
To: Relevant shipowners, ship management companies, shipyards and designers, product manufacturer, related departments of the Headquarters of CCS, the Society's surveyors, Plan Approval Centers

Notice on Interim Guidelines on the Second Generation Intact

Stability Criteria of MSC.1/Circ.1627 Issued by IMO

1. Background

The Maritime Safety Committee of International Maritime Organization (IMO), at its 102th session (11 November 2020), approved the MSC.1/Circ.1627 “Interim Guidelines on the Second Generation Intact Stability Criteria”.

2. Main content

The interim guidelines provides technical criteria requirements for the five dynamic stability failure modes in waves of parametric roll, pure loss of stability, excessive acceleration, surf-riding/broaching and dead ship, such as Level 1 and Level 2 vulnerability criteria, direct stability failure assessment and operational measures, etc. As a supplement to the mandatory requirements of Part A of the “International Code on Intact Stability, 2008”, this guidelines provides a performance-based criteria for solving the problem of dynamic stability safety of ships in waves. IMO encourages all parties to apply the guidelines to new ship design and also to operating ships, compare the experience gained through the trial use with practical experience, and feedback these experience to IMO.

3. Class notation of CCS

Upon application, the class notation is to be assigned to international sea-going ship that meets the relevant requirements of Interim Guidelines on the Second Generation Intact Stability Criteria. “X” represents the suffix of the sub-elements of the second generation intact stability criteria.

This Notice is made public on CCS website (www.ccs.org.cn), and is to be distributed to relevant shipyards, ship owners, shipping management companies and ship designers by CCS branches within their responsible areas. Please contact the Technology & Information Department of CCS for any inquiry in the implementation. E-mail address: ti@ccs.org.cn.

Annex: MSC.1/Circ.1627- Interim Guidelines on the Second Generation Intact Stability Criteria

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INTERIM GUIDELINES ON THE SECOND GENERATION INTACT STABILITY CRITERIA

1 The Maritime Safety Committee, at its 102nd session (4 to 11 November 2020), recognizing that performance-oriented criteria for dynamic stability phenomena in waves needed to be developed and implemented to ensure a uniform international level of safety, as specified in part A, section 1.2 of the International Code on Intact Stability, 2008 (resolution MSC.267(85), as amended), approved the *Interim guidelines on the second generation intact stability criteria* (Interim Guidelines), as set out in the annex.

2 The Committee agreed to keep the Interim Guidelines under review, taking into account experience in design and operation of ships gained during their application.

3 Member States are invited to use the annexed Interim Guidelines as complementary measures when applying the requirements of the mandatory criteria of part A of the Code and to bring them to the attention of all parties concerned, in particular shipbuilders, shipmasters, shipowners, ship operators and shipping companies, and recount their experience gained through the trial use of these Interim Guidelines to the Organization.

ANNEX

INTERIM GUIDELINES ON THE SECOND GENERATION INTACT STABILITY CRITERIA

Preamble

1 In view of a wide variety of ship types, sizes, operational profiles and environmental conditions, the problems related to dynamic stability failures have generally not yet been solved. Administrations should be aware of the fact that some ships are more at risk of encountering critical stability in waves. The Administration may, for a particular ship or group of ships, apply dynamic stability criteria which demonstrate that the safety level of a ship in waves is sufficient.

2 For this purpose, performance-based criteria for assessing five dynamic stability failure modes in waves are provided in these guidelines, namely, dead ship condition, excessive acceleration, pure loss of stability, parametric rolling and surf-riding/broaching.

3 The physics and evaluation methods for these five stability failure modes had not been well understood or developed when the mandatory intact stability criteria were established. As such, the herewith presented dynamic stability criteria utilize the recent progress using best practices and the most advanced scientific tools available, for practical regulatory-oriented application. Accordingly, the background of the dynamic stability criteria is principally based on first principles and latest technology, as opposed to predominant use of casualty records which form the basis of the mandatory intact stability criteria. For this reason, the presented dynamic stability criteria may be considered as the second generation intact stability criteria.

4 The methodologies contained in these Interim Guidelines are based on general first-principle approaches derived from the analysis of ship dynamics. However, in the development process, it was also necessary to simplify some of the assessment methodologies and to perform some semi-empirical tuning.

5 In developing the framework of these Interim Guidelines, it was recognized that an integrated perspective, combining design methods and operational measures, is the most effective way for properly addressing and continuously improving safety against accidents related to stability for ships in a seaway.

6 Therefore, the second generation intact stability criteria should be used for helping to ensure a uniform international level of safety of ships with respect to dynamic stability failure modes in waves.

CONTENTS

Chapter 1	General
1.1	Introduction
1.2	Definitions
1.3	Nomenclature
Chapter 2	Guidelines on vulnerability criteria
2.1	Preface
2.2	Assessment of ship vulnerability to the dead ship condition failure mode
2.3	Assessment of ship vulnerability to the excessive acceleration failure mode
2.4	Assessment of ship vulnerability to the pure loss of stability failure mode
2.5	Assessment of ship vulnerability to the parametric rolling failure mode
2.6	Assessment of ship vulnerability to the surf-riding/broaching failure mode
2.7	Parameters common to stability failure mode assessments
Chapter 3	Guidelines for direct stability failure assessment
3.1	Objective
3.2	Requirements
3.3	Requirements for a method that adequately predicts ship motions
3.4	Requirements for validation of software for numerical simulation of ship motions
3.5	Procedures for direct stability assessment
Chapter 4	Guidelines for operational measures
4.1	General principles
4.2	Stability failures
4.3	Operational measures
4.4	Acceptance of operational measures
4.5	Preparation procedures
4.6	Application

1 GENERAL

1.1 Introduction

1.1.1 Purpose

1.1.1.1 The purpose of these Guidelines is to enable the use of the second generation intact stability criteria for the assessment of dynamic stability failure modes in waves, as requested in section 1.2 of part A of the 2008 Intact Stability (IS) Code. These dynamic stability failure modes are as follows: dead ship condition, excessive acceleration, pure loss of stability, parametric rolling and surf-riding/broaching. In this sense, the overarching aim is to use the latest technology and knowledge on ship dynamics to provide guidance for ship designers on dynamic stability failure modes and to provide operational guidance for ship masters. This is undertaken to further improve the safety level of a ship beyond the mandatory intact stability criteria.

1.1.1.2 The main purpose of these criteria is to enable the use of the latest numerical simulation techniques for evaluating the safety level of a ship from an intact stability viewpoint. By using such tools for simulating the dynamic ship behaviours in a random seaway, the safety level of a ship can be estimated with a probabilistic measure. This approach is hereby called direct stability assessment. However, applying such tools to all new ships that are subject to the 2008 IS Code is not practical due to the limitation of human resources and facilities that are required for experimentally validating the numerical tools. Thus, the vulnerability of a ship can be assessed using simpler vulnerability criteria or more comprehensive direct stability assessment. The guidance for vulnerability criteria and the guidance for direct stability assessment are provided in chapters 2 and 3 of the Interim Guidelines, respectively.

1.1.1.3 It is noted that compliance with the criteria contained within part A of the 2008 IS Code, good seamanship, appropriate ship-handling and appropriate operation may avoid the potential danger of excessive roll, excessive lateral accelerations or capsizing due to a dynamic stability failure mode. Mindful of this fact, operational measures for a ship may be provided as an alternative to the vulnerability criteria or direct stability assessment. For this purpose, the guidelines for operational measures are provided in chapter 4 of the Interim Guidelines. Whereas the natural order of application is from the vulnerability criteria to direct stability assessment and operational measures, all these alternatives are equivalent in the regulatory sense and any of them can be used independently of others, in the way that is most suitable for the particular design.

1.1.2 Framework

1.1.2.1 For the purpose of this framework, the following definitions apply:

- .1 *criterion* is a procedure, an algorithm or a formula used for the assessment on the likelihood of a stability failure;
- .2 *standard* is a boundary separating acceptable and unacceptable likelihood of a stability failure; and
- .3 *rule* (or *regulation*) is a specification of a relationship between a standard and a value produced by a criterion.

1.1.2.2 The second generation intact stability criteria are tools to judge the likelihood of intact stability failures. Intact stability failure is an event that includes the occurrence of very large roll (heel, list) angles or excessive rigid body accelerations, which may result in capsizing or

impairs normal operation of the ship and could be dangerous to crew, passengers, cargo or ship equipment. Three subtypes of intact stability failure are included:

- .1 heel/list exceeding a prescribed limit;
- .2 roll angles exceeding a prescribed limit; and
- .3 lateral accelerations exceeding prescribed limit.

1.1.3 Application logic

1.1.3.1 The application logic is summarized in figure 1.1.3. Although the user may be guided by a sequential logic of the Interim Guidelines (see 1.1.3.2), it is also acceptable that the users apply any alternative design assessment or operational measure option (see 1.1.1.3). For example, a user may wish to immediately commence with the application of direct stability assessment procedures without passing through Levels 1 and 2 of the vulnerability criteria or develop operational measures without performing design assessment.

1.1.3.2 A sequential application logic can be summarized, as follows:

As the simplest options, the vulnerability criteria are presented in two levels: Level 1 and Level 2. The assessment of the five stability failure modes should begin with the use of these levels. Level 1 is an initial check and then, if the ship in a particular loading condition is assessed as not vulnerable for the tested failure mode, the assessment for that failure mode may conclude; otherwise, the design would progress to Level 2. If the ship in a particular loading condition is assessed as not vulnerable for the tested failure mode in Level 2, then the assessment would conclude; otherwise, the design would progress to the application of direct stability assessment, application of operational limitations, revising the design of the ship or discarding the loading condition. If the ship in a particular loading condition is not found acceptable with respect to direct stability assessment procedures, then the logic is that the design would then progress to the application of operational measures or operational guidance, revising the design or discarding the loading condition.

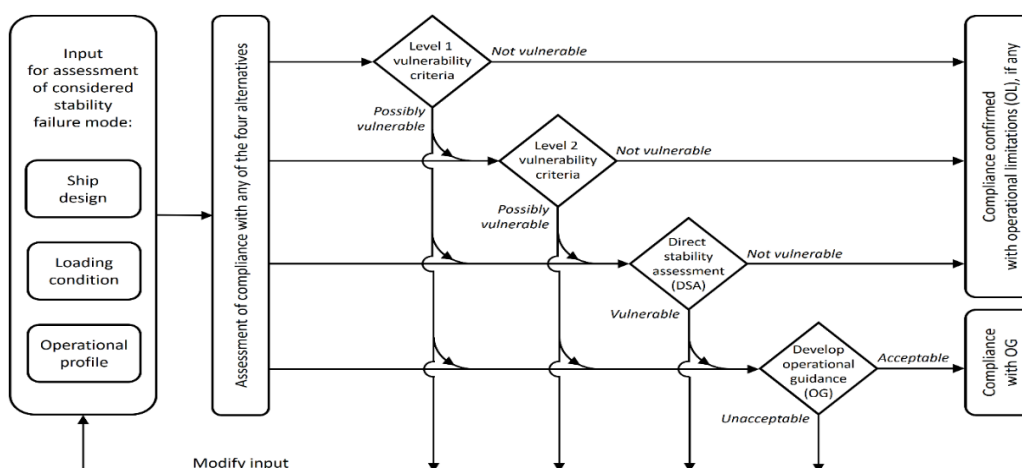


Figure 1.1.3 – Simplified scheme of the application structure of the second generation intact stability criteria. For actual application details, reference is to be made to the text of these Interim Guidelines.

1.1.4 Testing

1.1.4.1 The second generation intact stability criteria have been developed envisioning a future incorporation into the 2008 IS Code. However, they require testing before using them as mandatory criteria. This is because the robustness of the new criteria is not the same for the different stability failure modes.

Specifically, results obtained in the development process, indicate that:

- .1 Level 1 and Level 2 vulnerability criteria for dead ship stability failure mode sometimes provide non-consistent results, i.e. Level 2 may be more conservative than Level 1 for some ships;
- .2 vulnerability criteria for excessive acceleration may require further refinements;
- .3 Level 2 vulnerability criterion for the pure loss of stability failure mode provides very conservative results for ships with low freeboard; therefore, results of testing for such ships should be treated with care; and
- .4 parametric rolling and surf-riding/broaching Level 1 and Level 2 vulnerability criteria have sufficient scientific background and feasible methods for regulatory use.

1.1.4.2 Therefore, these criteria should be used on a trial basis at this stage. Such criteria usage and subsequent reporting are necessary to gain experience and consequently enable the introduction of this approach to the analysis of intact stability. It is also highly recommended to apply the criteria to ships already in service and to compare the results with operational experience.

1.1.5 Feedback

1.1.5.1 The second generation intact stability criteria methodology has been developed using the latest technology and scientific knowledge for assessing ship dynamics in waves. The methodology has been tested on a number of sample ships and, to this end, these draft Interim Guidelines are intended to generate data and feedback for a large number of ships.

1.1.5.2 These guidelines have been issued as "Interim Guidelines" in order to gain experience in their use. They should be reviewed in order to facilitate future amendments based on the experience gained.

1.1.5.3 Member States and international organizations are invited to submit information, observations, suggestions, comments and recommendations based on the practical experience gained through the application of these Interim Guidelines. To support the objective of obtaining robust criteria for regulatory use, suggestions for alternatives to and/or refinements of the criteria elements contained in the Interim Guidelines are encouraged. The suggestions should compare the outcomes with the criteria elements included in the Interim Guidelines.

1.1.5.4 With such feedback not only on the technical results but also their usability and clarity, the Organization will be able to subsequently refine the second generation intact stability criteria, if necessary.

1.1.6 Relationship with mandatory criteria

1.1.6.1 These Interim Guidelines are not intended to be used in lieu of the mandatory intact stability criteria contained in the 2008 IS Code. They are intended for use as a guide for ship

designers to assess the aspects of ship stability not adequately covered by the mandatory criteria and to provide operational guidance for ship masters. Therefore, they should be used as a supplementary set of stability assessment methods.

1.1.7 Notes for application

1.1.7.1 These Interim Guidelines are intended to be applied to ships that are also subject to the 2008 IS Code.

1.1.7.2 These Interim Guidelines have not been specifically developed for multihulls. Moreover, for ships with an extended low weather deck, additional application provisions are provided in the relevant chapters.

