 power law profile for tidal current, combined with linear varying wind-driven current have been compared with formulations in ISO 19905-1:2012, A.6.4.3 for a tidal current speed of 1 m/s at sea level and a wind-driven current of 0,3 m/s. The water depth is taken as 100 m. The comparison shows that the base shear is 27 % higher and the overturning moment 13 % higher for the ISO 19905-1:2012, A.6.4.3 formulation than for the ISO 19901-1 power law profile.

Calculations with the above current combined with a wave with a height of 24,3 m and period of 14,7 s, and with stretching of the current and wave profiles to the instantaneous water level, gives a maximum base shear which is 5 % higher and a maximum overturning moment which is 2,3 % higher for the ISO 19905-1:2012, A.6.4.3 formulation than for the ISO 19901-1 power law profile.

Typically, the combined effect current and waves for the ISO 19905-1:2012, A.6.4.3 recipe may be up to 8 % to 10 % on the conservative side compared to the ISO 19901-1 power law profile.

TR.6.4.4 Water depths

ISO 19905-1 references water depths to the lowest astronomical tide (LAT). In some instances the water depth may be referenced to Chart Datum. It is modern practice for these reference levels in hydrographic

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surveys to be the same, however caution should be exercised when using older data or navigation charts and the relation of Chart Datum to LAT should be checked and any necessary corrections applied.

See also ISO 19905-1:2012, A.6.4.2.4 regarding wave heights for airgap determination.

TR.6.4.5 Wind

TR.6.4.5.1 General

ISO 19901-1:2005, A.7.3, specifies a logarithmic function for the vertical variation of the mean wind speed. It is also noted in ISO 19901-1:2005, A.7.3 that the logarithmic equations may be approximated by a power law.

In the ISO 19901-1 equations, the wind speed as function of averaging time and height above mean sea level is defined based on a reference wind speed for an averaging period of 1 h and at 10 m height above mean sea level. From these equations, the following expression for conversion of reference wind speed between different averaging periods at 10 m height above mean sea level can be developed:

$$U_{w,T}(10) = [1 - 0{,}024\,6 \ln(T / 3\,600)]\, U_{w0} - 0{,}001\,058 \ln(T / 3\,600)\, U_{w0}^2 \qquad \text{(TR.6.4-15)}$$

where

$U_{w,T}(10)$ is the sustained wind speed at 10 m height above mean sea level, averaged over a time interval T < 3 600 s;

U_{w0} is the 1 h sustained wind speed at the reference elevation 10 m above mean sea level and is the standard reference speed for sustained winds;

T is the time averaging interval with $T < T_0$ = 3 600 s;

T_0 is the standard reference time averaging interval for wind speed of 1 h = 3 600 s

In case the reference wind speed needed for a 1 min average and the average time for the given wind speed is different from 1 h, e.g. 10 min, the above equation should first be solved to get the 1 h average wind speed. Thereafter the 1 min reference wind speed can be calculated from the equation based on the 1 h average speed.

A comparison of different reference wind speeds as function of the 1 h average speed is shown in Figure TR.6.4.5-1.

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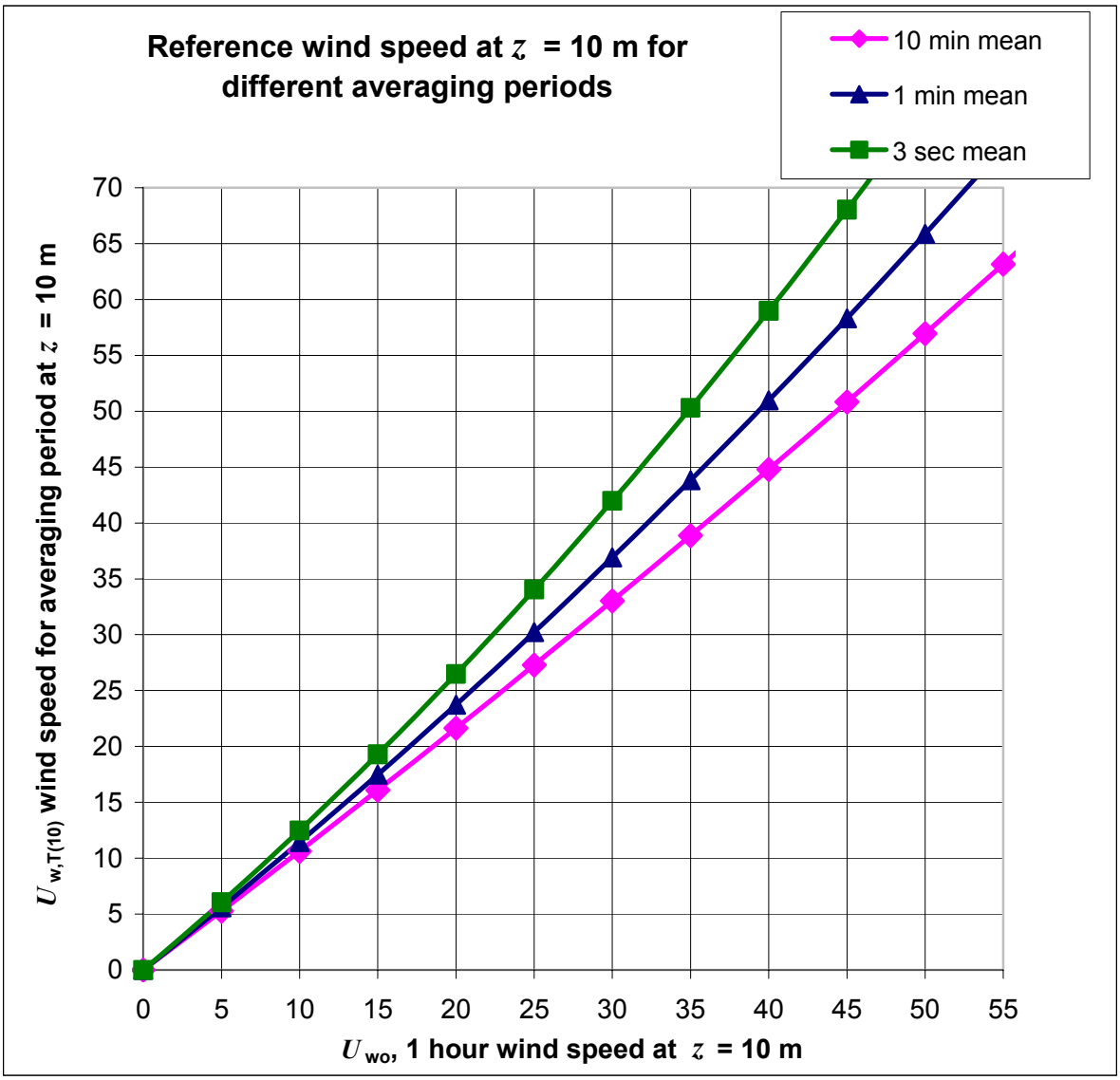

Figure TR.6.4.5-1 — Reference wind speed at z = 10 m for different averaging periods

In ISO 19905-1 the vertical variation of the wind speed may be approximated by a power law based on the 1 min sustained wind for determining the wind loadings on the jack-up.

The effect of the power law approximation compared to the logarithmic formulations of ISO 19901-1 is illustrated in Figure TR.6.4.5-2 and Figure TR.6.4.5-3. Comparisons are made for different values of the 1 min average wind speed at 10 m above mean sea level. It is seen that the power law approximation is slightly on the conservative side. For the most relevant heights, i.e. 20 m to 50 m above sea level, it is seen that the average effect is in the range of 7 % for the 1 min average wind speed at 10 m above sea level, equal to 20 m/s, and 2 % for the 1 min average wind speed at 10 m above sea level, equal to 40 m/s.

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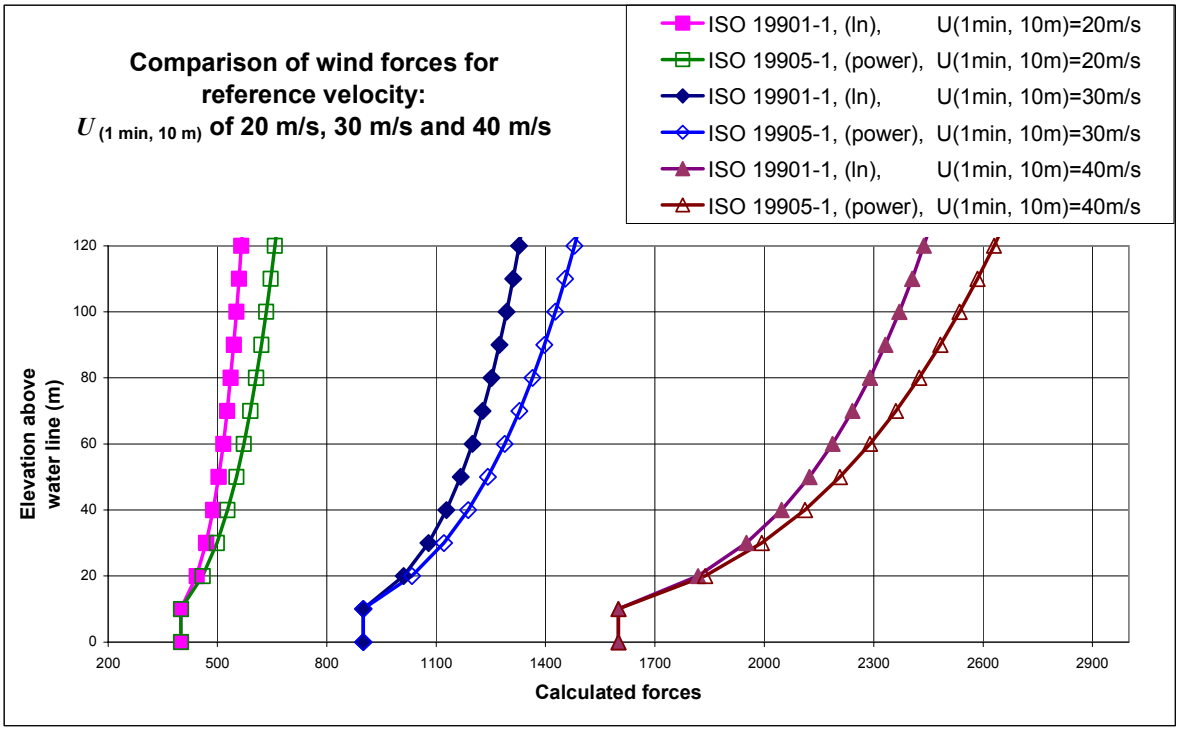