1.2 Definitions

1.2.1 *Loading condition*, in the context of these Interim Guidelines, is defined by the mean draught d , trim angle θ , metacentric height GM and mass moments of inertia I_{xx} (or natural roll period T_r), I_{yy} and I_{zz} .

1.2.2 *Fully loaded departure condition* means the loading condition, as defined in section 3.4.1 of part B of the 2008 IS Code.

1.2.3 *Sea state* is the stationary condition of the free water surface and wind at a certain location and time, described in these Interim Guidelines by the significant wave height H_S , mean zero-crossing wave period T_Z , mean wave direction μ , wave elevation energy spectrum S_{zz} , and mean wind speed, gustiness characteristics and direction. For combined wind sea and swell, significant wave height, mean zero-crossing wave period and mean wave direction may be defined separately for each of the two wave systems.

1.2.4 *Sailing condition* is a short notation for the combination of the ship forward speed V_S and heading relative to mean wave direction μ .

1.2.5 *Assumed situation* is a condition of the ship that refers to the sailing condition combined with sea state. Thus, a situation is defined by the ship forward speed v_0 , mean wave direction μ , significant wave height H_S and mean zero-crossing wave period T_Z , direction and gustiness characteristics of wind.

1.2.6 *Design situation* is an assumed situation representative for a particular stability failure mode.

1.2.7 *Wave scatter table* is a table containing the probabilities of each range of sea states encountered in the considered operational area or operational route. In these Interim Guidelines, the probabilities contained in a wave scatter table are defined to sum to unity.

1.2.8 *Limited wave scatter table* is a table obtained from the full wave scatter table by removing all sea state ranges with the significant wave height above a certain limit.

1.2.9 *Operational area* and *operational route* are the geographical areas specified for the ship operation. In the context of these Interim Guidelines, operational area or operational route are specified by the long-term wave statistics (wave scatter table) and wind statistics.

1.2.10 *Nominal ship forward speed* means the ship speed in calm water under action of the ship's propulsion at a given setting.

1.2.11 *Maximum service speed* means maximum ahead service speed, as defined in SOLAS regulation II-1/3.14.

1.2.12 *Design assessment* corresponds to the application of vulnerability criteria according to chapter 2 or direct stability assessment according to chapter 3 of these Interim Guidelines or a combination of the two.

1.2.13 *Operational measures* mean operational limitations or operational guidance.

1.2.14 *Guidelines for vulnerability assessment* means the content of chapter 2 of these Interim Guidelines.

1.2.15 *Guidelines for direct stability assessment* means the content of chapter 3 of these Interim Guidelines.

1.2.16 *Guidelines for operational measures* means the content of chapter 4 of these Interim Guidelines.

1.2.17 *2008 IS Code* means the International Code on Intact Stability, 2008, as amended.

1.2.18 *Mean 3-hour maximum amplitude* means the average value of several maximum amplitudes, each of which is determined for an exposure time of 3 hours.

1.3 Nomenclature

1.3.1 The general nomenclature used in these Interim Guidelines is set forth in 1.3.2, 1.3.3, 1.3.4 and 1.3.5. Nomenclature that is specific to a particular section is defined in that location and prevails over the general nomenclature reported here. If not otherwise stated, reference should be made to the nomenclature used in the 2008 IS Code.

1.3.2 General ship characteristics:

L	=	length of the ship, as defined in paragraph 2.12 of the introduction part of the 2008 IS Code (m)
B	=	moulded breadth of the ship (m)
B_{wl}	=	moulded breadth at waterline (m)
D	=	moulded depth, as defined in the 2008 IS Code (m)
V_s	=	service speed (m/s)
v_0	=	forward speed (m/s)
Fn	=	Froude number = $V_s / \sqrt{L g}$
A_k	=	total overall area of the bilge keels (no other appendages) (m ²)
∇_D	=	volume of displacement at waterline equal to D at zero trim (m ³)
D_p	=	propeller diameter (m);
x_i	=	longitudinal distance from the aft perpendicular to a station i (m), positive forward

1.3.3 Constants:

- g = acceleration due to gravity, taken as 9.81 (m/s²)
 ρ = density of salt water, taken as 1025 (kg/m³)
 ρ_{air} = density of air, taken as 1.222 (kg/m³)

1.3.4 Loading condition characteristics:

- d_{full} = draft corresponding to the fully loaded departure condition in calm water (m)
 $C_{B,full}$ = block coefficient of the fully loaded departure condition in calm water
 $C_{m,full}$ = midship section coefficient of the fully loaded departure condition in calm water
 d = mean draught, i.e. draft amidships corresponding to the loading condition under consideration in calm water (m)
 L_{WL} = length of the ship on the waterline corresponding to the loading condition under consideration (m)
 KB = height of the centre of buoyancy above baseline corresponding to the loading condition under consideration (m)
 KG = height of the centre of gravity above baseline corresponding to the loading condition under consideration (m)
 ∇ = volume of displacement corresponding to the loading condition under consideration (m³)
 C_B = block coefficient corresponding to the loading condition under consideration (-)
 Δ = displacement (t)
 A_W = waterplane area at the draft equal to d (m²)
 I_T = transverse moment of inertia of water-plane area (m⁴)
 I_{xx} = dry roll moment of inertia (t m²)
 I_{yy} = dry pitch moment of inertia (t m²)
 I_{zz} = dry yaw moment of inertia (t m²)
 m = mass of the ship (t)
 k_{xx} = dry roll radius of gyration around axis $x = \sqrt{I_{xx} / m}$ (m)
 k_{yy} = dry pitch radius of gyration around axis $y = \sqrt{I_{yy} / m}$ (m)
 k_{zz} = dry yaw radius of gyration around axis $z = \sqrt{I_{zz} / m}$ (m)
 GM = metacentric height of the loading condition in calm water (m), with or without correction for free surface effect, as required
 A_L = projected lateral area of the portion of the ship and deck cargo above the waterline (m²)
 Z = vertical distance from the centre of A_L to the centre of the underwater lateral area or approximately to a point at one-half the mean draft, d (m)

T_r	=	linear natural roll period in calm water (s)
ω_r	=	natural roll frequency = $2\pi / T_r$ (rad/s)
φ	=	angle of roll, heel, or list (rad or deg)
θ	=	angle of pitch or trim (rad or deg)
ψ	=	angle of yaw, heading or course (rad or deg)
φ_s	=	stable heel angle under the action of steady heeling moment calculated as the first intersection between the righting lever curve (GZ curve) and the heeling lever curve, (rad or deg)
φ_v	=	angle of vanishing stability. In presence of a heeling moment, it should be calculated as the second intersection between the righting lever curve (GZ curve) and the applied heeling lever curve (rad or deg)

1.3.5 Environmental condition characteristics:

λ	=	wavelength (m)
H	=	wave height (m)
H_s	=	significant wave height for the short-term environmental condition under consideration (m)
s	=	wave steepness = H/λ
T_Z	=	mean zero-crossing period for the short-term environmental condition under consideration (s)
T_p	=	wave period corresponding to peak of spectrum for the short-term environmental condition under consideration (s)
μ	=	mean wave direction with respect to ship centre plane (deg)
S_{zz}	=	wave elevation energy spectrum ($m^2/(rad/s)$)
ω	=	circular frequency (rad/s)
k	=	wave number = $2\pi/\lambda$ (rad/m)

1.3.6 Other parameters

N_s	=	number of simulations
f_s	=	joint probability density of sea state (probability of sea states per unit range of significant wave heights and mean zero-crossing periods) ($1/m \cdot s$)

2 Guidelines on vulnerability criteria

2.1 Preface

As described in section 1.2 of part A of the 2008 IS Code, the Administration may for a particular ship or group of ships apply criteria demonstrating that the safety of the ship in waves is sufficient. For this purpose, the criteria for the dynamic stability failure modes in waves have been developed, which address the dead ship condition, excessive acceleration, pure loss of stability, parametric rolling, and surf-riding/broaching failure modes. These criteria should be used for ensuring a uniform international level of safety of ships with respect to these failure modes.

2.2 Assessment of ship vulnerability to the dead ship condition failure mode

2.2.1 Application

2.2.1.1 The provisions given hereunder apply to all ships, except for ships with an extended low weather deck.¹

2.2.1.2 For each loading condition, a ship that:

- .1 meets the standard contained in the criteria contained in 2.2.2 is considered not to be vulnerable to the dead ship condition failure mode; or
- .2 does not meet the standard contained in the criteria contained in 2.2.2 should be subject to more detailed assessment of vulnerability to the dead ship condition failure mode by applying the criteria contained in 2.2.3.

2.2.1.3 Alternatively to the criteria contained in 2.2.2 or 2.2.3, for each loading condition a ship may be subject to either:

- .1 direct stability assessment for the dead ship condition failure mode that is performed according to the Guidelines for direct stability assessment in chapter 3; or
- .2 operational limitations related to operational area or route and season developed in accordance with the Guidelines for operational measures in chapter 4.

2.2.1.4 A detailed assessment of Level 2 vulnerability according to the criteria contained in 2.2.3 may be performed without the requirement to conduct a more simplified assessment in 2.2.2. Similarly, a detailed direct stability assessment as provided in 2.2.1.3.1 may be performed without the requirement to conduct a more simplified assessment in 2.2.2 or 2.2.3.

2.2.1.5 Stability limit information for determining the safe zones as functions of GM, draught and trim is to be provided based on matrix calculations according to the criteria contained in 2.2.2 or 2.2.3, and, if appropriate, direct stability assessment according to the Guidelines for direct stability assessment in chapter 3. If relevant, the stability limit information for determining safe zones should take into account operational limitations related to specific operational areas or routes and specific season according to the Guidelines for operational measures in chapter 4.

2.2.1.6 Reference environmental conditions to be used in the assessment may be modified when introducing operational limitations permitting operation in specific operational areas or routes and, if appropriate, specific season, according to the Guidelines for operational measures in chapter 4.

2.2.1.7 Free surface effects should be accounted for as recommended in chapter 3 of part B of the 2008 IS Code.

¹ The criteria for this failure mode may not be applicable to a ship with an extended low weather deck due to increased likelihood of water on deck or deck-in-water.

2.2.2 Level 1 vulnerability criterion for the dead ship condition

2.2.2.1 A ship is considered not to be vulnerable to the dead ship condition failure mode, if its ability to withstand the combined effects of beam wind and rolling is demonstrated, with reference to figure 2.2.2.1, as follows:

- .1 the ship is subjected to a steady wind pressure acting perpendicular to the ship's centreline which results in a steady wind heeling lever, l_{w1} ;
- .2 from the resultant angle of equilibrium, φ_0 , the ship is assumed to roll owing to wave action to an angle of roll, φ_1 , to windward; and the angle of heel under action of steady wind, φ_0 , should not exceed 16° or 80% of the angle of deck edge immersion, whichever is less;
- .3 the ship is then subjected to a gust wind pressure which results in a gust wind heeling lever, l_{w2} ; and
- .4 under these circumstances, area b should be equal to or greater than area a , as indicated in figure 2.2.2.1,

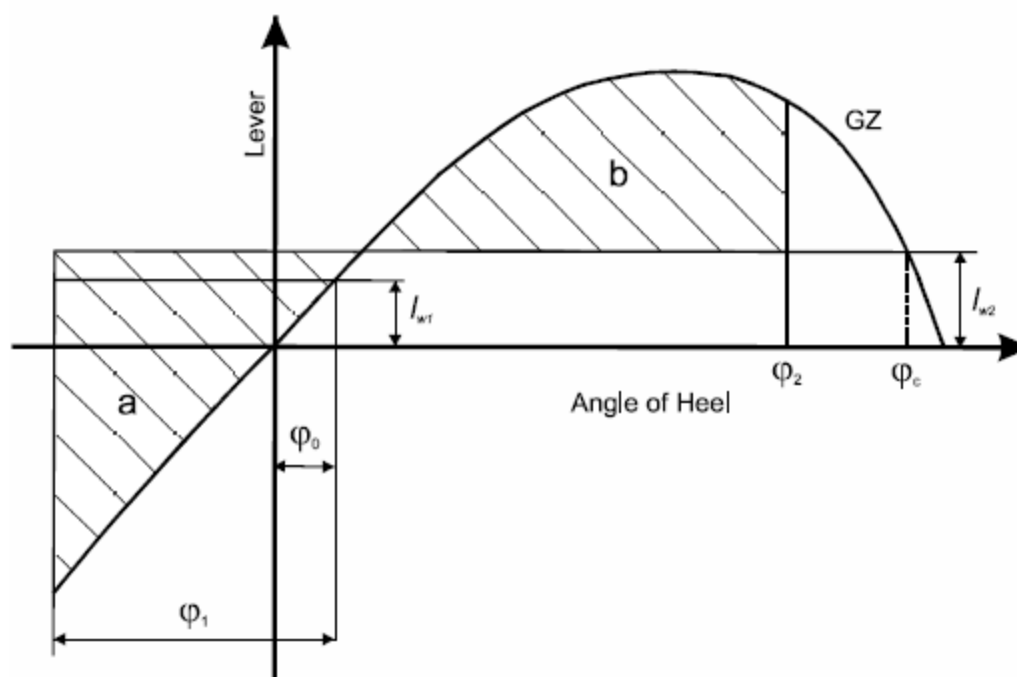


Figure 2.2.2.1 – Definition of area a and area b

where the angles in figure 2.2.2.1 are defined as follows:

- φ_0 = angle of heel under action of steady wind (deg)
- φ_1 = angle of roll to windward due to wave action (deg)(see 2.2.2.1.2 and 2.2.2.4)²
- φ_2 = angle of downflooding, φ_f , or 50° or φ_c , whichever is least,

² Refer to the *Explanatory Notes to the 2008 IS Code* (MSC.1/Circ.1281).

where:

φ_f = angle of heel at which openings in the hull, superstructures or deck houses which cannot be closed weathertight immerse. In applying this criterion, small openings through which progressive flooding cannot take place need not be considered as open.

φ_c = angle of second intercept between wind heeling lever l_{w2} and GZ curves.

2.2.2.2 The wind heeling levers l_{w1} and l_{w2} referred to in 2.2.2.1.1 and 2.2.2.1.3 are constant values at all angles of inclination and should be calculated as follows:

$$l_{w1} = \frac{P \cdot A_L \cdot Z}{1000 \cdot g \cdot \Delta} \text{ (m) and}$$

$$l_{w2} = 1.5 \cdot l_{w1} \text{ (m)}$$

where:

P = wind pressure of 504 (Pa). The value of P used for ships with operational limitations according to 2.2.1.6 may be reduced.