Figure TR.6.4.5-2 — Comparison of wind forces for different $U_{(1min,10m)}$ reference velocities

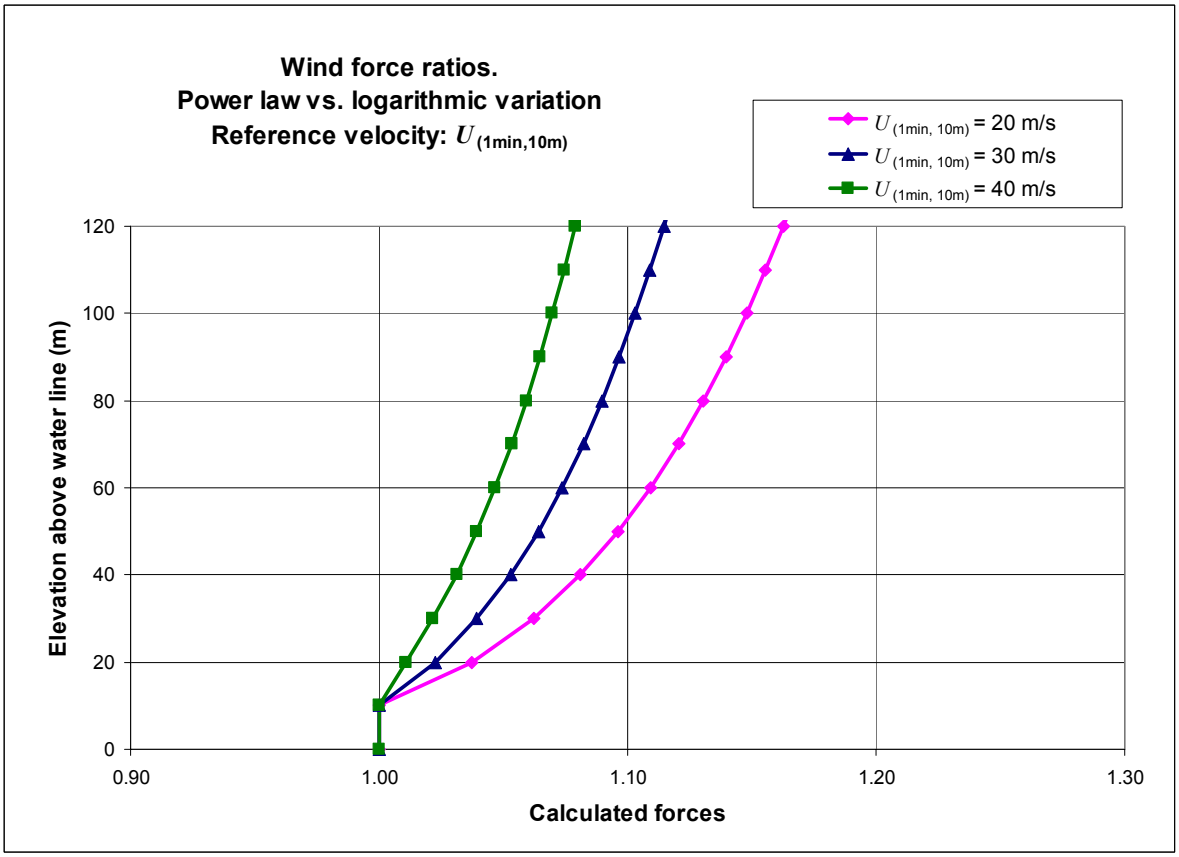

Figure TR.6.4.5-3 — Wind force ratios of power law vs. logarithmic variation for different $U_{(1min,10m)}$ reference velocities

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7 Commentary to ISO 19905-1:2012, Clauses 7 and A.7

TR.7.1 Scope

The main objective of Clause 7 is to provide documentation of the numbers, methods and formulations of ISO 19905-1:2012, A.7.

Clause 7 is limited to considering wind loading on legs and hulls and hydrodynamic forces acting on the legs and appurtenances under the action of waves and current. Typical jack-up leg designs consist of legs with an open lattice frame structure with typical member dimensions of 0,25 m to 1,0 m in diameter, although some may be composed of larger diameter tubular legs. A special feature of most jack-ups is the racks fitted to the chord elements for jacking purposes. The fact that jack-ups are mobile limits marine growth build-up generally, except when jack-ups are deployed in long-term assignments (see ISO 19905-1:2012, Clause 11).

The models, methods and coefficients for computing the forces were considered together in the development of ISO 19905-1:2012, A.7, and represent a consistent method such that the whole clause should be considered in its entirety. This means that no coefficients should be taken from this clause or ISO 19905-1:2012, A.7 unless the corresponding method is applied.

Clause 7 is organized such that the main subclauses have the same numbers as the corresponding subclause in ISO 19905-1. This means that subclause TR.7.2 in this report corresponds to ISO 19905 1:2012, A.7.2 and so on.

TR.7.3.2 Hydrodynamic model

TR.7.3.2.1 General

The hydrodynamic modelling of the leg of a jack-up can be carried out by utilizing either “detailed” or “equivalent” techniques. In both cases the geometric orientation of the elements are accounted for. The hydrodynamic properties are then found as described here.

TR.7.3.2.1.1 Length of members

Lengths of members are normally to be taken as the node-to-node distance of the members, in order to account for small non-structural items.

TR.7.3.2.1.2 Spudcan

A criteria for considering the spudcan is suggested such that the effect of the wave and current forces on the spudcan may normally be neglected at deep water or deep penetrations. However, there may be special cases, e.g. with large spudcans in combination with high currents, that should be considered also outside the suggested criteria.

TR.7.3.2.1.3 Shielding and solidification

Shielding is normally neglected for computations of the hydrodynamic model as presented herein. The shielding is dependent on KC- and Re-numbers. Since it is difficult to quantify shielding, and shielding in waves is less than in constant flow[7-1],[7-2], shielding is neglected. The same criteria are used for solidification as for shielding such that both effects should be considered if advantage is taken due to shielding in wave and current loads.

According to Reference [7-3], shielding should be neglected for $S/D \leq 4$ for an array of elements, where S is the outer diameter of the array and D is the diameter of individual elements. This is also considered in Reference [7-1].

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If information on shielding is obtained from experiments, care should be taken to distinguish between shielding and the effect discussed in ISO 19905-1:2012, A.7.3.3.4. These effects are different but could possibly be confused in tests on small models in large tanks.

Solidification is an increase of wave forces due to interference from objects “side by side” in the flow field. This is normally not included in the hydrodynamic coefficient formulation for jack-ups since shielding is also neglected. Jack-up rigs are usually space frame structures with few parallel elements in close proximity so that this effect is usually not important.

In Reference [7-1] solidification effects are quantified for two elements and for a group of elements. The drag coefficient may increase 100 % if two tubulars are placed side by side, or be reduced for a group of elements, e.g. a conductor array, where shielding is also present.

The effect is less than 10 % in the worst direction and it is therefore suggested that it be omitted in ISO 19905-1, when:

$$A_s/A_t < 0{,}5 \qquad \text{(TR.7.3-1)}$$

where

A_s is the sum of projected areas for all members in the considered plane;

A_t is the total projected envelope area of the considered plane.

Solidification should be considered if shielding is included.

TR.7.3.2.2 “Detailed” leg model

All relevant members are modelled with their own unique descriptions for the Morison term values and with correct orientation to determine v_n , $\dot{u}_n$ and $\ddot{r}_n$ and the corresponding drag coefficient times diameter $C_D D = C_{Di} D_i$ and inertia coefficient times sectional area $C_M A = C_{mi} \pi D_i^2/4$, as defined in ISO 19905-1:2012, A.7.3.2.4.

TR.7.3.2.3 “Equivalent” leg model

The hydrodynamic model of a bay is comprised of one “equivalent” vertical tubular to be located at the geometric centre of the actual leg. The corresponding (horizontal) v_n , $\dot{u}_n$ and $\ddot{r}_n$ are to be applied with equivalent $C_D D = \sum C_{De} D_e$ and $C_M A = \sum C_{Me} A_e$, given in ISO 19905-1:2012, A.7.3.2.3. The model should be varied with elevation, as necessary, to account for changes in dimensions, marine growth thickness, etc.

TR.7.3.2.3.1 Equivalent drag coefficient

In order to comprise the information on drag forces for individual members of a lattice leg into an equivalent vertical member over the bay length s, a fixed diameter and a directional dependent drag coefficient is specified. This model accounts for the geometrical orientation of the individual members. In this model the principle of no shielding and no blockage is assumed.

The equivalent diameter is recommended such that the inertia coefficient normally follows without any further computations. The equivalent value of the drag coefficient, C_{De}, times the equivalent diameter, D_e, is specified. If another reference diameter D_e is preferred, the product of $C_{De} D_e$ should in any case be equal to that specified in ISO 19905-1:2012, A.7.3.2.3. The expression for C_{Dei} may be simplified for horizontal and vertical members as follows:

— vertical member (e.g. a chord) : $C_{Dei} = C_{Di}\,(D_i/D_e)$ (TR.7.3-2)

— horizontal member : $C_{Dei} = \sin^3\alpha_i\, C_{Di}\,(D_i l_i/D_e s)$ (TR.7.3-3)

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TR.7.3.2.3.2 Equivalent inertia coefficient

The equivalent value of the inertia coefficient, C_{Me}, and the equivalent area, A_e, to be used in ISO 19905-1:2012, A.7.3.3.2, represent the C_{MA} chosen as:

C_{Me} may normally be taken as equal to 2,0 when using A_e

= 1,0 for flat plates (brackets);

A_e is the equivalent area of leg per unit height = $(\Sigma A_i l_i)/s$;

A_i is the equivalent area of element = $\pi D_i^2/4$;

D_i is the reference diameter as defined in ISO 19905-1:2012, A.7.3.2.4.