2.2.2.3 Alternative means for determining the wind heeling lever, l_{w1} , may be used as an equivalent to the calculation in 2.2.2.2. When such alternative tests are carried out, reference should be made to the Guidelines developed by the Organization.³ The wind velocity used in the tests should be 26 m/s in full scale with uniform velocity profile. The value of wind velocity used for ships with operational limitations according to 2.2.1.6 may be reduced.

2.2.2.4 The angle of roll, φ_1 , referred to in 2.2.2.1 should be calculated as follows:

$$\varphi_1 = 109 \cdot k \cdot X_1 \cdot X_2 \cdot \sqrt{r \cdot s} \text{ (deg)}$$

where:

X_1 = factor as shown in table 2.2.2.4-1

X_2 = factor as shown in table 2.2.2.4-2

k = factor as follows:

k = 1.0 for a round-bilged ship having no bilge or bar keels

k = 0.7 for a ship having sharp bilges

k = as shown in table 2.2.2.4-3 for a ship having bilge keels, a bar keel, or both

r = $0.73 + 0.6 \cdot OG / d$, where: $OG = KG - d$

s = wave steepness shown in table 2.2.2.4-4

A_k = total overall area of bilge keels or area of the lateral projection of the bar keel or sum of these areas (m²)

³ Refer to the *Interim guidelines for alternative assessment of the weather criterion* (MSC.1/Circ.1200).

The angle of roll, φ_1 , for ships with anti-rolling devices should be determined without taking into account the operation of these devices unless the Administration is satisfied with the proof that the devices are effective even with sudden shutdown of their supplied power.

Table 2.2.2.4-1 – Values of factor X_1

B/d	X_1
≤ 2.4	1.0
2.5	0.98
2.6	0.96
2.7	0.95
2.8	0.93
2.9	0.91
3.0	0.90
3.1	0.88
3.2	0.86
3.4	0.82
≥ 3.5	0.80

Table 2.2.2.4-2 – Values of factor X_2

C_B	X_2
≤ 0.45	0.75
0.50	0.82
0.55	0.89
0.60	0.95
0.65	0.97
≥ 0.70	1.00

Table 2.2.2.4-3 – Values of factor k

$\frac{A_k \cdot 100}{L_{WL} \cdot B}$	k
0	1.0
1.0	0.98
1.5	0.95
2.0	0.88
2.5	0.79
3.0	0.74
3.5	0.72
≥ 4.0	0.70

Table 2.2.2.4-4 – Values of wave steepness, s

Natural roll period, T_r (s)	Wave steepness factor, s
≤ 6	0.100
7	0.098
8	0.093
12	0.065
14	0.053
16	0.044
18	0.038
20	0.032
22	0.028
24	0.025
26	0.023
28	0.021
≥ 30	0.020

Note: Intermediate values in these tables should be obtained by linear interpolation.

2.2.2.5 For ships subject to operational limitations according to 2.2.1.6, the wave steepness, s , in table 2.2.2.4-4 may be modified.

2.2.2.6 For any ship, the angle of roll, φ_1 , may also be determined by alternative means on the basis of the Guidelines developed by the Organization.⁴

2.2.3 Level 2 vulnerability criterion for the dead ship condition

2.2.3.1 A ship is considered not to be vulnerable to the dead ship condition failure mode if:

$$C \leq R_{DS0}$$

where:

$$R_{DS0} = 0.06;$$

C = long-term probability index that measures the vulnerability of the ship to a stability failure in the dead ship condition based on the probability of occurrence of short-term environmental conditions, as specified according to 2.2.3.2.

2.2.3.2 The value of C is calculated as a weighted average from a set of short-term environmental conditions, as follows:

$$C = \sum_{i=1}^N W_i C_{S,i}$$

where:

W_i = weighting factor for the short-term environmental condition, as specified in 2.7.2;

$C_{S,i}$ = short-term dead ship stability failure index for the short-term environmental condition under consideration, calculated as specified in 2.2.3.2.1;

N = total number of short-term environmental conditions, according to 2.7.2.

2.2.3.2.1 The short-term dead ship stability failure index, $C_{S,i}$, for the short-term environmental condition under consideration, is a measure of the probability that the ship will exceed specified heel angles at least once in the exposure time considered, taking into account an effective relative angle between the ship and the waves. Each index, $C_{S,i}$, is calculated according to the following formula:

$C_{S,i} = 1$, if either:

1. the mean wind heeling lever $\bar{l}_{wind,tot}$ (according to 2.2.3.2.2) exceeds the righting lever, GZ , at each angle of heel to leeward, or

⁴ Refer to the procedure described in the *Interim guidelines for alternative assessment of the weather criterion* (MSC.1/Circ.1200).

.2 the stable heel angle under the action of steady wind, ϕ_S , is greater than the angle of failure to leeward, $\phi_{fail,+}$; and

$$= 1 - \exp(-r_{EA} T_{exp}), \text{ otherwise;}$$

where:

Heel angles are to be taken as positive to leeward and negative to windward;

T_{exp} = exposure time, to be taken as equal to 3600 s;

$$r_{EA} = \frac{1}{T_{z,C_S}} \cdot \left[\exp\left(-\frac{1}{2 \cdot RI_{EA+}^2}\right) + \exp\left(-\frac{1}{2 \cdot RI_{EA-}^2}\right) \right] \text{ (1/s);}$$

$$RI_{EA+} = \frac{\sigma_{C_S}}{\delta\phi_{res,EA+}};$$

$$RI_{EA-} = \frac{\sigma_{C_S}}{\delta\phi_{res,EA-}};$$

T_{z,C_S} = reference average zero-crossing period of the effective relative roll motion under the action of wind and waves determined according to 2.2.3.2.3 (s);

σ_{C_S} = standard deviation of the effective relative roll motion under the action of wind and waves determined according to 2.2.3.2.3 (rad);

$\delta\phi_{res,EA+}$ = range of residual stability to the leeward equivalent area limit angle, to be calculated as

$$\phi_{EA+} - \phi_S \text{ (rad);}$$

$\delta\phi_{res,EA-}$ = range of residual stability to the windward equivalent area limit angle, to be calculated as

$$\phi_S - \phi_{EA-} \text{ (rad);}$$

ϕ_{EA+} = equivalent area virtual limit angle to leeward, to be calculated as

$$\phi_{EA+} = \phi_S + \left(\frac{2 \cdot A_{res,+}}{GM_{res}} \right)^{1/2} \text{ (rad);}$$

ϕ_{EA-} = equivalent area virtual limit angle to windward, to be calculated as

$$\phi_{EA-} = \phi_S - \left(\frac{2 \cdot A_{res,-}}{GM_{res}} \right)^{1/2} \text{ (rad);}$$

- φ_S = stable heel angle due to the mean wind heeling lever, $\bar{l}_{wind,tot}$, determined according to 2.2.3.2.2 (rad);
- $A_{res,+}$ = area under the residual righting lever curve (i.e., $GZ - \bar{l}_{wind,tot}$) from φ_S to $\varphi_{fail,+}$ (m rad);
- $A_{res,-}$ = area under the residual righting lever curve (i.e., $GZ - \bar{l}_{wind,tot}$) from $\varphi_{fail,-}$ to φ_S (m rad);
- GM_{res} = residual metacentric height, to be taken as the slope of the residual righting lever curve (i.e., $GZ - \bar{l}_{wind,tot}$) at φ_S (m);
- $\varphi_{fail,+}$ = angle of failure to leeward, to be taken as $\min\{\varphi_{VW,+}, \varphi_{crit,+}\}$ (rad);
- $\varphi_{fail,-}$ = angle of failure to windward, to be taken as $\max\{\varphi_{VW,-}, \varphi_{crit,-}\}$ (rad);
- $\varphi_{VW,+}$ = angle of second intercept to leeward between the mean wind heeling lever $\bar{l}_{wind,tot}$ and the GZ curve;
- $\varphi_{VW,-}$ = angle of second intercept to windward between the mean wind heeling lever $\bar{l}_{wind,tot}$ and the GZ curve;
- $\varphi_{crit,+}$ = critical angle to leeward, to be taken as $\min\{\varphi_{f,+}, 50 \text{ deg}\}$ (rad);
- $\varphi_{crit,-}$ = critical angle to windward, to be taken as $\max\{\varphi_{f,-}, -50 \text{ deg}\}$ (rad);
- $\varphi_{f,+}, \varphi_{f,-}$ = angles of downflooding to leeward and windward, respectively, in accordance with the definition of "angle of downflooding" in the 2008 IS Code, Part A, 2.3.1 (rad);

2.2.3.2.2 The mean wind heeling lever $\bar{l}_{wind,tot}$ is a constant value at all angles of heel and is calculated according to the following formula:

$$\bar{l}_{wind,tot} = \frac{\bar{M}_{wind,tot}}{\rho \cdot g \cdot \nabla} \text{ (m)}$$

where:

$\bar{M}_{wind,tot}$ = mean wind heeling moment, to be calculated as:

$$\frac{1}{2} \rho_{air} \cdot U_w^2 \cdot C_{whm} \cdot A_L \cdot Z \quad \text{(N m)}$$

U_w = mean wind speed, to be calculated as:

$$\left(\frac{H_S}{0.06717} \right)^{2/3} \quad \text{(m/s)}$$

Different expressions can be used when considering alternative environmental conditions, in accordance with 2.2.1.6;

C_{whm} = wind heeling moment coefficient, to be taken as equal to 1.22 or as determined by other methods;

H_S = significant wave height for the short-term environmental condition under consideration, according to 2.7.2.

2.2.3.2.3 For the short-term environmental condition under consideration, the reference average zero-crossing period of the effective relative roll motion, T_{z,C_S} , and the corresponding standard deviation, σ_{C_S} , to be used in the calculation of the short-term dead ship stability failure index, $C_{S,i}$, are determined using the spectrum of the effective relative roll motion under to the action of wind and waves, in accordance with the following formulae:

$$\sigma_{C_S} = (m_0)^{1/2} \text{ (rad)}$$

$$T_{z,C_S} = 2\pi \cdot (m_0 / m_2)^{1/2} \text{ (s)}$$

where:

m_0 = area under the spectrum $S(\omega)$ (rad²);

m_2 = area under the function of $\omega^2 \cdot S(\omega)$ (rad⁴/s²);

$S(\omega)$ = spectrum of the effective relative roll angle, to be calculated as follows:

$$H_{rel}^2(\omega) \cdot S_{\alpha\alpha,c}(\omega) + H^2(\omega) \cdot \frac{S_{\delta M_{wind,tot}}(\omega)}{(\rho \cdot g \cdot \nabla \cdot GM)^2} \text{ (rad}^2\text{/(rad/s))}$$

$$H_{rel}^2(\omega) = \frac{\omega^4 + (2 \cdot \mu_e \cdot \omega)^2}{(\omega_{0,e}^2 - \omega^2)^2 + (2 \cdot \mu_e \cdot \omega)^2}$$

$$H^2(\omega) = \frac{\omega_0^4}{(\omega_{0,e}^2 - \omega^2)^2 + (2 \cdot \mu_e \cdot \omega)^2}$$

$S_{\alpha\alpha,c}(\omega)$ = spectrum of the effective wave slope, to be calculated as

$$r^2(\omega) \cdot S_{\alpha\alpha}(\omega) \text{ (rad}^2\text{/(rad/s))}$$

$S_{\alpha\alpha}(\omega)$ = spectrum of the wave slope, to be calculated as

$$\frac{\omega^4}{g^2} \cdot S_{zz}(\omega) \text{ (rad}^2\text{/(rad/s))}$$

$S_{zz}(\omega)$ = sea wave elevation energy spectrum (m²/(rad/s)). The standard expression for $S_{zz}(\omega)$ is defined in 2.7.2.1.1.

Different expressions can be used when considering alternative environmental conditions, in accordance with 2.2.1.6;

$S_{\delta M_{wind,tot}}(\omega)$ = spectrum of moment due to the action of the gust, to be calculated as

$$\left[\rho_{air} \cdot U_w \cdot C_{whm} \cdot A_L \cdot Z \right]^2 \cdot \chi^2(\omega) \cdot S_v(\omega) \quad ((N \cdot m)^2/(rad/s))$$

$\chi(\omega)$ = standard aerodynamic admittance function, to be taken as a constant equal to 1.0;

$S_v(\omega)$ = gustiness spectrum. The standard expression for $S_v(\omega)$ is as follows:

$$4 \cdot K \cdot \frac{U_w^2}{\omega} \cdot \frac{X_D^2}{(1 + X_D^2)^{\frac{4}{3}}} \quad ((m/s)^2/(rad/s))$$

with $K = 0.003$ and $X_D = 600 \cdot \omega / (\pi \cdot U_w)$. Different expressions can be used when considering alternative environmental conditions in accordance with 2.2.1.6;

μ_e = equivalent linear roll damping coefficient (1/s), calculated according to the stochastic linearization method. This coefficient depends on linear and nonlinear roll damping coefficients and on the specific roll velocity standard deviation in the considered short-term environmental conditions;

$\omega_{0,e}(\varphi_s)$ = modified roll natural frequency close to the heel angle, φ_s , to be calculated as:

$$\omega_0 \cdot \left(\frac{GM_{res}}{GM} \right)^{1/2} \quad (rad/s);$$

ω_0 = upright natural roll frequency = $2\pi/T_r$ (rad/s);

$r(\omega)$ = effective wave slope function determined according to 2.2.3.2.4;

and other variables as defined in 2.2.3.2.1 and 2.2.3.2.2.

2.2.3.2.4 The effective wave slope function, $r(\omega)$, should be specified using a reliable method, based on computations or derived from experimental data,⁵ and accepted by the Administration.

2.2.3.2.5 In the absence of sufficient information, the recommended methodology for the estimation of the effective wave slope function should be used, which is based on the following assumptions and approximations:

- .1 The underwater part of each transverse section of the ship is substituted by an "equivalent underwater section" having, in general, the same breadth at waterline and the same underwater sectional area of the original section;

⁵ Refer to the procedure described in *the Interim guidelines for alternative assessment of the weather criterion* (MSC.1/Circ.1200) for guidance.

However:

- .1 sections having zero breadth at waterline, such as those in the region of the bulbous bow, are neglected; and
 - .2 the draught of the "equivalent underwater section" is limited to the ship sectional draught.
- .2 The effective wave slope coefficient for each wave frequency is determined by using the "equivalent underwater sections" considering only the undisturbed linear wave pressure; and
- .3 For each section a formula is applied which is exact for rectangles.

2.2.3.2.6 The recommended methodology is applied considering the actual trim of the ship. The recommended methodology for the estimation of the effective wave slope is applicable only to monohull ships. For a ship that does not fall in this category, alternative prediction methods should be applied.

2.3 Assessment of ship vulnerability to the excessive acceleration failure mode

2.3.1 Application

2.3.1.1 The provisions given hereunder apply to each ship in each loading condition provided that:

- .1 the distance from the waterline to the highest location along the length of the ship where passengers or crew may be present exceeds 70% of the breadth of the ship; and
- .2 the metacentric height exceeds 8% of the breadth of the ship.

2.3.1.2 For each loading condition and location along the length of the ship where passengers or crew may be present, a ship that:

- .1 meets the standard contained in the criteria contained in 2.3.2 is considered not to be vulnerable to the excessive acceleration failure mode; and
- .2 does not meet the standard contained in the criteria contained in 2.3.2 should be subject to more detailed assessment of vulnerability to the excessive acceleration failure mode by applying the criteria contained in 2.3.3.

2.3.1.3 Alternatively to the criteria contained in 2.3.2 or 2.3.3, for each loading condition a ship may be subject to either:

- .1 direct stability assessment for the excessive acceleration failure mode that is performed in accordance with chapter 3; or
- .2 operational measures developed in accordance with chapter 4.

2.3.1.4 A detailed assessment of Level 2 vulnerability according to the criteria contained in 2.3.3 may be performed without the requirement to perform a more simplified assessment in 2.3.2. Similarly, a detailed direct stability assessment as provided in 2.3.1.3.1 may be

performed without the requirement to perform a more simplified assessment in 2.3.2 or 2.3.3.

2.3.1.5 Stability limit information for determining the safe zones as functions of GM, draught and trim is to be provided based on matrix calculations according to the criteria contained in sections 2.3.2 or 2.3.3 and, if appropriate, direct stability assessment according to the provisions in chapter 3 on direct stability assessment. If relevant, the stability limit information for determining safe zones should take into account operational measures or operational guidance according to the provisions in chapter 4 on operational measures.

2.3.1.6 Reference environmental conditions to be used in the assessment may be modified, according to the Guidelines for operational measures in chapter 4.

2.3.1.7 Free surface corrections should not be applied.

2.3.2 Level 1 vulnerability criterion for the excessive acceleration failure mode

2.3.2.1 A ship is considered not to be vulnerable to the excessive acceleration stability failure mode if, for each loading condition and location along the length of the ship where passengers or crew may be present,

$$\varphi \cdot k_L \cdot (g + 4\pi^2 h_r / T_r^2) \leq R_{EA1}$$

where:

$$R_{EA1} = 4.64 \text{ (m/s}^2\text{)}$$

$$\varphi = \text{characteristic roll amplitude (rad)} = 4.43 r s / \delta_\varphi^{0.5};$$

$$k_L = \text{factor taking into account simultaneous action of roll, yaw and pitch motions,}$$

$$= 1.125 - 0.625 x / L, \quad \text{if } x < 0.2 L,$$

$$= 1.0, \quad \text{if } 0.2 L \leq x \leq 0.65 L,$$

$$= 0.527 + 0.727 x / L, \quad \text{if } x > 0.65 L;$$

$$x = \text{longitudinal distance (m) of the location where passengers or crew may be present from the aft end of } L;$$

$$h_r = \text{height above the assumed roll axis of the location where passengers or crew may be present (m), for which definition, the roll axis may be assumed to be located at the midpoint between the waterline and the vertical centre of gravity;}$$

$$r = \text{effective wave slope coefficient} = \frac{K_1 + K_2 + (OG)(F)}{\frac{B^2}{12C_B d} - \frac{C_B d}{2} - OG};$$

$$K_1 = g \beta T_r^2 (\tau + \tau \tilde{\tau} - 1 / \tilde{\tau}) / (4 \pi^2);$$

$$K_2 = g \tau T_r^2 (\beta - \cos \tilde{\beta}) / (4 \pi^2);$$

$$OG = KG - d;$$

$$F = \beta (\tau - 1 / \tilde{\tau});$$

$$\beta = \sin(\tilde{\beta}) / \tilde{\beta};$$

- τ = $\exp(-\tilde{\tau}) / \tilde{\tau}$;
 \tilde{B} = $2 \pi^2 B / (g T_r^2)$;
 \tilde{T} = $4 \pi^2 C_B d / (g T_r^2)$;
 s = wave steepness as a function of the natural roll period T_r (see 2.7.1), as determined from table 2.3.2.1; and
 δ_φ = non-dimensional logarithmic decrement of roll decay.

Table 2.3.2.1 – Values of wave steepness, s
(Intermediate values in the table should be obtained by linear interpolation)

Natural roll period, T_r (s)	Wave steepness, s
≤ 6	0.100
7	0.098
8	0.093
12	0.065
14	0.053
16	0.044
18	0.038
20	0.032
22	0.028
24	0.025
26	0.023
28	0.021
≥ 30	0.020

2.3.3 Level 2 vulnerability criterion for the excessive acceleration failure mode

2.3.3.1 A ship in a loading condition is considered not to be vulnerable to the excessive acceleration stability failure mode if, for each location along the length of the ship where passengers or crew may be present:

$$C \leq R_{EA2}$$

where:

$$R_{EA2} = 0.00039;$$

C = long-term probability index that measures the vulnerability of the ship to a stability failure due to excessive acceleration for the loading condition and location under consideration based on the probability of occurrence of short-term environmental conditions, as specified according to 2.3.3.2.

2.3.3.2 The value of C is calculated as a weighted average from a set of short-term environmental conditions, as follows:

$$C = \sum_{i=1}^N W_i C_{S,i}$$

where:

W_i = weighting factor for the short-term environmental condition, as specified in 2.7.2;

$C_{S,i}$ = short-term excessive acceleration failure index for the short-term environmental condition under consideration, calculated as specified in 2.3.3.2.1; and

N = total number of short-term environmental conditions, according to 2.7.2.

2.3.3.2.1 The short-term excessive acceleration failure index, $C_{S,i}$, for the loading condition, location and for the short-term environmental condition under consideration is a measure of the probability that the ship will exceed a specified lateral acceleration, calculated according to the following formula:

$$C_{S,i} = \exp(-R_2^2 / (2 \sigma_{LAI}^2));$$

where:

R_2 = 9.81 (m/s²);

σ_{LAI} = standard deviation of the lateral acceleration at zero speed and in a beam seaway determined according to 2.3.3.2.2 (m/s²).

2.3.3.2.2 The standard deviation of the lateral acceleration at zero speed and in a beam seaway, σ_{LAI} , is determined using the spectrum of roll motion due to the action of waves. The square of this standard deviation is calculated according to the following formula:

$$\sigma_{LAI}^2 = \frac{3}{4} \sum_{j=1}^N (a_y(\omega_j))^2 S_{zz}(\omega_j) \Delta\omega$$

where:

$\Delta\omega$ = interval of wave frequency (rad/s) = $(\omega_2 - \omega_1) / N$ (rad/s);

ω_2 = upper frequency limit of the wave spectrum in the evaluation range = $\min((25 / T_r), 2.0)$ (rad/s);

ω_1 = lower frequency limit of the wave spectrum in the evaluation range = $\max((0.5 / T_r), 0.2)$ (rad/s);

N = number of intervals of wave frequency in the evaluation range, not to be taken less than 100;

ω_j = wave frequency at the mid-point of the considered frequency interval = $\omega_1 + ((2j - 1) / 2) \Delta\omega$ (rad/s);

$S_{zz}(\omega_j)$ = sea wave elevation spectrum (m²/(rad/s)). The standard expression for $S_{zz}(\omega)$ is defined in 2.7.2.1.1;

$a_y(\omega_j)$ = lateral acceleration = $k_L (g + h_r \cdot \omega_j^2) \cdot \phi_a(\omega_j)$ per unit wave amplitude ((m/s²)/m);

k_L, h_r = as defined in 2.3.2.1;

$\phi_a(\omega_j)$ = roll amplitude in regular beam waves of unit amplitude and circular frequency ω_j at zero speed, = $(\phi_r(\omega_j)^2 + \phi_i(\omega_j)^2)^{0.5}$ (rad/m);

$$\varphi_r(\omega_j) = \frac{a \left(\frac{\rho g \nabla GM}{1000} - J_{T,roll} \omega_j^2 \right) + b B_e \omega_j}{\left(\frac{\rho g \nabla GM}{1000} - J_{T,roll} \omega_j^2 \right)^2 + (B_e \omega_j)^2} \quad (\text{rad/m});$$

$$\varphi_i(\omega_j) = \frac{b \left(\frac{\rho g \nabla GM}{1000} - J_{T,roll} \omega_j^2 \right) - a B_e \omega_j}{\left(\frac{\rho g \nabla GM}{1000} - J_{T,roll} \omega_j^2 \right)^2 + (B_e \omega_j)^2} \quad (\text{rad/m});$$

a, b = cosine and sine components, respectively, of the Froude-Krylov roll moment in regular beam waves of unit amplitude (kN·m/m), calculated directly or using an appropriate approximation;

B_e = equivalent linear roll damping factor (kN m s), with $B_e = 2J_{T,roll} \mu_e$ where μ_e (1/s) is the equivalent linear roll damping coefficient;

$J_{T,roll}$ = roll moment of inertia comprising added inertia = $\frac{1}{1000} \frac{\rho g \nabla GM T_r^2}{4\pi^2}$ (t·m²).

Other suitable formulations for the numerical integration in the range from ω_1 to ω_2 can be used as an alternative.

2.4 Assessment of ship vulnerability to the pure loss of stability failure mode

2.4.1 Application

2.4.1.1 The provisions given hereunder apply to all ships, except for ships with an extended low weather deck,⁶ for which the Froude number, Fn , corresponding to the service speed exceeds 0.24.

2.4.1.2 For each loading condition, a ship that:

- .1 meets the standard contained in the criteria contained in 2.4.2 is considered not to be vulnerable to the pure loss of stability failure mode; and
- .2 does not meet the standard contained in the criteria contained in 2.4.2 should be subject to more detailed assessment of vulnerability to the pure loss of stability failure mode by applying the criteria contained in 2.4.3.

2.4.1.3 Alternatively to the criteria contained in 2.4.2 or 2.4.3, for each loading condition a ship may be subject to either:

- .1 direct stability assessment for the pure loss of stability failure mode that is performed according to the Guidelines for direct stability assessment in chapter 3; or
- .2 operational measures according to the Guidelines for operational measures in chapter 4.

⁶ The criteria for this failure mode may not be applicable to a ship with an extended low weather deck due to increased likelihood of water on deck or deck-in-water.

2.4.1.4 A detailed assessment of Level 2 vulnerability according to the criteria contained in 2.4.3 may be performed without the requirement to perform a more simplified assessment in 2.4.2. Similarly, a detailed direct stability assessment, as provided in 2.4.1.3.1, may be performed without the requirement to perform a more simplified assessment in 2.4.2 or 2.4.3.

2.4.1.5 Stability limit information for determining the safe zones as functions of GM , draught and trim is to be provided based on matrix calculations according to the criteria contained in sections 2.4.2 or 2.4.3 and, if appropriate, direct stability assessment according to the provisions in chapter 3 on direct stability assessment. If relevant, the stability limit information for determining safe zones should take into account operational measures according to the provisions in chapter 4.

2.4.1.6 Reference environmental conditions to be used in the assessment may be modified, according to the Guidelines for operational measures in chapter 4.

2.4.1.7 Free surface effect should be accounted for as recommended in chapter 3 of part B of the 2008 IS Code.

2.4.2 Level 1 vulnerability criterion for the pure loss of stability failure mode

2.4.2.1 A ship is considered not to be vulnerable to the pure loss of stability failure mode, if:

$$GM_{\min} \geq R_{PLA} \text{ and } \frac{\nabla_D - \nabla}{A_w(D-d)} \geq 1.0$$

where:

$$R_{PLA} = 0.05 \text{ (m); and}$$

$$GM_{\min} = \text{minimum value of the metacentric height (m) calculated as provided in 2.4.2.2.}$$

2.4.2.2 As provided by 2.4.2.1, GM_{\min} should be determined according to:

$$GM_{\min} = KB + \frac{I_{TL}}{\nabla} - KG$$

where:

$$I_{TL} = \text{transverse moment of inertia of the waterplane at the draft } d_L \text{ (m}^4\text{);}$$

$$d_L = d - \delta d_L \text{ (m);}$$

$$\delta d_L = \min\left(d - 0.25d_{full}, \frac{L \cdot S_W}{2}\right) \text{ (m);}$$

and $d - 0.25d_{full}$ should not be taken less than zero; and

$$S_W = 0.0334.$$

2.4.2.3 The use of the simplified conservative estimation of GM_{\min} described in 2.4.2.2 without initial trim effect can be applied for ships having non-even keel condition.

2.4.3 Level 2 vulnerability criteria for the pure loss of stability failure mode

2.4.3.1 A ship is considered not to be vulnerable to the pure loss of stability failure mode if, when underway at the service speed, V_s ,

$$\max(CR_1, CR_2) \leq R_{PL0}$$

where:

$$R_{PL0} = 0.06; \text{ and}$$

$$CR_1, CR_2 = \text{criteria calculated according to 2.4.3.2.}$$

2.4.3.2 Each of the two criteria, CR_1 and CR_2 in 2.4.3.1, represents a weighted average of certain stability parameters for a ship considered to be statically positioned in waves of defined height, H_i , and length, λ_i , obtained according to 2.4.3.2.2. CR_1 and CR_2 are calculated as follows:

$$CR_1 = \sum_{i=1}^N W_i C1_i$$

$$CR_2 = \sum_{i=1}^N W_i C2_i$$

where:

CR_1 = weighted criterion 1, computed using Criterion 1, $C1_i$, as evaluated according to 2.4.3.3;

CR_2 = weighted criterion 2, computed using Criterion 2, $C2_i$, as evaluated according to 2.4.3.4;

W_i = weighting factor for the short-term environmental condition, as specified in 2.4.3.2.2;

N = total number of wave cases for which $C1_i$ and $C2_i$ are evaluated, according to 2.4.3.2.2.