The reference diameters D_i and corresponding area of member A_e are chosen such that the use of an inertia coefficient C_{Me} = 2,0 or C_{Me} = 1,0 is consistent with the inertia forces for chords and brackets respectively. A conservatism is present since the inertia coefficient for rough tubulars is set to 1,8 and there is no reduction of forces for inclined members. For normal lattice leg designs the conservatism will not play any significant role as the drag forces are dominant. The inertia force will also be dominated by chords due to their larger diameter, such that the conservatism is judged to be insignificant for extreme wave forces.

If, however, a more accurate model is wanted, an alternative is given using the individual member inertia coefficients, as specified in ISO 19905-1:2012, A.7.3.2.4, and including the effect of inclined members. The equivalent inertia coefficient C_{Me} is then determined by the summation shown in ISO 19905-1:2012, A.7.3.2.3. This model is in closer agreement with the “detailed model”. It should be stressed that the coefficients must be defined together with their reference dimensions D_i.

As comments to this formulation the following may be observed:

— for horizontal members with flow along the length axis, the inertia coefficient is:

C_{Mei} = 1,0

— for a vertical rough tubular, the inertia coefficient will be:

C_{Mei} = 1,8

— for other vertical members, the inertia coefficient will be:

C_{Mei} = 2,0

— for other flat plates (brackets), the inertia coefficient will be:

C_{Mei} = 1,0

TR.7.3.2.4 Drag and inertia coefficients

TR.7.3.2.4.1 General

The coefficients determined herein are based on tests where the particle velocities and accelerations are measured simultaneously with the forces, usually in a controlled environment. This is the logical way to determine the loading coefficients. However, the important result in engineering is the overall forces predicted by the Morison's equation over the jack-up legs. Since some wave theory has to be applied, which does not perfectly predict the wave particle motions in all cases, additional scaling is suggested in ISO 19905-1:2012, A.6.4.2 (see also Appendix TR.7.B). This is important to consider when reading this chapter as the stated coefficients can differ from those applied in other recommendations or classification rules.

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TR.7.3.2.4.2 Hydrodynamic coefficients for tubulars

TR.7.3.2.4.2.1 General

There exists a wealth of data on hydrodynamic coefficients (drag and inertia coefficients) for tubulars, mainly from model tests. A number of model tests have been performed in wind tunnels, others in oscillating water environments or in steady water flow, while (to our knowledge) only a few model tests have been performed in a wave environment. In addition, a few full-scale tests have been reported.

In the following section an overview is given of the literature that has been applied for the purpose of recommending values for the hydrodynamic coefficients of jack-up platforms.

Before choosing the appropriate hydrodynamic coefficients for tubular parts of jack-up platforms, the following questions have to be answered:

— Are the coefficients to be used for a fatigue analysis or an ultimate strength analysis?

— Are the tubular parts smooth or rough and, if they are rough, what is the roughness to be applied?

The parameters to be considered in determining the hydrodynamic coefficients are as follows:

Keulegan-Carpenter number $$KC = \frac{U_m T}{D} \quad \text{(TR.7.3-4)}$$

Reynolds number $$Re = \frac{UD}{\nu} \quad \text{(TR.7.3-5)}$$

Relative roughness $$= \frac{k}{D} \quad \text{(TR.7.3-6)}$$

where

k is the roughness height;

D is the diameter;

U_m is the maximum orbital particle velocity;

T is the wave period;

U is the flow velocity at the depth of the considered element;

ν is the kinematic viscosity of water ($\nu \approx 1{,}4 \times 10^{-6}$ m^2/s, t = 10°C).

Concerning the first question above, it is important to determine the range of Reynolds numbers and Keulegan-Carpenter numbers of interest. Both the drag coefficient C_D and the inertia coefficient C_M are dependent on the Reynolds number and the Keulegan-Carpenter number. In the ultimate strength case one is interested in the C_D and C_M coefficients in relatively long and steep waves, i.e. wave steepness $S = H_s/\lambda$ in the range 1/10-1/15. A typical ultimate strength case may be, for example, a tubular with diameter D = 0,3 m standing in a seastate with average zero-upcrossing period T_z = 10 s (λ = 156 m) and significant wave height H_s = 13,0 m. The representative water particle velocity for this wave will be:

$$U_W = \frac{H_s \pi}{T_z} = 4{,}1 \text{ m/s.}$$

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Assuming a current velocity U_C of about 1,0 m/s, the total water particle velocity will be $U = U_W + U_C$ = 5,1 m/s. This results in the following Reynolds number and Keulegan-Carpenter numbers (close to the water surface):

$$Re = \frac{UD}{\nu} = 1{,}1 \times 10^6 \qquad KC = \frac{UT_z}{D} = 170$$

This means that in the ultimate strength case we are dealing with high KC-numbers and post-critical Re-numbers. Sarpkaya (see for example Reference [7-4]) uses a parameter $\beta = Re/KC$ to describe the test environment. In the ultimate strength environment described above, the value of β is approximately 6 500.

A typical fatigue case may, for example, be the same tubular in a seastate with T_z = 6 s. (λ = 56 m) and H_s = 5,6 m. In this case the representative water particle velocity will be $U_W = H_s\pi/T_z$ = 2,9 m/s. In the fatigue case, current is not part of the water particle velocity which is to be applied. This results in the following Reynolds number and Keulegan-Carpenter number (close to the water surface):

$$Re = 0{,}62 \times 10^6 \qquad KC = 58$$

This means that post-critical Re-numbers and relatively high KC-numbers are also to be dealt with in the fatigue case. Sarpkaya's β-parameter has a value β = 10 860 for the described fatigue case.

It may be concluded that, in general, for jack-up tubulars, the following ranges of Re-numbers and KC-numbers will be of interest:

— Re-numbers: ultimate strength, roughly from $Re \approx 1{,}0 \times 10^6$ to $4{,}5 \times 10^6$

fatigue, roughly from $Re \approx 0{,}5 \times 10^6$ to $1{,}0 \times 10^6$

— KC-numbers: ultimate strength, $KC > 100$

fatigue, $KC \approx 25$ to 60

Since quite a large amount of the literature survey is dealing with papers written by Sarpkaya, the following range of Sarpkaya's β-parameter may be regarded to be of interest: $\beta \approx$ 6 000 to 20 000 (depending on the KC-number).

The answer to the second question concerning the roughness of the tubulars depends largely on the type of paint used and the smoothness of the steel surface, whether the tubular is new or has been in the water for quite some time (marine growth), or whether the tubular mainly stays in air, etc.

Smooth cylinders are defined as cylinders having a roughness of k/D < 0,000 1, while rough cylinders are assumed to have a roughness of k/D > 0,004 (i.e. highly rusted steel $k/D \approx$ 0,005 to 0,01). Marine roughness due to marine growth implies a roughness in the range $k/D \approx$ 0,01 to 0,15.

TR.7.3.2.4.2.2 Literature survey and recommended values

Table TR.7.3.2.4-1 presents the result of a survey of relevant literature with respect to inertia coefficients (C_M) and drag coefficients (C_D) for tubulars. Of course, there exists more relevant literature than that presented in Table TR.7.3.2.4-1, but it should give a reasonably representative overview.

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Table TR.7.3.2.4-1 — Survey of relevant literature on C_M and C_D values for tubulars

Source	Geometric shape	*Re*-number	*KC*-number	C_D	C_M	Comments
Keulegan Carpenter 1958[7-5]	Smooth Cylinder	0,1-0,3 10^5 0,1 10^5	25-50 >100	1,3-1,5 1,0-1,2	1,3-1,8 2,4-2,6	Sub-Critical and Critical Flow. Low *Re*-numbers.
Sarpkaya 1976[7-6]	Smooth Cylinder	>0,5 10^6 >0,7 10^6	20-40 60-100	0,6-0,7 0,6-0,7	1,7-1,8 1,7-1,9	Post-Crit. Oscillating Flow.
Sand Roughened	Rough Cylinders k/D = 0,005 k/D = 0,01 k/D = 0,02	>0,5 10^6	20-40	1,5-1,7 1,6-1,8 1,7-1,9	1,2-1,4 1,2-1,4 1,1-1,3	Post-Crit. Oscillating Flow.
Sand Roughened	Rough Cylinders k/D = 0,005 k/D = 0,01 k/D = 0,02	>0,5 10^6	60-100	1,4-1,6 1,5-1,6 1,6-1,7	1,5-1,7 1,4-1,6 1,4-1,6	Post-Crit. Oscillating Flow.
Hogben et al. 1977[7-7] Survey Paper State of the Art	Smooth Cylinder Rough Cylinders k/D = 0,000 2 k/D = 0,002 k/D = 0,01 k/D = 0,05	>1,0 10^6 >1,0 10^6 >0,5 10^6 >0,5 10^6 >0,1 10^6	>25 >25 >25 >25 >25	≈0,6 0,6-0,7 ≈1,0 ≈1,0 ≈1,25	≈1,5	Post-Crit. Flow. Post-Crit. Flow.
Sarpkaya et al. 1982[7-4]	Smooth Cylinder Rough Cylinder k/D = 0,01	>0,1 10^6 >0,1 10^6	25-40 25-40	0,6-0,8 1,5-1,7	1,5-1,7 1,0-1,2	Critical - Super-Crit. Oscillating Flow. β = 4 000.
Sarpkaya et al. 1984[7-8]	Smooth Cylinder Rough Cylinder k/D = 0,01	≈0,1 10^6 ≈0,15 10^6 ≈0,1 10^6 ≈0,15 10^6	25-40 60 25-40 60	0,7-0,8 0,6-0,65 1,4-1,5 1,4-1,5	1,5-1,7 1,5-1,6 1,4-1,6 1,5-1,6	Critical - Super-Crit. Oscillating Flow. β = 2 500.
Sarpkaya et al. 1985[7-9]	Rough Cylinder k/D = 0,01	0,1-0,2 10^6 ≈0,21 10^6	25-40 50	1,4-1,5 1,4-1,5	1,0-1,3 1,2-1,3	Critical - Super-Crit. Oscillating Flow. β = 4 200.
According to Sarpkaya, available data with current and oscillatory flow substantiate the fact that drag coefficients obtained from tests at sea in general will be smaller than those obtained under laboratory conditions.						
Sarpkaya 1985[7-10]	Smooth Cylinder	0,2-0,3 10^6	20-25	0,6-0,7	1,6-1,8	Super-Crit. Oscillating Flow. β = 11 240.