2.4.3.2.1 For calculating the restoring moment in waves, the following wavelength and wave heights should be used:

Length $\lambda = L$; and

Height $h = 0.01 \cdot iL$ $i = 0, 1, \dots, 10$.

The index for the two criteria, based on φ_v and φ_s , should be calculated according to the formulations given in 2.4.3.3 and 2.4.3.4, respectively. This is undertaken for the loading condition under consideration and the ship assumed to be balanced in sinkage and trim in a series of waves with the characteristics as described above.

In these waves to be studied, the wave crest is to be centred amidships, and at $0.1L$, $0.2L$, $0.3L$, $0.4L$ and $0.5L$ forward and $0.1L$, $0.2L$, $0.3L$ and $0.4L$ aft thereof.

2.4.3.2.2 For each combination of H_s and T_z specified in 2.7.2, W_i is obtained as the value in table 2.7.2.1.2 divided by the amount of observations given in this table, which is associated with a H_i as calculated in 2.4.3.2.3 below and λ_i is taken as equal to L . The indices for each H_i should be linearly interpolated from the relationship between h used in 2.4.3.2.1 and the indices obtained in 2.4.3.2.1 above.

2.4.3.2.3 The 3% largest effective wave height, H_i , for use in the evaluation of the requirements is calculated by filtering waves within the ship length. For this purpose, an appropriate wave spectrum shape should be assumed.

2.4.3.3 Criterion 1

Criterion 1, $C1_i$, is a criterion based on the calculation of the angle of vanishing stability, φ_V , as provided in the following formula:

$$C1_i = \begin{cases} 1 & \varphi_V < K_{PL1} \\ 0 & \text{otherwise} \end{cases}$$

where:

$$K_{PL1} = 30 \text{ (deg)}$$

The angle of vanishing stability, φ_V , should be determined as the minimum value calculated, as provided in 2.4.3.2.1, 2.4.3.2.2 and 2.4.3.2.3 for the ship without consideration of the angle of downflooding.

2.4.3.4 Criterion 2

Criterion 2, $C2_i$, is a criterion based on the calculation of the angle of heel, φ_{sw} , under action of heeling lever specified by l_{PL2} as provided in the following formula:

$$C2_i = \begin{cases} 1 & \varphi_{sw} > K_{PL2} \\ 0 & \text{otherwise} \end{cases}$$

where:

$$K_{PL2} = 15 \text{ degrees for passenger ships; and}$$

$$= 25 \text{ degrees for all other ship types}$$

$$l_{PL2} = 8(H_i/\lambda) dFn^2 \text{ (m);}$$

$$H_i = \text{as provided in 2.4.3.2.2 and 2.4.3.2.3;}$$

$$\lambda = \text{as provided in 2.4.3.2.2;}$$

The angle of heel, φ_{sw} , should be determined as the maximum value calculated as provided in 2.4.3.2.1, 2.4.3.2.2 and 2.4.3.2.3, for the ship without consideration of the angle of downflooding.

2.5 Assessment of ship vulnerability to the parametric rolling failure mode

2.5.1 Application

2.5.1.1 For each loading condition, a ship that:

- .1 meets the standard contained in the criteria contained in 2.5.2 is considered not to be vulnerable to the parametric rolling failure mode;
- .2 does not meet the standard contained in the criteria contained in 2.5.2 should be subject to more detailed assessment of vulnerability to the parametric rolling failure mode by applying the criteria contained in 2.5.3.

2.5.1.2 Alternatively to the criteria contained in 2.5.2 or 2.5.3, for each loading condition a ship may be subject to either:

- .1 a direct stability assessment for the parametric rolling failure mode that is performed according to the Guidelines for direct stability assessment in chapter 3; or
- .2 operational measures for the parametric rolling failure mode according to the Guidelines for operational measures in chapter 4.

2.5.1.3 A detailed assessment of Level 2 vulnerability according to the criteria contained in 2.5.3 may be performed without the requirement to perform a more simplified assessment in 2.5.2. Similarly, a detailed direct stability assessment as provided in 2.5.1.3.1 may be performed without the requirement to perform a more simplified assessment in 2.5.2 or 2.5.3.

2.5.1.4 Stability limit information for determining the safe zones as functions of GM, draught and trim is to be provided based on matrix calculations according to the criteria contained in 2.5.2 or 2.5.3 and, if appropriate, direct stability assessment according to the provisions in chapter 3 on direct stability assessment. If relevant, the stability limit information for determining safe zones should take into account operational measures according to the provisions in chapter 4.

2.5.1.5 Reference environmental conditions to be used in the assessment may be modified, according to the Guidelines for operational measures in chapter 4.

2.5.1.6 Free surface effects should be accounted for as recommended in chapter 3 of part B of 2008 IS Code.

2.5.2 Level 1 vulnerability criterion for the parametric rolling failure mode

2.5.2.1 A ship is considered not to be vulnerable to the parametric rolling failure mode if

$$\frac{\delta GM_1}{GM} \leq R_{PR} \quad \text{and} \quad \frac{\nabla_D - \nabla}{A_W(D-d)} \geq 1.0$$

where:

$$\begin{aligned} R_{PR} &= 1.87, \text{ if the ship has a sharp bilge; and, otherwise,} \\ &= 0.17 + 0.425 \left(\frac{100A_k}{LB} \right), \text{ if } C_{m,full} > 0.96; \\ &= 0.17 + (10.625 \times C_{m,full} - 9.775) \left(\frac{100A_k}{LB} \right), \text{ if } 0.94 \leq C_{m,full} \leq 0.96; \\ &= 0.17 + 0.2125 \left(\frac{100A_k}{LB} \right), \text{ if } C_{m,full} < 0.94; \text{ and} \\ &\text{for each formula, } \left(\frac{100A_k}{LB} \right) \text{ should not exceed 4;} \\ \delta GM_1 &= \text{amplitude of the variation of the metacentric height (m) calculated as provided in 2.5.2.2.} \end{aligned}$$

2.5.2.2 As provided by 2.5.2.1, δGM_1 should be determined according to:

$$\delta GM_1 = \frac{I_{TH} - I_{TL}}{2V}$$

where:

$$\delta d_H = \min\left(D - d, \frac{L \cdot S_W}{2}\right) \text{ (m);}$$

$$\delta d_L = \min\left(d - 0.25d_{full}, \frac{L \cdot S_W}{2}\right) \text{ (m);}$$

and $d - 0.25d_{full}$ should not be taken less than zero;

$$d_H = d + \delta d_H \text{ (m);}$$

$$d_L = d - \delta d_L \text{ (m);}$$

$$S_W = 0.0167;$$

I_{TH} = transverse moment of inertia of the waterplane at the draft d_H (m⁴); and

I_{TL} = transverse moment of inertia of the waterplane at the draft d_L (m⁴).

2.5.2.3 The use of the simplified conservative estimation of δGM_1 described in 2.5.2.2, without initial trim effect, can be applied for ships having a non-even keel condition.

2.5.3 Level 2 vulnerability criteria for the parametric rolling failure mode

2.5.3.1 A ship is considered not to be vulnerable to the parametric rolling failure mode, if

.1 $C1 \leq R_{PR1}$; or

.2 $C2 \leq R_{PR2}$;

where:

$$R_{PR1} = 0.06;$$

$$R_{PR2} = 0.025;$$

$C1$ = criterion calculated according to 2.5.3.2; and

$C2$ = criterion calculated according to 2.5.3.3.

2.5.3.2 The value for $C1$ is calculated as a weighted average from a set of waves specified in 2.5.3.2.3, as:

$$C1 = \sum_{i=1}^N W_i C_i$$

where:

W_i = weighting factor for the respective wave specified in 2.5.3.2.3;

- C_i = 0, if the requirements of either the variation of GM in waves contained in 2.5.3.2.1 or the ship speed in waves contained in 2.5.3.2.2 is satisfied;
= 1, if not;
- N = the number of wave cases evaluated, as specified in 2.5.3.2.3.

2.5.3.2.1 For each wave specified in 2.5.3.2.3, the requirement for the variation of GM in waves is satisfied if:

$$GM(H_i, \lambda_i) > 0 \quad \text{and} \quad \frac{\delta GM(H_i, \lambda_i)}{GM(H_i, \lambda_i)} < R_{PR}$$

where:

- R_{PR} = as defined in 2.5.2.1;
- $\delta GM(H_i, \lambda_i)$ = one-half the difference between the maximum and minimum values of the metacentric height calculated for the ship (m), corresponding to the loading condition under consideration, considering the ship to be balanced in sinkage and trim on a series of waves characterized by a wave height H_i , and a wavelength λ_i ;
- $GM(H_i, \lambda_i)$ = the average value of the metacentric height calculated for the ship (m), corresponding to the loading condition under consideration, considering the ship to be balanced in sinkage and trim on a series of waves characterized by a wave height H_i , and a wavelength λ_i ;
- H_i = wave height specified in 2.5.3.2.3 (m); and
- λ_i = wavelength specified in 2.5.3.2.3 (m).

2.5.3.2.2 For each wave specified in 2.5.3.2.3, the requirement for the ship speed in waves is satisfied if:

$$V_{PRi} > V_s$$

where:

- V_{PRi} = the reference ship speed (m/s) corresponding to parametric resonance conditions, when $GM(H_i, \lambda_i) > 0$:
- $$= \left| \frac{2\lambda_i}{T_r} \cdot \sqrt{\frac{GM(H_i, \lambda_i)}{GM}} - \sqrt{g \frac{\lambda_i}{2\pi}} \right|$$
- $GM(H_i, \lambda_i)$ = as defined in 2.5.3.2.1 (m);
- λ_i = wavelength specified in 2.5.3.2.3 (m);
- $||$ = the absolute value operation.

2.5.3.2.3 The specified wave cases for evaluation of the requirements contained in 2.5.3.2.1 and 2.5.3.2.2 are presented in table 2.5.3.2.3. In table 2.5.3.2.3, W_i , H_i , λ_i are as defined in 2.5.3.2.

Table 2.5.3.2.3
Wave cases for parametric rolling evaluation

Wave case number	Weight factor W_i	Wavelength λ_i (m)	Wave height H_i (m)
1	0.000013	22.574	0.350
2	0.001654	37.316	0.495
3	0.020912	55.743	0.857
4	0.092799	77.857	1.295
5	0.199218	103.655	1.732
6	0.248788	133.139	2.205
7	0.208699	166.309	2.697
8	0.128984	203.164	3.176
9	0.062446	243.705	3.625
10	0.024790	287.931	4.040
11	0.008367	335.843	4.421
12	0.002473	387.440	4.769
13	0.000658	442.723	5.097
14	0.000158	501.691	5.370
15	0.000034	564.345	5.621
16	0.000007	630.684	5.950

2.5.3.2.4 In the calculation of $\delta GM(H_i, \lambda_i)$ and $GM(H_i, \lambda_i)$ in 2.5.3.2.1, the wave crest should be located amidships, and at $0.1 \lambda_i$, $0.2 \lambda_i$, $0.3 \lambda_i$, $0.4 \lambda_i$, and $0.5 \lambda_i$ forward and $0.1 \lambda_i$, $0.2 \lambda_i$, $0.3 \lambda_i$, and $0.4 \lambda_i$ aft thereof.

2.5.3.3 The value of $C2$ is calculated as an average of values of $C2(Fn_i, \beta_i)$, each of which is a weighted average from the set of waves specified in 2.5.3.4.2, for each set of Froude numbers and wave directions specified:

$$C2 = \left[\sum_{i=1}^{12} C2(Fn_i, \beta_h) + \frac{1}{2} \{ C2(0, \beta_h) + C2(0, \beta_f) \} + \sum_{i=1}^{12} C2(Fn_i, \beta_f) \right] / 25$$

where:

$C2(Fn_i, \beta_h) = C2(Fn, \beta)$ calculated as specified in 2.5.3.3.1 with the ship proceeding in head waves with a speed equal to V_i ;

$C2(Fn_i, \beta_f) = C2(Fn, \beta)$ calculated as specified in 2.5.3.3.1 with the ship proceeding in following waves with a speed equal to V_i ;

$Fn_i = V_i / \sqrt{Lg}$, Froude number corresponding to ship speed V_i ;

$V_i = V_s \cdot K_i$, ship speed (m/s); and

$K_i =$ as obtained from table 2.5.3.3.

Table 2.5.3.3
Speed factor, K_i

i	K_i
1	1.0
2	0.991
3	0.966
4	0.924
5	0.866
6	0.793
7	0.707
8	0.609
9	0.500
10	0.383
11	0.259
12	0.131

2.5.3.3.1 The weighted criteria $C2(Fn_i, \beta)$ are calculated as a weighted average of the short-term parametric rolling failure index considering the set of waves specified in 2.5.3.4.2, for a given Froude number and wave direction, as follows:

$$C2(Fn_i, \beta) = \sum_{i=1}^N W_i C_{S,i}$$

where:

- W_i = weighting factor for the respective wave cases specified in 2.5.3.4.2;
- $C_{S,i}$ = 1, if the maximum roll angle evaluated according to 2.5.3.4 exceeds 25 degrees, and
= 0, otherwise;
- N = total number of wave cases for which the maximum roll angle is evaluated for a combination of speed and heading.

2.5.3.4 The maximum roll angle in head and following waves is evaluated as recommended in 2.5.3.4.1 for each speed, V_i , defined in 2.5.3.3. For each evaluation, the calculation of stability in waves should assume the ship to be balanced in sinkage and trim on a series of waves with the following characteristics:

- wavelength, $\lambda = L$;
- wave height, $h_j = 0.01 \cdot jL$, where $j = 0, 1, \dots, 10$.

For each wave height, h_j , the maximum roll angle is evaluated.

2.5.3.4.1 The evaluation of roll angle should be carried out using the time domain simulation method with GZ calculated in waves.

2.5.3.4.2 W_i is obtained as the value in table 2.7.2.1.2 divided by the number of observations given in the table. Each cell of the table corresponds to an average zero-crossing wave period, T_z , and a significant wave height, H_s . With these two values, a representative wave height, H_{r_i} , should be calculated by filtering waves within the ship length. The maximum roll angle, corresponding to the representative wave height, H_{r_i} , is obtained by linear interpolation of the maximum roll angles for different wave heights, h_j , obtained in 2.5.3.4. This maximum roll angle should be used for the evaluation of $C_{S,i}$ in 2.5.3.3.1.