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Source	Geometric shape	*Re*-number	*KC*-number	C_D	C_M	Comments
Sarpkaya 1985[7-11], 1986[7-12] Survey Articles	Smooth Cylinder Rough Cylinder k/D = 0,02	>0,5 10^6 >0,5 10^6 >0,5 10^6 >0,5 10^6	25-40 >50 25-40 >50	0,6-0,8 0,6-0,7 1,4-1,8 1,4-1,6	1,5-1,8 1,6-1,8 1,2-1,4 1,3-1,5	Post-Crit. Oscillating Flow.
Nath 1982[7-13]	Smooth Cylinder Rough Cylinder k/D = 0,02 k/D >0,1 Smooth Cylinder Rough Cylinder k/D = 0,02 k/D >0,1	≈0,5 10^6 ≈0,5 10^6 ≈0,5 10^6 0,15-0,2 10^6 0,15-0,2 10^6 0,15-0,2 10^6	∞ ∞ ∞ 15-25 15-25 15-25	0,4-0,5 0,9-1,0 1,0-1,2 0,3-0,6 0,6-1,0 1,0-2,0	 0,8-1,4 0,4-1,0 0,8-2,3	Super-Crit. Steady Flow. Post-Crit. Steady Flow. Super-Crit. Oscillating Flow.
There is very large scatter in the data presented by Nath.						
Bearman et al. 1985[7-14]	Smooth Cylinder	0,15-0,5 10^6	≈20	0,6-0,7	1,4-1,5	Super/Post-Crit. Flow, Regular Waves.
The authors present results for random waves as well, but it is difficult to draw any conclusion from these results.						
Kasahara et al. 1987[7-15]	Smooth Cylinder Rough Cylinder k/D = 0,008 3 k/D = 0,004 2	0,5-1,0 10^6 0,5-1,0 10^6 0,5-1,0 10^6	20-40 20-40 ≈50 20-40 ≈50	0,5-0,6 1,1-1,4 1,1-1,2 0,9-1,3 0,9-1,1	1,6-1,8 1,3-1,7 1,6-2,3 1,3-2,1 1,6-2,1	Post-Crit. Oscillating Flow. Large Scatter in C_M-values.
Chaplin 1988[7-16]	Smooth Cylinder	≈0,2 10^6	≈20	0,6-0,7	1,4-1,5	Super/Post-Crit. Oscillating Flow.
Davies et al. 1990[7-17]	Smooth Cylinder Smooth Cylinder	>0,5 10^6 >0,5 10^6	≈20 ≈18	0,6-0,7 0,5-0,7	1,5-1,6 1,5-1,7	Post-Crit. Flow, Reg. Waves. Post-Crit. Flow. Random Waves.
The authors conclude that for smooth cylinders and KC > 4, drag and inertia coefficients in periodic waves may be used to represent average C_D and C_M values in random waves						

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Source	Geometric shape	*Re*-number	*KC*-number	C_D	C_M	Comments
Rodenbusch et al. 1983[7-18]	Smooth Cylinder Rough Cylinder *k*/*D* = 0,02	>1,0 10^6 >1,0 10^6	∞ ∞	≈0,6 0,9-1,1		Post-Crit. Steady Flow (Steady Tow).
	Smooth Cylinder Rough Cylinder *k*/*D* = 0,02	>1,0 10^6 >1,0 10^6	>30 >30	0,6-0,7 1,4-1,5	1,6-1,7 1,1-1,3	Post-Crit. Oscilla-ting Flow (Forced Motion).
	Smooth Cylinder Rough Cylinder *k*/*D* = 0,02	>1,0 10^6 >1,0 10^6	20-40 20-40	0,6-0,8 1,0-1,8	1,4-2,0 1,0-1,9	Post-Crit. Random Flow (Forced Motion).
	Smooth Cylinder Rough Cylinder *k*/*D* = 0,02	>1,0 10^6 >1,0 10^6	60-90 60-90	0,6-0,8 1,1-1,4	1,5-1,7 1,0-1,4	Post-Crit. Random Flow (Forced Motion).
The random tests show a relatively large spread, especially for the lower *KC*-numbers (20-40).						
Rodenbusch et al. 1986[7-19]	Smooth Cylinder Rough Cylinder *k*/*D* >0,000 5	>1,0 10^6 >0,5 10^6	>60 >60	0,65-0,75 1,1-1,3	1,5-1,7 1,1-1,5	Post-Crit. Random Flow (ForcedMotion).
Theophanatos et al. 1989[7-20]	Rough Cylinder *k*/*D* = 0,005 *k*/*D* = 0,0095 *k*/*D* = 0,025	>0,8 10^6		0,95-1,05 1,0-1,1 1,15-1,25	=>	Post-Crit. Steady Flow (Steady Tow). Sand Rough.
	k/*D* = 0,049 *k*/*D* = 0,098			1,15-1,25 1,3-1,4	=>	Pyramids
	k/*D* = 0,067			1,2-1,3	=>	Mussels
Klopman et al. 1990[7-21]	"Rough" Cylinder *k*/*D* = 0,000 12	≈0,5 10^6	≈15	0,6-0,9	1,3-1,6	Post-Crit. Random Waves.
Heideman et al. 1979[7-22]	Smooth Cylinder	>0,2 10^6 >0,2 10^6	15-30 >30	0,5-1,2 0,6-0,8	1,2-1,9	Post-Crit. Random Waves. Ocean Test Structure.
	Rough cylinder *k*/*D* ≈0,03-0,05	>0,2 10^6 >0,2 10^6	15-30 >30	0,9-1,8 0,8-1,3	0,9-1,7	
Large spread for lower *KC*-numbers (<30). Authors state that for large *KC*-numbers (>30), smooth cylinder C_D approaches an asymptote C_D = 0,68, while rough cylinder C_D approaches an asymptote C_D = 1,0. Tests performed in an ocean environment.						
Nath 1988[7-23]	Rough Cylinder Barnacles: *k*/*D* = 0,073 *k*/*D* = 0,104		∞ ∞	0,95 0,98-1,2		Post-Crit. Steady Flow. .

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Source	Geometric shape	*Re*-number	*KC*-number	C_D	C_M	Comments
Wolfram & Theophanatos 1990[7-24]	Artificial Hard Fouling: k/D = 0,078		∞	0,98-1,2		Post-Crit. Steady Flow.
	Rough Cylinder Mussels: k/D = 0,075 k/D = 0,085		∞ ∞	1,22 1,26		Post-Crit. Steady Flow.
	Mixed Hard Fouling: k/D = 0,076		∞	1,11		
	Kelp: k/D = 1,25 k/D = 2,5		∞ ∞	1,51 1,69		
	Sea Anemones: k/D = 0,16		∞	1,35		
Roshko 1961[7-25]	Smooth Cylinder	>3,5 10^6	∞	0,65-0,75		Post-Crit. Steady Flow Wind Tunnel.
Miller 1976[7-26]	Smooth Cylinder	>3,0 10^6	∞	0,60-0,65		Post-Crit. Steady Flow Wind Tunnel.
Sand Roughened	Rough Cylinder k/D = 0,000 4 k/D = 0,000 9 k/D = 0,001 4 k/D = 0,002 1 k/D = 0,003 1 k/D = 0,005 0	>3,0 10^6	∞ ∞ ∞	≈0,80 0,8-0,9 0,8-0,9 0,9-1,0 1,0-1,1 1,0-1,1		Post-Crit. Steady Flow Wind Tunnel
Pearl Barley	k/D = 0,015 k/D = 0,023 k/D = 0,044	>0,5 10^6		≈1,1 ≈1,1 1,1-1,2		
Dried Peas	k/D = 0,042 k/D = 0,063	>0,5 10^6		1,1-1,2 1,2-1,4		
Pearcey et al. 1982[7-27]	Smooth Cylinder	>3,5 10^6	∞	≈0,6		Post-Crit. Steady Flow Wind Tunnel
	Rough Cylinder k/D = 0,000 4 k/D = 0,001 4 k/D = 0,0028	>2,0 10^6	∞	≈0,8 ≈0,88 ≈0,92		

In addition to the literature review presented in Table TR.7.3.2.4-1, an interesting and useful overview of existing literature is presented in a survey report prepared by Advanced Mechanics Engineering Limited for the Health and Safety Executive[7-28].

The literature review presented in Table TR.7.3.2.4-1 shows that the test results at different facilities agree reasonably well with respect to the drag coefficients for smooth cylinders in post-critical flow. The majority of tests show C_D values between 0,6 and 0,7, both for the lower KC range for fatigue (25 to 60) and the higher KC range for ultimate strength. The suggested C_D value for smooth tubular elements (k/D < 0,000 1) in post-critical flow is therefore chosen to be C_D = 0,65.

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For rough cylinders, the spread between the individual tests with respect to C_D values is considerably larger. Especially Sarpkaya[7-6] operates with very high post-critical C_D values for rough cylinders. It should be noted that none of the values obtained by the other authors referenced in Table TR.7.3.2.4-1 support the Sarpkaya values in the post-critical region. The differences between individual tests may partly be due to the different types of post-critical flow (different test conditions) and to the non-uniform definition of roughness used by the different authors.

One should also bear in mind that the wave particle velocities decrease with increasing depth below the water surface, which might mean a transition from the post-critical regime to the super-critical or even critical regime. This will result in a reduction in C_D values for smooth cylinders (although in the lower Re-number part of the critical regime it may result in an increase in C_D values, but here the water particle velocities are so low that the resulting contribution to the overall drag force will be significantly smaller than the contributions higher up on the cylinder). For rough cylinders the critical regime occurs at lower Re-numbers and there is no reduction in the drag coefficient in the super-critical regime. For large roughnesses an increase in the drag coefficient has in fact been reported in this regime[7-7],[7-35].

Based on the literature survey presented in Table TR.7.3.2.4-1 and the discussion above, the drag coefficient for rough cylinders (roughness k/D > 0,004) is chosen as equal to C_D = 1,0, both for the ultimate strength and the fatigue cases.

TR.7.3.2.4.2.3 Marine growth dependence

Rust and hard marine growth has been found to behave in essentially the same manner as artificial hard roughness, but a surface with hard marine growth behaves quite differently from a surface with soft marine growth. Another point of consideration is that different types of marine growth on a submerged tubular may dominate at different depths below the sea surface.

The use of anti-fouling coating will at least delay the development of marine growth but after a few years the anti-fouling coating becomes less effective. Regular cleaning of the tubulars is another possible way to limit the development of marine growth. In ISO 19905-1:2012, A.7.3.2, Table A.7.3-3, it is assumed that severe marine growth is not allowed. This is in accordance with the operational profile of mobile jack-up rigs, with cleaning of legs at intervals preventing severe marine growth.

The main contribution to forces is in the surface region, such that the extension of the marine growth below the surface zone is not important for the overall forces. The paint will in addition be somewhat roughened when exposed to the salt water for a longer period. Above the marine growth region, the use of values for a smooth cylinder has been recommended. This is mainly based on the fact that the marine growth will be limited to the region below MSL + 2 m, limiting the roughness above this region.

In addition, measurements also indicate that the wave forces in ocean waves are less than predicted by use of a constant C_D [7-30],[7-31]; see also Figure TR.7.3.2.4-1

Based on this, it is recommended that the value C_D for a smooth surface (C_D = 0,65) generally be used for the legs above MSL + 2 m and the value for a rough surface below MSL + 2 m (C_D = 1,0), as stated in ISO 19905-1:2012, Table A.7.3-2.

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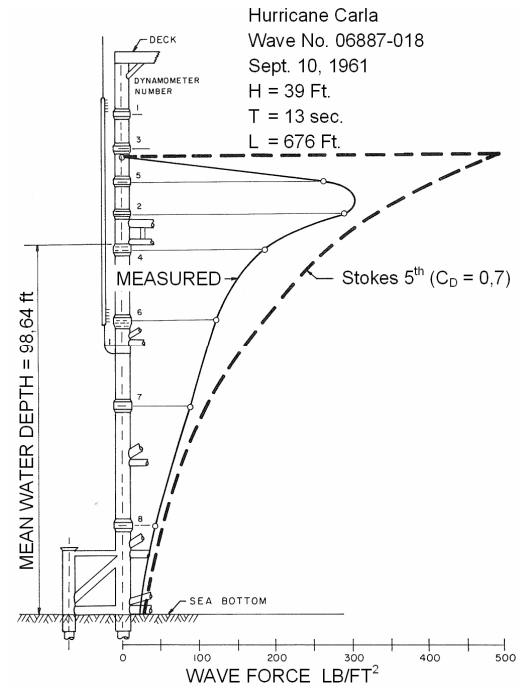

Figure 1 — TR.7.3.2.4-1 Comparison between measured and computed forces on a pile up to free surface[7-30],[7-31]

TR.7.3.2.4.2.4 Definition of relevant parameters

The drag coefficient (C_D) for tubulars may be considered as a function of roughness (k/D), Keulegan-Carpenter number (KC) and Reynolds number (Re) as an alternative to ISO 19905-1:2012, Table A.7.3-2. This explicit dependence is intended to be used in cases where there is more detailed knowledge, first of all on the roughness and in addition on the flow conditions around the members at a specific site. A definition of these governing parameters are included in subclause TR.7.3.2.4.2.

TR.7.3.2.4.2.5 Dependence on roughness

The roughness may be accounted for explicitly if the roughness is documented to be of an intermediate value compared with the smooth and rough k/D values assumed above. Recommended values for the roughness, k, may be found from Table TR.7.3.2.4-2.

Table TR.7.3.2.4-2 — Recommended roughness values for tubulars[7-1]

Surface	k (m)
Steel, new uncoated	5,0E-5
Steel, painted	5,0E-6
Steel, highly rusted	3,0E-3
Marine growth	5,0E-3 to 5,0E-2

Several authors have presented, in graphical form, the C_D dependence on the relative roughness k/D at post-critical Re-numbers. Figure TR.7.3.2.4-2 presents a graph from Miller[7-26], showing the variation of C_D with varying k/D based on several model experiments at post-critical Re-numbers. Figure TR.7.3.2.4-3 and Figure TR.7.3.2.4-4 show similar graphs presented by, respectively, Wolfram et al[7-24] and Pearcey et al[7-32]. Based on the available data with respect to the dependence of C_D on k/D, the expressions presented in Equation (TR.7.3-7) have been proposed to describe this dependence for the purposes of ISO 19905-1. The drag coefficient C_{Di} may then be obtained from Equation (TR.7.3-7):

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$$C_{Di(k/D)} = \begin{cases} C_{Dsmooth} = 0{,}65 & ; \quad k/D < 0{,}000\,1 \\ C_{Dsmooth} = 0{,}65\left[2{,}36 + 0{,}34\log_{10}(k/D)\right] & ; \quad 0{,}000\,1 < k/D < 0{,}004 \\ C_{Drough} = 1{,}0 & ; \quad 0.004 < k/D \end{cases} \qquad \text{(TR.7.3-7)}$$

A graphic representation of Equation (TR.7.3-7) is shown in Figure TR.7.3.2.4-5. With respect to the inertia coefficients for smooth cylinders, all the references from Table TR.7.3.2.4-1 report post-critical C_M values lower than the asymptote C_M = 2,0. The C_M values lie mainly in the range 1,6 to 1,7. However, the question is whether (in general) some inertia contribution has been included in the drag forces used for the C_D determination. This would mean that the C_D values are slightly overestimated and the C_M values slightly underestimated. At the same time, since both fatigue and ultimate strength imply Keulegan-Carpenter numbers > 25, it is the drag dominated region which is of most interest and the chosen C_M values are not really critical. Based on this argument, the inertia coefficient for smooth cylinders in the post-critical regime is set equal to the asymptotic value C_M = 2,0.

The C_M values for rough cylinders, are in general reported to be slightly lower than the C_M values for smooth cylinders. Based on the same argument as used for the smooth cylinders, the inertia coefficient for rough cylinders in the post-critical regime is set equal to C_M = 1,8.

A summary of the recommended values for the hydrodynamic coefficients for tubulars is given in Table TR.7.3.2.4-3.

Table TR.7.3.2.4-3 — Recommended hydrodynamic coefficients for tubulars

Tubular	C_{Di}	C_{Mi}
Smooth (k/D<0,000 1)	0,65	2,0
Rough (k/D>0,004)	1,00	1,8
Intermediate k/D	Equation 4.7.1	2,0

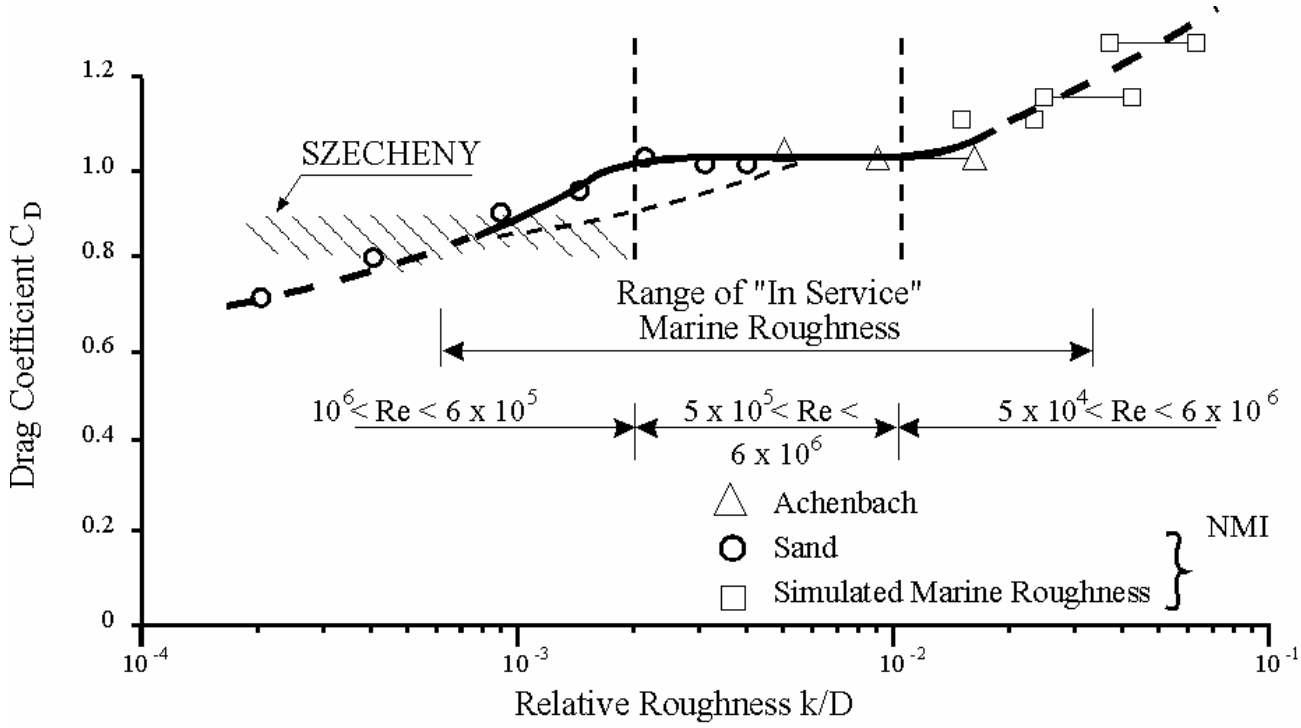

Figure TR.7.3.2.4-2 — Drag coefficient for rough cylinders at high Reynolds number[7-26]