2.6 Assessment of ship vulnerability to the surf-riding/broaching failure mode

2.6.1 Application

2.6.1.1 For each loading condition, a ship that:

- .1 meets the standard contained in the criteria contained in 2.6.2 is considered not to be vulnerable to the surf-riding/broaching failure mode;
- .2 does not meet the standard contained in the criteria in 2.6.2 should be subject to either:
 - .1 the procedures of ship handling on how to avoid dangerous conditions for surf-riding/broaching, as recommended in section 4.2.1 of the *Revised guidance to the master for avoiding dangerous situations in adverse weather and sea conditions* (MSC.1/Circ.1228), subject to the approval of the Administration; or
 - .2 more detailed assessment of vulnerability to the surf-riding/broaching failure mode by applying the criteria contained in 2.6.3.

2.6.1.2 Alternatively to the criteria contained in 2.6.2 or 2.6.3, for each loading condition a ship may be subject to either:

- .1 direct stability assessment for the surf-riding/broaching failure mode that is performed according to the Guidelines for direct stability assessment in chapter 3; or
- .2 operational measures based on the Guidelines for operational measures in chapter 4.

2.6.1.3 A detailed assessment of Level 2 vulnerability according to the criteria contained in 2.6.3 may be performed without the requirement to perform a more simplified assessment in 2.6.2. Similarly, a detailed direct stability assessment as provided in 2.6.1.3.1 may be performed without the requirement to conduct a more simplified assessment in 2.6.2 or 2.6.3.

2.6.1.4 For ships that do not meet the standard contained in 2.6.2 and which are not applying MSC.1/Circ.1228 according to 2.6.1.1 above, relevant consistent safety information should be provided according to the criteria contained in either 2.6.3 of these Guidelines, Guidelines for direct stability assessment in chapter 3 or Guidelines for operational measures in chapter 4, as appropriate.

2.6.1.5 Reference environmental conditions to be used in the assessment may be modified according to the Guidelines for operational measures in chapter 4.

2.6.2 Level 1 vulnerability criteria for the surf-riding/broaching failure mode

2.6.2.1 A ship is considered not to be vulnerable to the surf-riding/broaching failure mode if:

- .1 $L \geq 200$ m; or
- .2 $Fn \leq 0.3$.

2.6.3 Level 2 vulnerability criterion for the surf-riding/broaching failure mode

2.6.3.1 A ship is considered not to be vulnerable to the surf-riding/broaching failure mode if

$$C \leq R_{SR}$$

where:

$$R_{SR} = 0.005;$$

C = criterion calculated according to 2.6.3.2.

2.6.3.2 The value of C is calculated as

$$C = \sum_{H_s} \sum_{T_z} (W2(H_s, T_z) \sum_{i=0}^{N_\lambda} \sum_{j=0}^{N_a} w_{ij} C2_{ij})$$

where:

$W2(H_s, T_z)$ = weighting factor of short-term sea state specified in 2.7.2.1 as a function of the significant wave height, H_s , and the zero-crossing wave period, T_z , in which $W2(H_s, T_z)$ is equal to the number of occurrences of the combination divided by the total number of occurrences in the table, and it corresponds to the factor W_i specified in 2.7.2;

w_{ij} = statistical weight of a wave specified in 2.6.3.3 with steepness $(H/\lambda)_j$ and wavelength to ship length ratio $(\lambda/L)_i$ calculated with the joint distribution of local wave steepness and lengths, which is, with specified discretization $N_\lambda = 80$ and $N_a = 100$; and

$C2_{ij}$ = coefficient specified in 2.6.3.4.

2.6.3.3 The value of w_{ij} should be calculated using the following formula:

$$w_{ij} = 4 \frac{\sqrt{g} L^{5/2} T_{01}}{\pi v (H_s)^3} s_j^2 r_i^{3/2} \left(\frac{\sqrt{1+v^2}}{1+\sqrt{1+v^2}} \right) \Delta r \Delta s \cdot \exp \left[-2 \left(\frac{L \cdot r_i \cdot s_j}{H_s} \right)^2 \left\{ 1 + \frac{1}{v^2} \left(1 - \sqrt{\frac{g T_{01}^2}{2\pi r_i L}} \right)^2 \right\} \right]$$

where:

$$v = 0.425;$$

$$T_{01} = 1.086 T_z;$$

$$s_j = (H/\lambda)_j = \text{wave steepness varying from 0.03 to 0.15 with increment } \Delta s = 0.0012; \text{ and}$$

r_i = $(\lambda/L)_i$ = wavelength to ship length ratio varying from 1.0 to 3.0 with increment $\Delta r = 0.025$.

2.6.3.4 The value of $C2_{ij}$ is calculated for each wave, as follows:

$$C2_{ij} = \begin{cases} 1 & \text{if } Fn > Fn_{cr}(r_j, s_i) \\ 0 & \text{if } Fn \leq Fn_{cr}(r_j, s_i) \end{cases}$$

where:

Fn_{cr} = critical Froude number corresponding to the threshold of surf-riding (surf-riding occurring under any initial condition) which should be calculated in accordance with 2.6.3.4.1 for the regular wave with steepness s_j and wavelength to ship length ratio r_i .

2.6.3.4.1 The critical Froude number, Fn_{cr} , is calculated as

$$Fn_{cr} = u_{cr} / \sqrt{Lg}$$

where the critical nominal ship speed, u_{cr} (m/s), is determined according to 2.6.3.4.2.

2.6.3.4.2 The critical nominal ship speed, u_{cr} , is determined by solving the following equation with the critical propulsor revolutions, n_{cr} :

$$T_e(u_{cr}; n_{cr}) - R(u_{cr}) = 0$$

where:

$R(u_{cr})$ = calm water resistance (N) of the ship at the ship speed of u_{cr} , see 2.6.3.4.3;

$T_e(u_{cr}; n_{cr})$ = thrust (N) delivered by the ship's propulsor(s) in calm water determined in accordance with 2.6.3.4.4; and

n_{cr} = commanded number of revolutions of propulsor(s) (1/s) corresponding to the threshold of surf-riding (surf-riding occurs under any initial conditions), see 2.6.3.4.6.

2.6.3.4.3 The calm water resistance, $R(u)$, is approximated based on available data with a polynomial fit suitable to represent the characteristics of the resistance for the ship in question. The fit should be appropriate to ensure the resistance is continuously increasing as a function of speed in the appropriate range.

2.6.3.4.4 For a ship using one propeller as the main propulsor, the propulsor thrust, $T_e(u;n)$, in calm water may be approximated using a second degree polynomial:

$$T_e(u;n) = (1 - t_p) \rho n^2 D_p^4 \{ \kappa_0 + \kappa_1 J + \kappa_2 J^2 \} \text{ (N)}$$

where:

u = speed of the ship (m/s) in calm water;

n = commanded number of revolutions of propulsor (1/s);

t_p = approximate thrust deduction factor;

w_p = approximate wake fraction;

$\kappa_0, \kappa_1, \kappa_2$ = approximation coefficients for the approximated propeller thrust coefficient in calm water;

J = $\frac{u(1-w_p)}{nD_p}$ = advance ratio.

In case of a ship having multiple propellers, the overall thrust can be calculated by summing the effect of the individual propellers calculated as indicated above.

For a ship using a propulsor(s) other than a propeller(s), the propulsor thrust should be evaluated by a method appropriate to the type of propulsor used.

2.6.3.4.5 The amplitude of wave surging force for each wave is calculated as:

$$f_{ij} = \rho g k_i \frac{H_{ij}}{2} \sqrt{F_{C_i}^2 + F_{S_i}^2} \text{ (N)}$$

where:

k_i = wave number = $\frac{2\pi}{r_i L}$ (1/m);

H_{ij} = wave height = $s_j r_i L$ (m);

s_j, r_i = as defined in 2.6.3.3;

$$F_{C_i} = \sum_{m=1}^N \delta x_m S(x_m) \sin(k_i x_m) \exp(-0.5k_i \cdot d(x_m))$$

$$F_{S_i} = \sum_{m=1}^N \delta x_m S(x_m) \cos(k_i x_m) \exp(-0.5k_i \cdot d(x_m))$$

F_{C_i} and F_{S_i} are parts of the Froude-Krylov component of the wave surging force (m)

x_m = longitudinal distance from the midship to a station (m), positive for a bow section;

δx_m = length of the ship strip associated with station m (m);

$d(x_m)$ = draft at station m in calm water (m);

$S(x_m)$ = area of submerged portion of the ship at station m in calm water (m²);

N = number of stations; and

m = index of a station.

2.6.3.4.6 The critical number of revolutions of the propulsor corresponding to the surf-riding threshold, $n_{cr}(r_j, s_i)$, can be determined by solving the following quadratic equation:

$$2\pi \frac{T_e(c_i, n_{cr}) - R(c_i)}{f_{ij}} + 8a_0 n_{cr} + 8a_1 - 4\pi a_2 + \frac{64}{3} a_3 - 12\pi a_4 + \frac{1024}{15} a_5 = 0$$

where:

$$a_0 = -\frac{\tau_l}{\sqrt{f_{ij} \cdot k_i \cdot (M + M_x)}};$$

$$a_1 = \frac{r_1 + 2r_2 c_i + 3r_3 c_i^2 + 4r_4 c_i^3 + 5r_5 c_i^4 - 2\tau_2 c_i}{\sqrt{f_{ij} \cdot k_i \cdot (M + M_x)}};$$

$$a_2 = \frac{r_2 + 3r_3c_i + 6r_4c_i^2 + 10r_5c_i^3 - \tau_2}{k_i \cdot (M + M_x)};$$

$$a_3 = \frac{r_3 + 4r_4c_i + 10r_5c_i^2}{\sqrt{k_i^3 (M + M_x)^3}} \cdot \sqrt{f_{ij}};$$

$$a_4 = \frac{r_4 + 5r_5c_i}{k_i^2 (M + M_x)^2} f_{ij};$$

$$a_5 = \frac{r_5}{\sqrt{k_i^5 (M + M_x)^5}} \sqrt{f_{ij}^3};$$

$r_1, r_2, r_3, r_4, r_5 =$ regression coefficients for the calm water resistance under a fifth degree polynomial approximation $R(u) \approx r_1u + r_2u^2 + r_3u^3 + r_4u^4 + r_5u^5$.

M = mass of the ship (kg);

M_x = added mass of the ship in surge (kg). In absence of ship specific data, M_x may be assumed to be $0.1 M$;

$c_i = \sqrt{\frac{g}{k_i}}$ = wave celerity (m/s).

$$\tau_1 = \kappa_1(1 - t_p)(1 - w_p)\rho D_p^3$$

$$\tau_2 = \kappa_2(1 - t_p)(1 - w_p)^2 \rho D_p^2$$

2.7 Parameters common to stability failure mode assessments

2.7.1 Inertial properties of a ship and natural period of roll motion

2.7.1.1 In the absence of direct calculations, the roll moment of inertia of the ship comprising the effect of added inertia, $J_{T,roll}$, may be estimated as follows:

$$J_{T,roll} = \frac{1}{1000} \frac{\rho g \nabla GM T_r^2}{4\pi^2} \text{ (t}\cdot\text{m}^2\text{)}$$

2.7.1.2 The natural roll period, T_r , in a given loading condition, in the absence of sufficient information, direct calculation or measurement, may be approximated using the formulae given in part A, 2.3 of the 2008 IS Code, which is repeated below,

$$T_r = \frac{2 \cdot C \cdot B}{\sqrt{GM}}, \text{ where } C = 0.373 + 0.023(B/d) - 0.043(L_{WL}/100),$$

or its alternatives.

2.7.2 Environmental data

2.7.2.1 A set of standard environmental conditions are assumed. The characterization of the standard environmental conditions refers to both the short-term and the long-term. The short-term characterization is given in terms of the spectrum of sea elevation, known as the spectral density of the sea wave elevation. The long-term characterization is given in terms of a wave scatter table. The standard short-term and long-term characterizations are given in 2.7.2.1.1 and 2.7.2.1.2, respectively.

2.7.2.1.1 The spectral density of sea wave elevation, $S_{zz}(\omega)$, is provided by the Bretschneider wave energy spectrum as a function of the wave frequency, ω , as follows:

$$S_{zz}(\omega) = \frac{H_s^2}{4\pi} \cdot \left(\frac{2\pi}{T_z}\right)^4 \omega^{-5} \exp\left(-\frac{1}{\pi} \left(\frac{2\pi}{T_z}\right)^4 \omega^{-4}\right)$$

2.7.2.1.2 The long-term characterization of the standard environmental conditions (used in unrestricted service) is given by means of a wave scatter table. The wave scatter table contains the number of occurrences W_i within each range of significant wave height H_s and zero crossing wave period T_z in 100,000 observations. The wave scatter table, given in table 2.7.2.1.2, specifies factors W_i as functions of H_s and T_z values which represent the mean values of corresponding ranges.⁷

Table 2.7.2.1.2 Wave scatter table

Number of occurrences: 100 000 / T_z (s) = average zero-crossing wave period / H_s (m) = significant wave height																
Tz (s) ►	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
Hs (m) ▼																
0.5	1.3	133.7	865.6	1186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0
1.5	0.0	29.3	986.0	4976.0	7738.0	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	0.1	0.0	0.0	0.0
2.5	0.0	2.2	197.5	2158.8	6230.0	7449.5	4860.4	2066.0	644.5	160.2	33.7	6.3	1.1	0.2	0.0	0.0
3.5	0.0	0.2	34.9	695.5	3226.5	5675.0	5099.1	2838.0	1114.1	337.7	84.3	18.2	3.5	0.6	0.1	0.0
4.5	0.0	0.0	6.0	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	455.1	130.9	31.9	6.9	1.3	0.2	0.0
5.5	0.0	0.0	1.0	51.0	498.4	1602.9	2372.7	2008.3	1126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1
6.5	0.0	0.0	0.2	12.6	167.0	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1
7.5	0.0	0.0	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1
8.5	0.0	0.0	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1
9.5	0.0	0.0	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1
10.5	0.0	0.0	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1
11.5	0.0	0.0	0.0	0.0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1
12.5	0.0	0.0	0.0	0.0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0.0
13.5	0.0	0.0	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0.0
14.5	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0.0	0.0
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0.0	0.0
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0

⁷ Refer to International Association of Classification Societies (IACS) Recommendation No.34 (Corr. Nov.2001).