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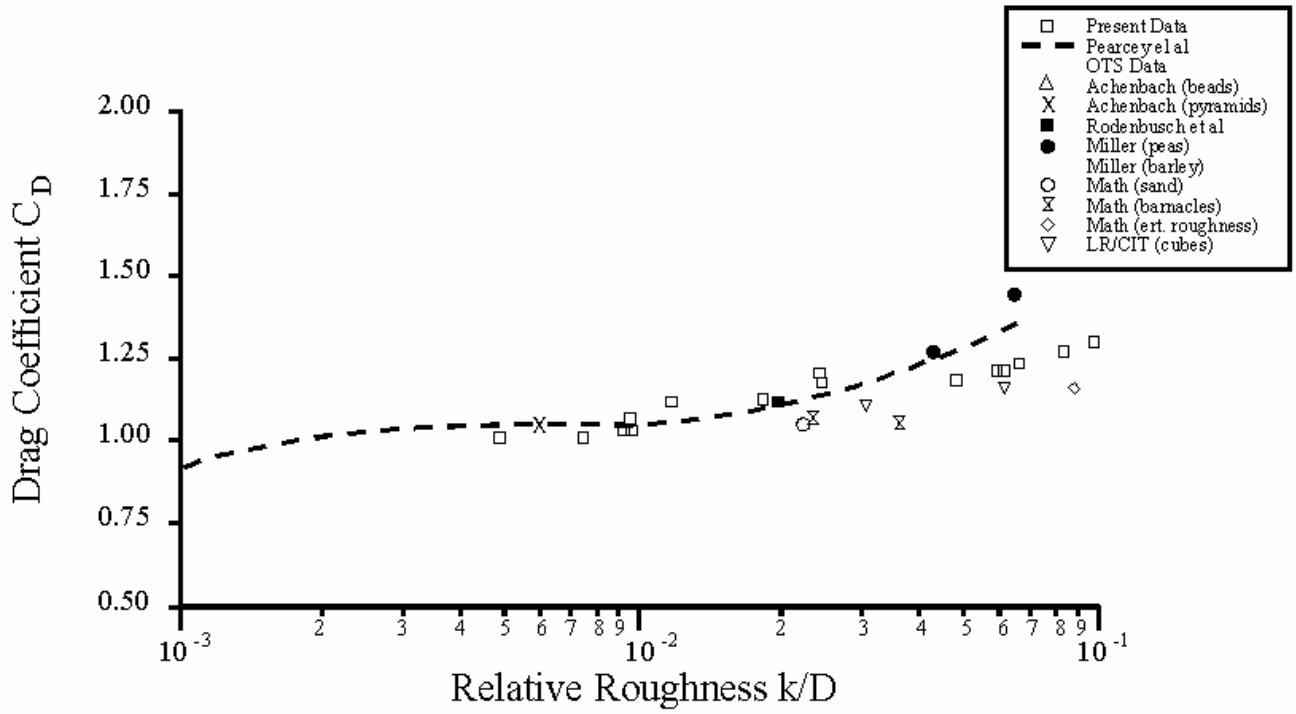

Figure TR.7.3.2.4-3 — Drag coefficient for post critical Reynolds numbers for rough cylinders[7-24]

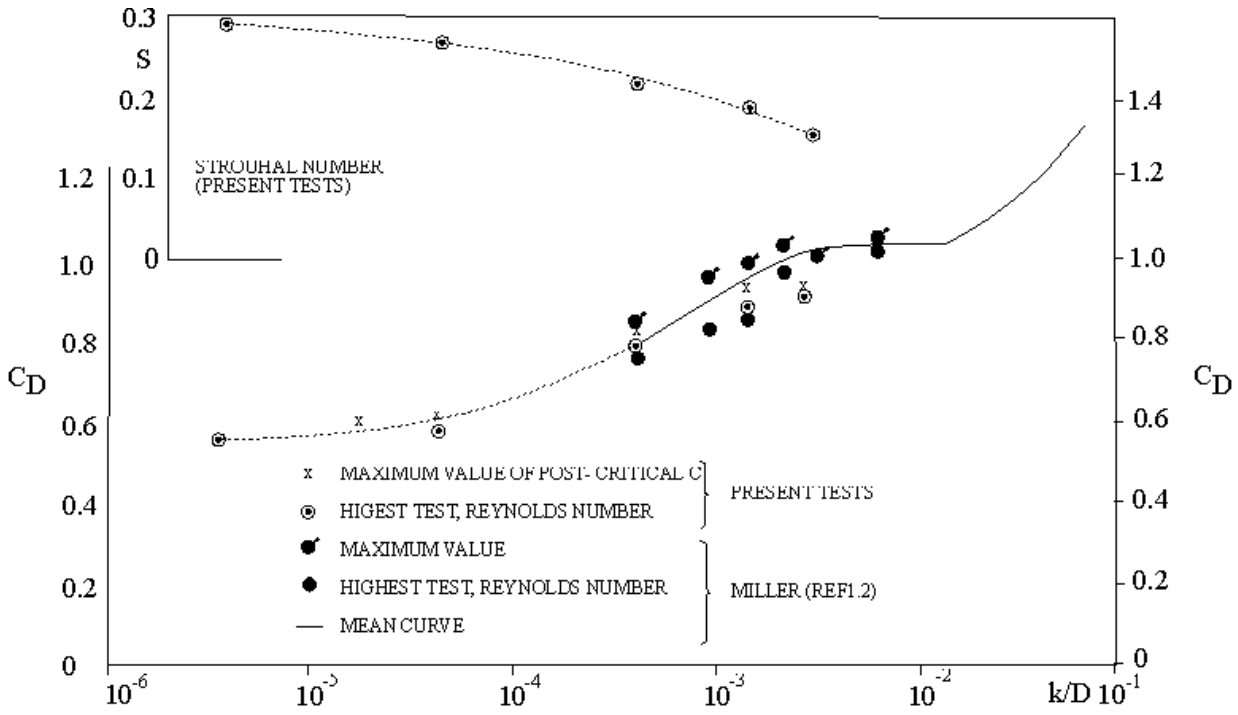

Figure TR.7.3.2.4-4 — Effect of roughness on drag coefficient and vortex shedding frequency for post-critical Reynolds numbers[7-32]

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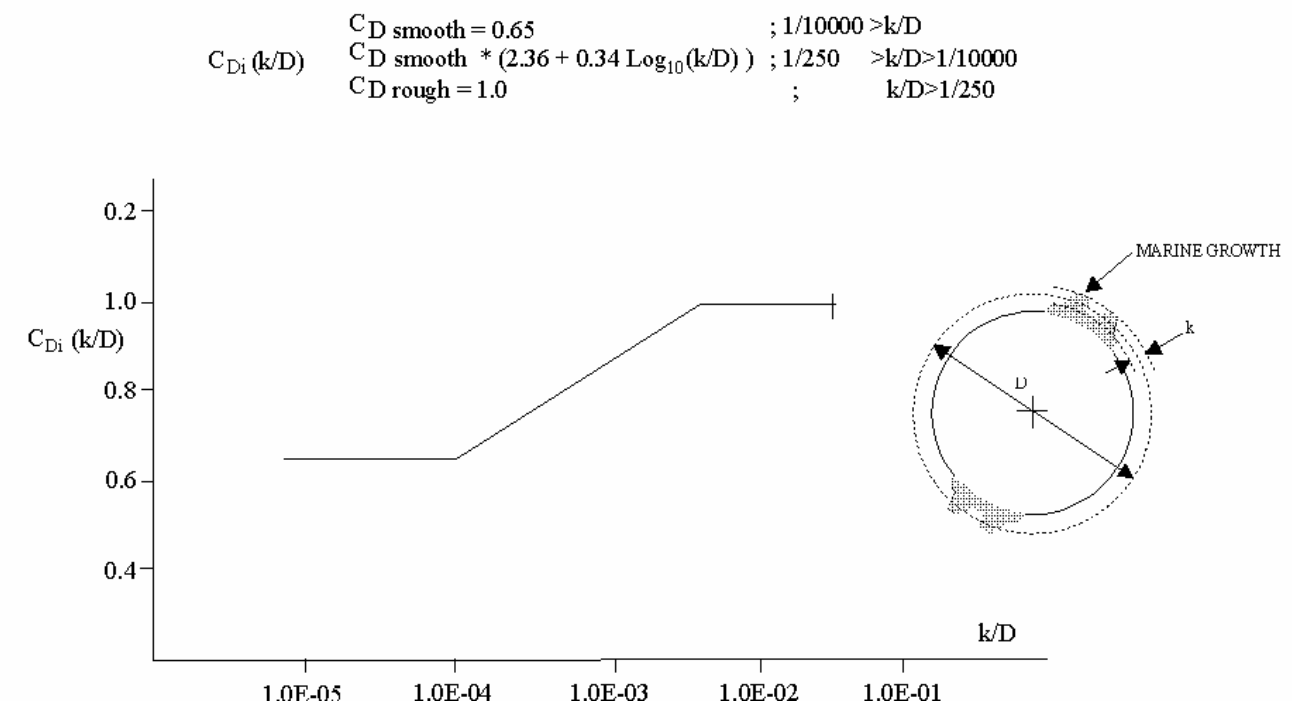

Figure TR.7.3.2.4-5 — Recommended values for the drag coefficient as function of relative roughness

TR.7.3.2.4.2.6 Keulegan-Carpenter number dependence

In post-critical conditions, for KC-numbers lower than approximately 30 to 40, there seems to be some dependence of the drag coefficient on the KC-number, at least for rough cylinders. For smooth cylinders this KC-dependence is more uncertain. The Christchurch Bay Tower (CBT) results for a clean cylinder reported by Bishop[7-33], for example, show this dependence for smooth cylinders, and so do the results reported from the Ocean Test Structure (OTS)[7-22]. Wolfram and Theophanatos[7-24], and the SSPA results reported by Rodenbusch and Gutierrez[7-18], do not show this dependence for smooth cylinders.

For rough cylinders in post-critical conditions, the KC-dependence of the drag coefficient for KC-numbers lower than approximately 30 to 40 seems to be a more generally observed trend, as in References [7-18], [7-22] and [7-34] amongst others.

It must be emphasized that for decreasing KC-numbers (< 30) the (post-critical) conditions will gradually be more inertia dominated and less drag dominated, implying an increasing uncertainty in the reported C_D values.

Figure TR.7.3.2.4-6 shows C_D as a function of the KC-number for cylinders in waves from Reference [7-35]. In a similar way, Figures TR.7.3.2.4-7 and TR.7.3.2.4-8 show C_D as a function of KC-number for, respectively, a clean cylinder and a rough, barnacle-covered cylinder of the Ocean Test Structure (OTS)[7-22] as presented in Reference [7-28].

Based on the discussion above and the results reported in the literature, the explicit KC-dependence presented in Equation (TR.7.3-8) may be included in the computations in addition to the roughness dependence:

$$C_{Di(KC,k/D)} = C_{Di(k/D)} * \begin{cases} 1{,}45 & ; \quad KC < 10 \\ 2/(KC-5)^{0{,}2} & ; \quad 10 < KC < 37 \\ 1{,}0 & ; \quad 37 < KC \end{cases} \qquad \text{(TR.7.3-8)}$$

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A graphic representation of Equation (TR.7.3-8) is given in Figure TR.7.3.2.4-9.

Equation (TR.7.3-8) should also be used for smooth cylinders, in spite of the uncertainty with respect to the KC-dependence. However, for low KC-values the choice of C_D-value is less critical due to the transition to inertia-dominated conditions. Furthermore, using Equation (TR.7.3-8) for the entire roughness range (from smooth to rough) results in a more uniform and easier handling of the KC-dependence.

An inertia coefficient C_M = 2,0 for smooth cylinders and C_M = 1,8 for rough cylinders is suggested for use if KC-dependence is used for the drag coefficients at low KC-numbers.

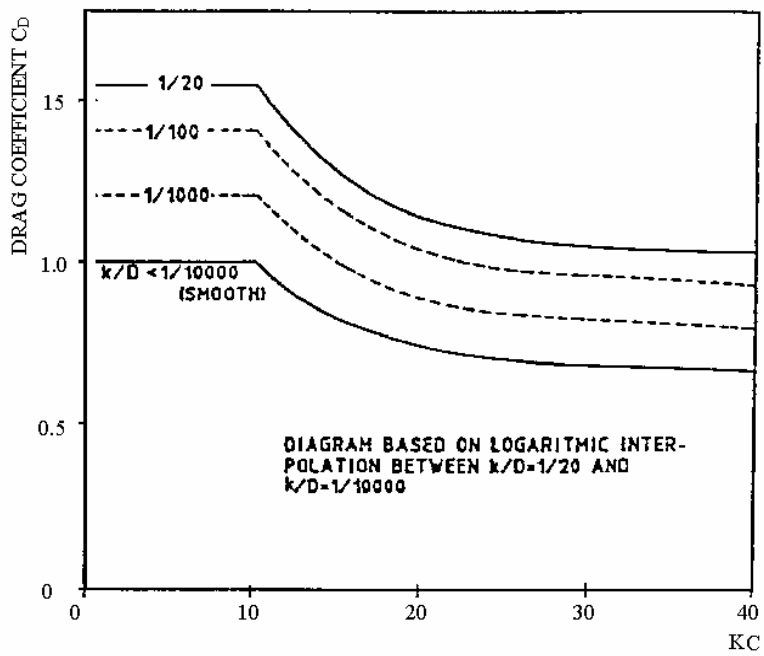

Figure TR.7.3.2.4-6 — Drag coefficient dependence on KC-number[7-35]

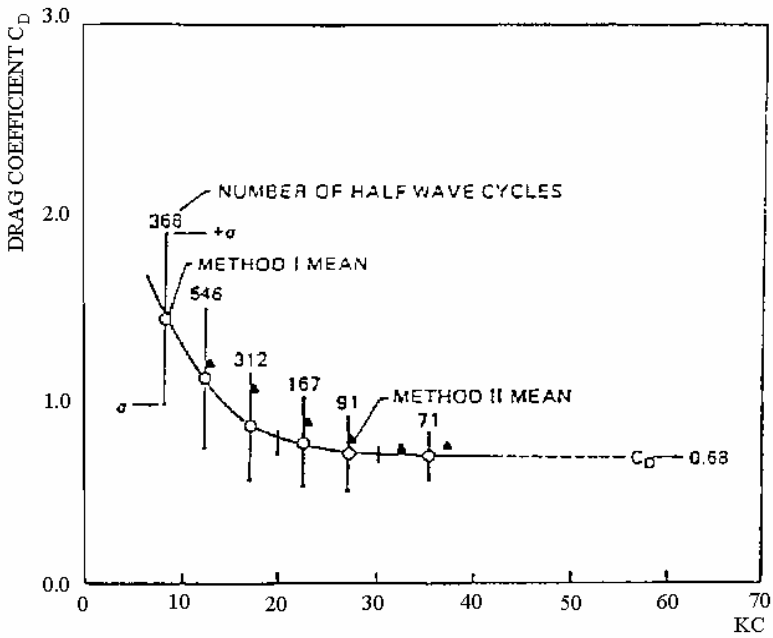

Figure TR.7.3.2.4-7 — Drag coefficient dependence on KC-number for clean cylinders of the Ocean Test Structures[7-22], [7-28]

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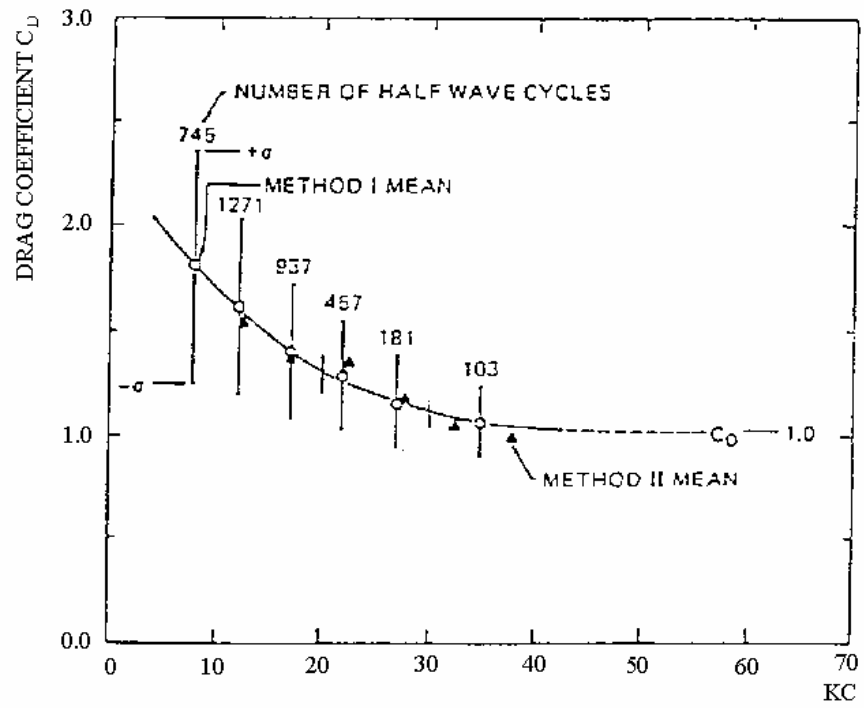

Figure TR.7.3.2.4-8 — Drag coefficient dependence on KC-number for barnacle-covered cylinders of the Ocean Test Structure[7-22], [7-28]

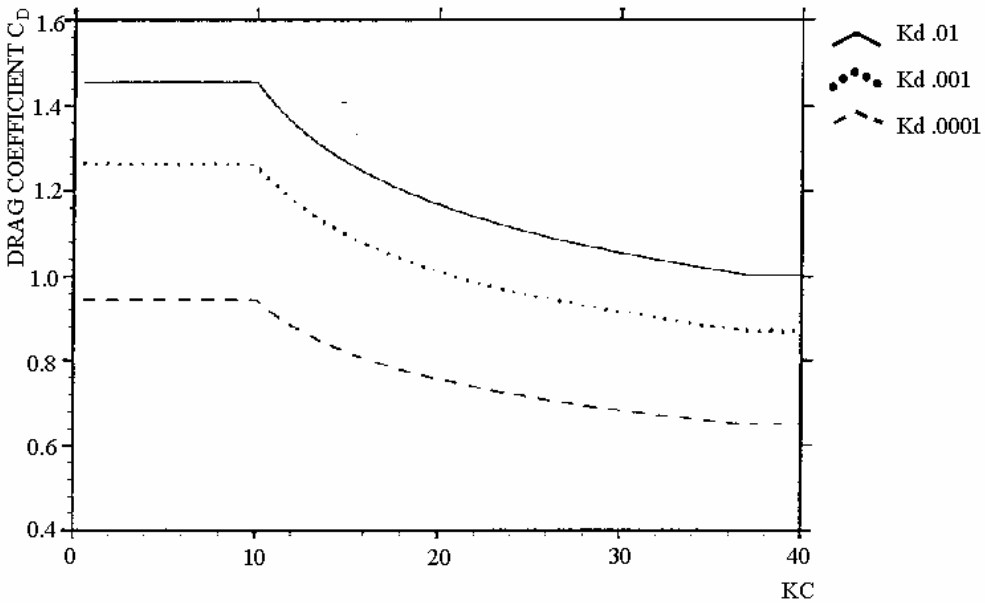

Figure TR.7.3.2.4-9 — Recommended drag coefficient dependence on KC-number for cylinders in waves, at high Reynolds numbers

TR.7.3.2.4.2.7 Reynolds number dependence

As previously discussed, the drag coefficient is dependent on the Re-number and this has been reported by several authors[7-7], [7-29] (Figures TR.7.3.2.4-11 and TR.7.3.2.4-12) and is reflected in some guidance on load computations, e.g. References [7-36] and [7-37] (Figure TR.7.3.2.4-10).

However, the use of test results reducing C_D in the critical region is not relevant for practical purposes as the roughness k/D < 1/100 000 implied in the curve for smooth cylinders is not applicable for jack-up structures.

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The change in the Reynolds dependence with respect to roughness is quite large and it is therefore not possible to recommend one single curve for this dependence. The recommended set of curves shown in Figure TR.7.3.2.4-13 are mainly based on a functional fit to the test results presented in Reference [7-29] and in addition the drag coefficient in the critical regime is set to a minimum of C_D = 0,45. Test results have indicated lower C_D values, but only in the ideal conditions of test facilities. A recommended set of curves are given in Figure TR.7.3.2.4-13, complying with the roughness dependence of Figure TR.7.3.2.4-5 at large Reynolds numbers. Using the curve for roughness k/D = 0,01, there is no reduction below C_D = 1,0 for Reynolds numbers above 105, which supports the use of a constant C_D in ISO 19905-1.