2.7.2.2 Alternative environmental conditions can be used for ships subject to operational measures according to chapter 4 and should be accepted by the Administration.

2.7.2.2.1 Such alternative environmental conditions should specify the short-term characteristics of wind and sea state, together with the probability of occurrence of each short-term environmental condition.

2.7.2.2.2 The short-term sea state characteristics should be given in terms of a sea elevation spectrum. The short-term wind state should be given in terms of a mean wind speed and a gustiness spectrum.

2.7.2.2.3 The long-term characterization of the environmental condition should be given in terms of probability of occurrence of each short-term condition. The probability of occurrence of each short-term environmental condition corresponds to the weighting factor, W_i . The set of short-term environmental conditions and corresponding weighting factors should be such that the sum of the weighting factors, i.e. the probabilities of occurrence, is unity.

2.7.3 Other common parameters

2.7.3.1 Active means of motion reduction, such as active anti-roll fins and anti-roll tanks, can significantly reduce roll motions in seaway. However, the safety of the ship should be ensured in cases of failure of such devices, therefore, the vulnerability assessment according to these Interim Guidelines should be conducted with such devices inactive or retracted, if they are retractable.

3 Guidelines for direct stability failure assessment

3.1 Objective

3.1.1 These Guidelines provide specifications for direct stability assessment procedures for the following stability failure modes:

- .1 dead ship condition;
- .2 excessive acceleration;
- .3 pure loss of stability;
- .4 parametric rolling; and
- .5 surf-riding/broaching.

3.1.2 The criteria, procedures and standards recommended in these guidelines ensure a safety level corresponding to the average stability failure rate not exceeding $2.6 \cdot 10^{-3}$ per ship per year.

3.1.3 Direct stability assessment procedures are intended to employ latest technology while being sufficiently practical to be uniformly accepted and applied using currently available infrastructure.

3.1.4 The provisions given hereunder apply to all ships and all failure modes. However, the provisions for both the dead ship condition and pure loss of stability failure modes should not apply to ships with an extended low weather deck.

3.2 Requirements

3.2.1 The failure event is defined as:

- .1 *exceedance of roll angle*, defined as: 40 degrees, angle of vanishing stability in calm water or angle of submergence of unprotected openings in calm water, whichever is less; or
- .2 *exceedance of lateral acceleration* of 9.81 m/s^2 , at the highest location along the length of the ship where passengers or crew may be present.

The Administrations may define stricter requirements, if deemed necessary.

3.2.2 Active means of motion reduction, such as active anti-roll fins and anti-roll tanks, can significantly reduce roll motions in seaway. However, the safety of the ship should be ensured in cases of failure of such devices, therefore, the vulnerability assessment according to these Interim Guidelines should be conducted with such devices inactive or retracted, if they are retractable.

3.2.3 The procedure for direct stability assessment consists of two major components:

- .1 a method that adequately replicates ship motions in waves (see 3.3); and
- .2 a prescribed procedure that identifies the process by which input values are obtained for the assessment, how the output values are processed, and how the results are evaluated (see 3.5).

3.3 Requirements for a method that adequately predicts ship motions

3.3.1 General considerations

3.3.1.1 The motion of ships in waves can be predicted by means of numerical simulations or model tests.

3.3.1.2 The choice between numerical simulations, model tests or their combination should be agreed with the Administration on a case-by-case basis taking into account these Interim Guidelines.

3.3.1.3 The procedures, calibrations and proper application of technology involved in the conduct of model tests should follow "Recommended Procedures, Model Tests on Intact Stability, 7.5-02-07-04.1" issued by the International Towing Tank Conference (ITTC) in 2008. Users may follow recent amended versions of the Recommended Procedures at the time of execution of tests, if deemed necessary.

3.3.1.4 Numerical simulation of ship motions may be defined as the numerical solution of the motion equations of a ship sailing in waves including or excluding the effect of wind (see 3.3.2).

3.3.2 General requirements

3.3.2.1 Modelling of waves

3.3.2.1.1 The mathematical model of waves should be consistent and appropriate for the calculation of the forces.

3.3.2.1.2 Modelling of irregular waves should be statistically and hydrodynamically valid. Caution should be exercised to avoid a self-repetition effect.

3.3.2.2 *Modelling of roll damping: avoiding duplication*

3.3.2.2.1 Roll damping forces should include wave, lift, vortex (i.e. eddy-making) and skin friction components.

3.3.2.2.2 The data to be used for the calibration of roll damping may be defined from:

- .1 roll decay or forced roll test;
- .2 CFD computations, if sufficient agreement with experimental results in terms of roll damping is demonstrated;
- .3 existing databases of measurements or CFD computations for similar ships, if suitable range is available; or
- .4 empirical formulae, applied within their applicability limits.

3.3.2.2.3 If the wave component of roll damping is already included in the calculation of radiation forces, measures should be taken to avoid including these effects more than once.

3.3.2.2.4 Similarly, if any components of roll damping (e.g. cross-flow drag) are directly computed whereas others are taken from the calibration data, similar measures should be taken to exclude these directly computed elements from the calibration data used.

3.3.2.2.5 Consideration of the essential roll damping elements more than once can be avoided through use of an iterative calibration procedure in which the roll decay or forced roll tests are replicated in numerical simulations. The results should be determined to be reasonably close to the original calibration model test data set.

3.3.2.3 *Mathematical modelling of forces and moments*

3.3.2.3.1 The Froude-Krylov forces should be calculated using body-exact formulations at least for the dead ship condition, pure loss of stability and parametric rolling failure modes, for instance using panel or strip-theory approaches.

3.3.2.3.2 Radiation and diffraction forces should be represented in one of three ways: one is to use approximate coefficients and the other two involve either a body linear formulation or a body-exact solution of the appropriate boundary-value problem.

3.3.2.3.3 Resistance forces should include wave, vortex and skin friction components. The preferred source for these data is a model test. The added resistance in waves can be approximated, if this element is not already included in the calculation of diffraction and radiation forces. If the radiation and diffraction forces are calculated as a solution of the hull boundary-value problem, measures must be taken to avoid including these effects more than once.

3.3.2.3.4 Hydrodynamic reaction sway forces, roll moment and yaw moments could be approximated, based on:

- .1 Coefficients derived from model tests in calm water with planar motion mechanism (PMM) or in stationary circular tests, by means of a rotating arm or an x-y carriage.⁸
- .2 CFD computations, provided that sufficient agreement is demonstrated with a model experiment in terms of values of sway force and yaw moment. If the radiation and diffraction forces are calculated as a solution of the hull boundary-value problem, measures must be taken to avoid including these effects more than once.
- .3 Empirical database or empirical formulae, used within their applicability range.

3.3.2.3.5 Thrust may be obtained by use of a coefficient-based model with approximate coefficients to account for propulsor-hull interactions.

3.3.3 Requirements for particular stability failure modes

3.3.3.1 For the dead ship condition failure mode:

- .1 Ship motion simulations should include at least the following four degrees of freedom: sway, heave, roll and pitch.
- .2 Three-component aerodynamic forces and moments generated on topside surfaces may be evaluated using model test results. CFD results may be admitted upon demonstration of sufficient agreement with a model experiment in terms of values of aerodynamic force and moments. Empirical data or formulae could be applied within their applicability range.

3.3.3.2 For the excessive acceleration failure mode, the ship motion simulations should include at least the following three degrees of freedom: heave, pitch and roll. If sway motion is not modelled, consideration should be given to accurate reproduction of lateral acceleration.

3.3.3.3 For the pure loss of stability failure mode, ship motion simulations should include at least the following four degrees of freedom: surge, sway, roll and yaw. For those degrees of freedom not included in the dynamic modelling, static equilibrium should be assumed.

3.3.3.4 For the parametric rolling failure mode, ship motion simulations should include at least the following three degrees of freedom: heave, roll and pitch.

3.3.3.5 For the surf-riding/broaching failure mode:

- .1 Ship motion simulations should include at least the following four degrees of freedom: surge, sway, roll and yaw. For those degrees of freedom not included in the dynamic modelling, static equilibrium should be assumed.

⁸ The captive model test procedure should be based on the ITTC recommended procedure 7.5-02-06-02, issued in 2014, as amended. The stationary circular test by means of an x-y carriage can reproduce a circular model motion with any specified drift angle by combining the motion of an x-y carriage and a turn table.

- .2 Hydrodynamic forces due to vortex shedding from a hull should be properly modelled. This should include hydrodynamic lift forces and moments due to the coexistence of wave particle velocity and ship forward velocity, other than manoeuvring forces and moments in calm water.

3.3.3.6 For the pure loss of stability and surf-riding/broaching failure modes, an appropriate autopilot should be used.

3.3.3.7 For the pure loss of stability and surf-riding/broaching failure modes, the initial condition should be set with a sufficiently small forward speed in order to avoid artificial surf-riding, which cannot occur for a self-propelled ship.

3.4 Requirements for validation of software for numerical simulation of ship motions

3.4.1 Validation

3.4.1.1 Validation is the process of determining the degree to which a numerical simulation is an accurate representation of the real physical world from the perspective of each intended use of the model or simulation.

3.4.1.2 Different physical phenomena are responsible for different modes of stability failure. Therefore, the validation of software for the numerical simulation of ship motions is failure-mode specific.

3.4.1.3 The validation data should be compatible with the general characteristics of the ship for which the direct stability assessment is intended to be carried out.

3.4.1.4 The process of validation should be performed in two phases: one qualitative and the other quantitative. In the qualitative phase, the objective is to demonstrate that the software is capable of reproducing the relevant physics of the failure mode considered. The objective of the quantitative phase is to determine the degree to which the software is capable of predicting the specific failure mode considered.

3.4.2 Qualitative validation requirements

Table 3.4.2 – Requirements and acceptance criteria for qualitative validation

Item	Required for	Objective	Acceptance criteria
Periodic properties of roll oscillator	Software where hydrostatic and Froude-Krylov forces are calculated with body exact formulation	Demonstrate consistency between calculated roll backbone curve (dependence of roll frequency in calm water on roll amplitude) and GZ curve in calm water	Based on the shape of calculated backbone curve. The backbone curve must follow a trend which is consistent with the righting lever
Response curve of roll oscillator	Software where hydrostatic and Froude-Krylov forces are calculated with body exact formulation	Demonstrate consistency between the calculated roll backbone curve and the calculated roll response curve (dependence of amplitude of excited roll motion on the frequency of excitation)	Based on the shape of the roll response curve. The roll response curve must "fold around" the backbone curve and may show hysteresis when the magnitude of excitation is increased

Change of stability in waves	Software where hydrostatic and Froude-Krylov forces are calculated with body exact formulation. Additional capability to track the instantaneous GZ curve in waves may be required	Demonstrate capability to reproduce wave pass effect	Typically in head and following waves, the stability decreases when the wave crest is located near the midship section (within the quarter of length) and the stability increases when the wave trough is located near the midship section (within the quarter of length)
Principal parametric resonance	Software where hydrostatic and Froude-Krylov forces are calculated with a body exact formulation	Demonstrate capability to reproduce principal parametric resonance	Usually, observing an increase and stabilization of amplitude of roll oscillation in exact following or head seas when encounter frequency is about twice of natural roll frequency

Table 3.4.2 (continued) – Requirements and acceptance criteria for qualitative validation

Item	Required for	Objective	Acceptance criteria
Surf-riding equilibrium	Software for numerical simulation of surf-riding/ broaching	Demonstrate capability to reproduce surf-riding, while yaw is fixed.	Observing sailing with the speed equal to wave celerity when the propeller RPM is set for the speed in calm water which is less than the wave celerity. The horizontal position of centre of gravity is expected to be located near a wave trough
Heel during turn	Software for numerical simulation of surf-riding/ broaching	Demonstrate capability to reproduce heel caused by turn	Observing development of heel angle during the turn
Turn in calm water	Software for numerical simulation of surf-riding/ broaching	Demonstrate correct modelling of manoeuvring forces	Observing correct direction of turn with large rudder angles
Straight captive run in stern quartering waves	Software for numerical simulation of surf-riding/ broaching	Demonstrate correct modelling of wave forces including effect of wave particle velocity	Observing correct tendency of phase difference of wave force to incident waves
Heel caused by drift and wind	Software for numerical simulation of ship motions in dead ship condition	Demonstrate capability to reproduce heel caused by a moment created by aerodynamic load and drag caused by drift	Observing slowly developed heel angle after applying aerodynamic load

3.4.3 Quantitative validation requirements

3.4.3.1 There are two objectives of quantitative validation of numerical simulation. The first is to find the degree to which the results of numerical simulation differ from the model test results. The results of a model test carried out in accordance with 3.3.1.3 should be recognized as reference values. The second objective is to judge if the observed difference between simulations and model tests is sufficiently small or conservative for direct stability assessment to be performed for the considered failure modes.

Table 3.4.3 – Indicative requirements and acceptance criteria for quantitative validation

Item	Required for	Objective	Acceptance criteria
Response curve for parametric rolling in regular waves	Parametric rolling	Demonstrate agreement between numerical simulation and model tests regarding amplitude of the roll response	Maximum (over encounter frequency) roll amplitude should not be underpredicted by more than 10%, if the amplitude is below the angle of maximum GZ or 20% otherwise. Underprediction less than 2 degrees may be disregarded.
Response curve for synchronous roll in regular waves	All modes	Demonstrate agreement between numerical simulation and model tests regarding amplitude of the roll response	Maximum (over encounter frequency) roll amplitude should not be underpredicted for more than 10%, if the amplitude is below the angle of maximum GZ or 20% otherwise. Under-prediction less than 2 degrees may be disregarded.
Variance test for synchronous roll	Software for numerical simulation of dead ship condition and excessive acceleration	Demonstrate correct (in terms of statistics) modelling of roll response in irregular waves	Reproduction of experimental results either within 95% confidence interval or conservative
Variance test for parametric rolling	Software for numerical simulation of parametric rolling	Demonstrate correct (in terms of statistics) modelling of roll response in irregular waves	Reproduction of experimental results either within 95% confidence interval or conservative
Wave conditions for surf-riding and broaching	Software for numerical simulation of surf-riding/ broaching	Demonstrate correct modelling of surf-riding/ broaching dynamics in regular waves	Wave steepness causing surf-riding and broaching at the wavelength 0.75 – 1.5 of ship length is within 15% of difference between model tests and numerical simulations. Speed settings are also within 15% difference between model tests and numerical simulations.