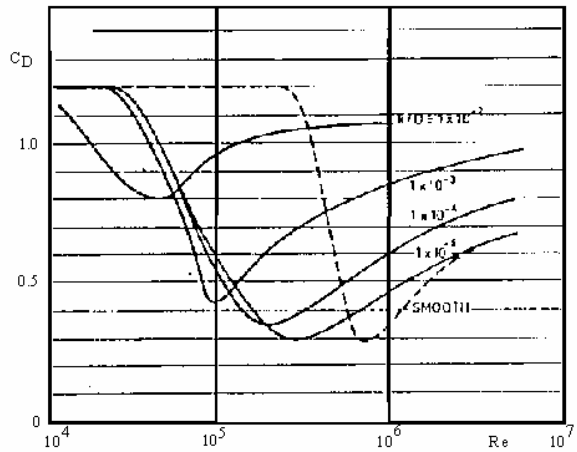

Figure TR.7.3.2.4-10 — Suggested Reynolds dependence in existing guidance[7-37]

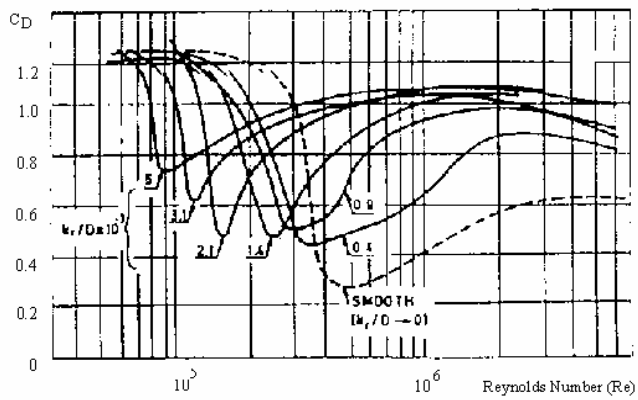

Figure TR.7.3.2.4-11 — Reynolds dependence of drag coefficient in test results[7-7]

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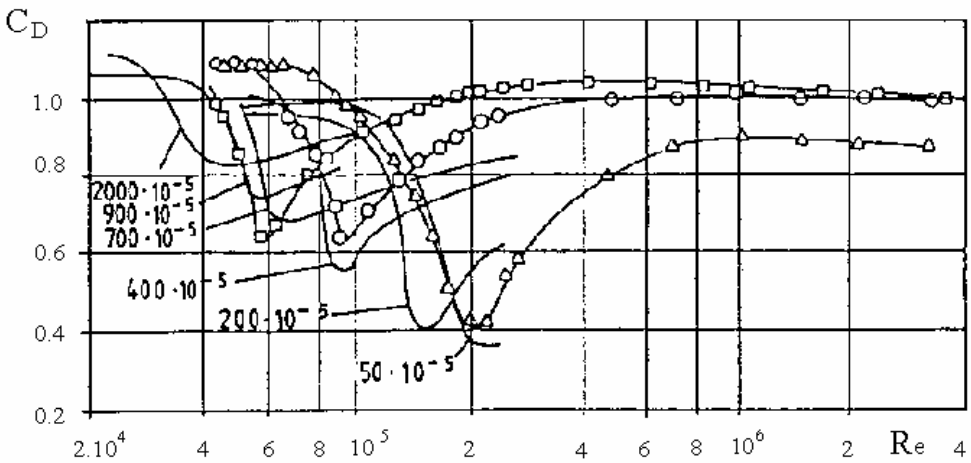

Drag coefficient C_D of rough circular cylinders in steady incident flow for different surface roughness values k/D (k = average height of surface roughness, D = cylinder diameter, $Rn = U_\infty D/\nu$, U_∞ = incident flow velocity.) Δ, $k/D = 110 \cdot 10^{-5}$; ○, $k/D = 450 \cdot 10^{-5}$; □, $k/D = 900 \cdot 10^{-5}$; ——, Fage & Warsap (1929), (Achenbach, 1971).

Figure TR.7.3.2.4-12 — Reynolds dependence of drag coefficient[7-29]

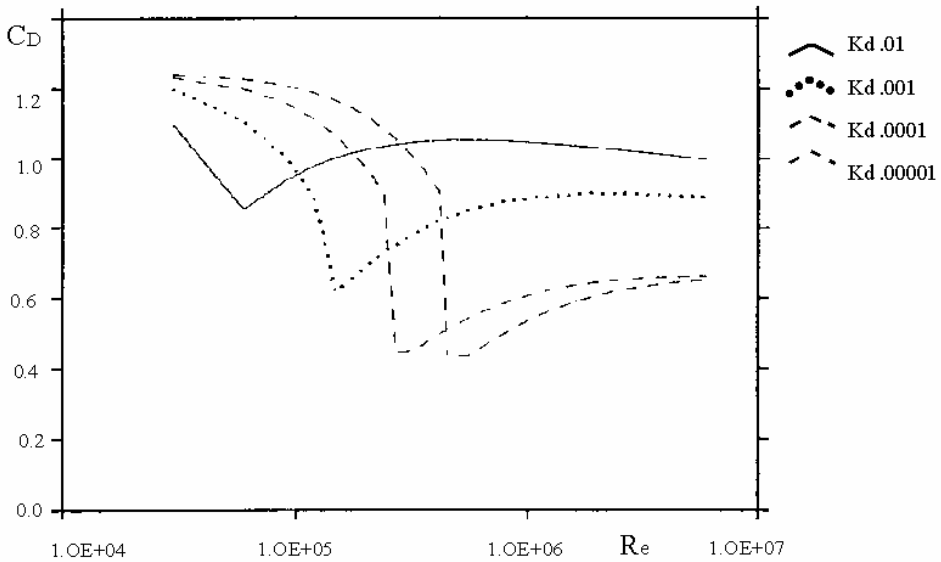

Figure TR.7.3.2.4-13 — Recommended values for Reynolds dependence for different values of relative roughness, KC > 40

TR.7.3.2.4.3 Hydrodynamic coefficients for gussets

Gussets are treated as flat plates implying that a C_{Di} = 2,0 and C_{Mi} = 1,0 is to be applied (considering the area associated with C_M as that of the circumscribed circle). For convenience, ISO 19905-1 proposes that gussets are included as equivalent horizontal members in the hydrodynamic model to assure proper directional dependence of forces. Shielding may be considered according to ISO 19905-1:2012, Figure A.7.3-2.

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TR.7.3.2.4.4 Hydrodynamic coefficients for chords

TR.7.3.2.4.4.1 Split tube chords

With respect to the test results for split tube chord data, the following aspects are considered:

— The tests are almost always performed with a smooth cylinder section.

— Most of the tests are performed in stable current or wind conditions.

The first aspect is the most important, also indicated by the test results evaluation of the tubulars presented in TR.7.3.2.4.2. The drag coefficient for smooth tubulars is about C_{Dsmooth} = 0,65, while for rough cylinder this increases to C_{Drough} = 1,0.

The second aspect on stable flow conditions should not affect the results very much as the KC values are very high in extreme load evaluations. However, the test result in Reference [7-38] showed higher values in waves than in stable current. This has not yet been fully explained, but comparisons made in Reference [7-28] indicates that test results in waves from flume experiments overpredict the drag forces. A number of test results[7-2] have been considered, from wind tunnel tests and towing in water, when evaluating hydrodynamic coefficients for split tube chords.

The drag coefficient is first estimated for the directions 0° and 90° as defined in Figure TR.7.3.2.4-14. The drag coefficients for 0° are dominated by the tubular part and no particular effect of the rack on the drag coefficient is seen from the tests. That is, for typical dimensions of the tubular diameter and rackplate thickness t, D_i/t >> 1,0, tests show values of about $C_{\text{D}} \approx$ 0,65. This indicates that the drag coefficients chosen for the tubular are also valid for the split tube chord for the 0° direction. In order to be consistent with the roughness dependence of the drag coefficient for tubulars, the drag coefficient in the marine growth region is increased due to roughness to C_{Drough} = 1,0 for θ = 0°.

NOTE For the 90° direction the drag coefficient should be similar to that of a flat plate for large W/D_i ratios, C_{Dplate} = 2,0. However, test results seem to indicate that the C_{D} values for this direction referring to the mean rack width W, are, on average, about 1,8, see Figure TR.7.3.2.4-15. The suggested drag coefficient in ISO 19905-1 is therefore set to be 1,8 for small W/D_i ratios, increasing to 2,0 for large W/D_i ratios. The interpolation between these two numbers is based on engineering judgment.

The drag coefficient for the wave flow normal to the rack, related to the rack width W, is recommended as:

$$C_{\text{D1}} = \begin{cases} 1{,}8 & W/D_i < 1{,}2 \\ 1{,}4 + W/3D_i & 1{,}2 < W/D_i < 1{,}8 \\ 2{,}0 & 1{,}8 < W/D_i < 2{,}0 \end{cases} \qquad \text{(TR.7.3-9)}$$

For the interpolation between the directions 0° and 90°, a number of formulations are available, but since there were a number of test results available, a best fit of a new formulation was decided.

The following interpolation formula was found to fit the data best (see Appendix TR.7.C) and at the same time be flexible with respect to the drag coefficient for rough and smooth surfaces at 0°:

$$C_{\text{D}i} = \begin{cases} C_{\text{Do}} & \theta < 20° \\ C_{\text{Do}} + (C_{\text{D1}} W/D_i - C_{\text{Do}}) \sin^2[(\theta - 20°)9/7] & 20° < \theta < 90° \end{cases} \qquad \text{(TR.7.3-10)}$$

where

C_{Do} is the drag coefficient for the chord at θ = 0° and is to be taken as that of a tubular with appropriate roughness, see TR.7.3.2.4.2, i.e. C_{Do} = 0,65 above MWL + 2,0 m and C_{Do} = 1,0, below MWL + 2,0 m; possible dependence on KC and Re numbers as for a tubular;

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