3.5 Procedures for direct stability assessment

3.5.1 General description

3.5.1.1 The procedures for direct stability assessment contain a description of the necessary calculations of ship motions including the choice of input data, pre- and post-processing.

3.5.1.2 The direct stability assessment procedure is aimed at the estimation of a likelihood of a stability failure in an irregular wave environment and because the stability failures may be rare, the direct stability assessment procedure may require a solution of the problem of rarity. This arises when the mean time to stability failure is very long in comparison with the natural roll period that serves as a main timescale for the roll motion process. The solution of the problem of rarity essentially requires a statistical extrapolation; for this reason, the validation must be performed for all elements of the direct stability assessment procedure.

3.5.1.3 These Guidelines provide two general approaches to circumvent the problem of rarity, namely assessment in design situations and assessment using deterministic criteria. Mathematical techniques are provided that reduce the required number of simulations or simulation time and can be used to accelerate assessment for both, the full assessment and the assessment performed in design situations.

3.5.2 Verification of failure modes

3.5.2.1 Once a failure is identified in a numerical simulation, it is necessary to examine whether it can be regarded as a failure mode for which the numerical method is validated and direct assessment is intended. The suggested judging criteria for this purpose are provided below.

3.5.2.2 If the local period of the obtained roll motion in following waves or in stern quartering waves is nearly equal to the local wave encounter period and the maximum roll angle occurs nearly at the relative wave position in which the metacentric height becomes the smallest, it can be regarded as pure loss of stability failure.

3.5.2.3 If the local period of the obtained roll motion is nearly equal to twice the local wave encounter period and is nearly equal to the ship natural roll period, it can be regarded as the parametric rolling stability failure considered in the vulnerability criteria, which is sometimes called as "principal parametric rolling". Other types of parametric rolling may occur with much smaller probability, which are not addressed by the second generation intact stability criteria.

3.5.2.4 The condition when the ship cannot keep a straight course despite the application of maximum steering efforts is known as broaching. The second generation intact stability criteria address broaching associated with surf-riding. Other types of broaching may occur at slower speed but are not considered here because the centrifugal force, due to such slow-speed broaching which could induce heel, is much smaller. The broaching associated with surf-riding can be identified if both the yaw angle and yaw angular velocity increase over time under the application of the maximum opposite rudder deflection.

3.5.2.5 If the local period of the obtained roll motion in beam waves is nearly equal to the local wave encounter period, it can be regarded as harmonic rolling, which is relevant to the dead ship condition failure mode, as well as the excessive acceleration failure mode.

3.5.3 Environmental and sailing conditions

3.5.3.1 General approaches for selection of environmental and sailing conditions

3.5.3.1.1 The sea states chosen for the direct stability assessment must be representative for the intended service of the ship.

3.5.3.1.2 Sea states are defined by the type of wave spectrum and statistical data of its integral characteristics, such as the significant wave height and the mean zero-crossing wave period. For ships of unrestricted service, the environment should be described by the wave scatter table shown in table 2.7.2.1.2. For ships of restricted service, the wave scatter table accepted by the Administration should be used.

3.5.3.1.3 It is recommended to use the Bretschneider wave energy spectrum (see 2.7.2.1.1) and cosine-squared wave energy spreading with respect to the mean wave direction. If short-crested waves are considered impracticable in model tests or numerical simulations, long-crested waves can be used.

3.5.3.1.4 For a given set of environmental conditions, the assessment can be performed using any of the following equivalent alternatives:

- .1 full probabilistic assessment according to 3.5.3.2;
- .2 assessment in design situations using probabilistic criteria according to 3.5.3.3; or
- .3 assessment in design situations using deterministic criteria according to 3.5.3.4.

3.5.3.2 Full probabilistic assessment

3.5.3.2.1 In this approach, the criterion used is the estimate of the mean long-term rate of stability failures, which is calculated as a weighted average over all relevant sea states, wave directions with respect to the ship heading and ship forward speeds, for each addressed loading condition.

3.5.3.2.2 To satisfy the requirements of this assessment, this criterion should not exceed the standard of $2.6 \cdot 10^{-8}$ (1/s).

3.5.3.2.3 The probabilities of the sea states are defined according to the wave scatter table (see 3.5.3.1). For the excessive accelerations, pure loss of stability, parametric rolling and surf-riding/broaching failure modes, the mean wave directions with respect to the ship heading are assumed uniformly distributed and the ship forward speed should be regarded as uniformly distributed from zero to the maximum service speed. For the dead ship condition failure mode, beam waves and wind should be assumed and the ship forward speed should be taken as zero.

3.5.3.3 Assessment in design situations using probabilistic criteria

3.5.3.3.1 Compared to the full probabilistic assessment, this approach significantly reduces the required simulation time and number of simulations since the assessment is conducted in fewer design situations. These design situations are specified for each stability failure mode as combinations of the ship forward speed, mean wave direction with respect to the ship heading, significant wave height and mean zero-crossing wave period for each addressed loading condition.

3.5.3.3.2 In this approach, the criterion is the maximum (over the design situations corresponding to a particular stability failure mode) stability failure rate, defined in each design situation as the upper boundary of its 95%-confidence interval.

3.5.3.3.3 To satisfy the requirements of this assessment, this criterion should not exceed the threshold corresponding to one stability failure every 2 hours in full scale in design sea states with probability density $10^{-5} \text{ (m}\cdot\text{s)}^{-1}$.

3.5.3.3.4 Table 3.5.3.3.4 shows the design situations for particular stability failure modes, including mean wave direction with respect to the ship heading, ship forward speed and range of wave periods; and the step of the zero-crossing wave period in the specified ranges should not exceed 1.0 s.

Table 3.5.3.3.4 – Design situations for each stability failure mode

Stability failure mode	Wave directions	Forward speeds	Wave period
Dead ship condition	Beam wind and waves	Zero	T_z/T_r from 0.7 to 1.3
Excessive acceleration	Beam	Zero	T_z/T_r from 0.7 to 1.3
Pure loss of stability	Following	Maximum nominal service speed	T_p corresponding to wavelengths comparable to ship length
Parametric rolling	Head and following	Zero	All wave periods in the wave scatter table
Surf-riding/broaching	Following	Maximum nominal service speed	T_p corresponding to wavelengths in the range from $1.0L$ to $1.5L$

3.5.3.3.5 For each mean zero-crossing wave period, the significant wave height is selected according to the probability density of the sea state, as specified in 3.5.3.3.3. For unrestricted service, the significant wave heights are shown in table 3.5.3.3.5 depending on the mean zero-crossing wave period.

Table 3.5.3.3.5 – Significant wave heights for design sea states with probability density $10^{-5} \text{ (m}\cdot\text{s)}^{-1}$ for unrestricted service

T_z (s)	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5
H_s (m)	2.8	5.5	8.2	10.6	12.5	13.8	14.6	15.1	15.1	14.8	14.1	12.9	10.9

3.5.3.4 Assessment in design situations using deterministic criteria

3.5.3.4.1 A probabilistic assessment may require a long simulation time even when using design situations and this can make it difficult to use model tests rather than numerical

simulations. Applying deterministic criteria, such as the mean 3-hour maximum roll amplitude, may reduce the required simulation time and this may make it easier to use model tests with, or instead of, numerical simulations. However, the inaccuracy of this approach needs to be balanced by additional conservativeness.

3.5.3.4.2 In this approach, the criteria are the greatest (with respect to all design situations for a particular stability failure mode) mean 3-hour maximum roll amplitude and lateral acceleration for each addressed loading condition.

3.5.3.4.3 To satisfy the requirements of this assessment, these criteria should not exceed half of the values in the definition of stability failure in 3.2.1.

3.5.3.4.4 The simulations or model tests for each design situation should comprise at least 15 hours in full scale. This duration can be divided into several parts. The results should be post-processed to provide at least five values of the 3-hour maximum amplitude of roll angle or lateral acceleration, which are averaged to define the mean 3-hour maximum amplitudes.

3.5.3.4.5 This approach uses design situations with the same mean wave directions with respect to the ship heading, the same ship forward speeds and the same ranges of the mean zero-crossing wave periods as the assessment in design situations using probabilistic criteria (see 3.5.3.3).

3.5.3.4.6 For each mean zero-crossing wave period, the significant wave height is selected according to the probability density of the sea state equal to $7 \cdot 10^{-5} \text{ (m}\cdot\text{s)}^{-1}$. Table 3.5.3.4.6 shows these significant wave heights for unrestricted service depending on the mean zero-crossing wave period.

Table 3.5.3.4.6 Significant wave heights, in metres, for design sea states with probability density $7 \cdot 10^{-5} \text{ (m}\cdot\text{s)}^{-1}$ for assessment using deterministic criteria for unrestricted service

T_z (s)	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5
H_s (m)	2.0	4.4	6.9	9.1	10.9	12.1	12.8	13.1	13.0	12.5	11.3	9.0

3.5.4 Direct counting procedure

3.5.4.1 The direct counting procedure uses ship motions resulting from multiple independent realisations of an irregular seaway to estimate the rate of stability failure, r .

3.5.4.2 The procedure used for direct counting should provide the upper boundary of the 95% confidence interval of the estimated rate of stability failure. This upper boundary is the one which is used in direct stability assessment and operational measures.

3.5.4.3 The counting procedure should ensure independence of the counted stability failure events.

3.5.4.4 The failure rate r and associated confidence interval can be estimated:

- .1 by carrying out a simulation for each realisation of an irregular seaway only until the first stability failure; or
- .2 on the basis of a set of independent simulations with fixed specified exposure time t_{exp} (s), under the assumption that the relation between the probability p of failure within t_{exp} and the failure rate r is $p = 1 - \exp(-r \cdot t_{exp})$.

3.5.4.5 Alternatively to direct counting, extrapolation procedures can be used as specified in section 3.5.5.

3.5.5 Extrapolation procedures

3.5.5.1 The extrapolation procedures to be used with these Guidelines should only include those procedures that have been successfully validated and applied and which should also include a detailed description of their application.

3.5.5.2 Cautions

3.5.5.2.1 The extrapolation method may be applied as an alternative to the direct counting procedure.

3.5.5.2.2 Caution should be exercised because uncertainty increases, as the extrapolation is associated with additional assumptions used for describing ship motions in waves.

3.5.5.2.3 The statistical uncertainty of the extrapolated values should be provided in a form of boundaries of the confidence interval evaluated with a confidence level of 95%.

3.5.5.2.4 To control the uncertainty caused by nonlinearity, the principle of separation may be used. Extrapolation methods based on the principle of separation consist of at least two numerical procedures addressing different aspects of the problem: "non-rare" and "rare".

3.5.5.2.5 The "non-rare" procedure focuses on the estimation of ship motions or waves of small-to-moderate level for which the stability failure events can be characterized statistically with acceptable uncertainty.

3.5.5.2.6 The "rare" procedure focuses on ship motions of moderate-to-severe level for which numerical simulation are rarely required. Large motions may be separated from the rest of the time domain data to obtain practical estimates of these motions.

3.5.5.2.7 Different extrapolation methods based on the separation principle may use different assumptions on how the separation is introduced.

3.5.5.3 Extrapolation over wave height

3.5.5.3.1 Extrapolation of the mean time to stability failure or mean rate of stability failures over significant wave height is a technique allowing the reduction of the required simulation time by performing numerical simulations or model tests at greater significant wave heights than those required in the assessment and extrapolating the results to lower significant wave heights.

3.5.5.3.2 The extrapolation is based on the approximation $\ln T = A + B/H_s^2$, where T (s) is the mean time to stability failure; H_s (m) is the significant wave height; and A, B are coefficients which do not depend on the significant wave height but depend on the other parameters specifying the situation (wave period, wave direction and ship forward speed).

3.5.5.3.3 The extrapolation can be performed when at least three values of the stability failure rate are available. These values should be obtained by direct counting for a range of significant wave heights of at least 2 m. Each of the values used in the extrapolation should correspond to the upper boundary of the 95%-confidence interval of stability failure rate and not exceed 5% of the reciprocal natural roll period of the ship. The results should be checked for the presence of outliers and non-conservative extrapolation and corrected, when necessary, by adding or removing points used for extrapolation.

3.5.5.4 *Other extrapolation procedures*

3.5.5.4.1 Other extrapolation procedures may be used, taking into account 3.5.5.1 and 3.5.5.2. Such procedures may include those listed below and others:

- .1 envelope peak-over-threshold (EPOT);
- .2 split-time/motion perturbation method (MPM); and
- .3 critical wave method.

3.5.6. Validation of extrapolation procedures

3.5.6.1 Extrapolation procedures used for direct stability assessment should be validated.

3.5.6.2 Validation of an extrapolation procedure is a demonstration that the extrapolated value is in reasonable statistical agreement with the result of the direct counting, if such volume of data would be available.

3.5.6.3 The data for validation of the extrapolation procedure may be produced by a mathematical model of reduced complexity (e.g. a set of ordinary differential equations instead of a numerical solution of a boundary value problem) or by running the full mathematical model on significantly more severe environmental and/or more onerous loading conditions. The objective is to decrease the computational cost by which a large data set can be obtained (the validation data set). Physical experiments can be used for the same purpose.

3.5.6.4 The direct counting procedure applied to the validation data set should produce the "true value". The extrapolation procedure applied to a minimally required fraction of the validation data set should re-produce the "true value" within 95% confidence.

3.5.6.5 Validation of the extrapolation procedure should be performed for 50 statistically independent data sets and evaluated for a number of ship speeds, relative wave headings and sea states.

3.5.6.6 A comparison should be made between the extrapolation and the "true value" for each data set. The comparison should be considered successful if the extrapolation confidence interval and the confidence interval of the "true value" overlap.

3.5.6.7 The validation should be considered successful if at least 88% of individual data set comparisons are successful.

4 Guidelines for operational measures

4.1 General principles

4.1.1 A combined consideration of design and operational aspects can effectively be used to achieve a sufficient safety level. In application, this principle requires guidance to be provided for the preparation of operational measures, consistent with the design assessment requirements.

4.1.2 Whereas the principles used in these Guidelines can be applied to consider any operational problems related to ship behaviour in a seaway, detailed procedures in these Guidelines cover the following stability failure modes:

- .1 dead ship condition;
- .2 excessive acceleration;
- .3 pure loss of stability;
- .4 parametric rolling; and
- .5 surf-riding/broaching.

4.1.3 These Guidelines consider the operational limitations and operational guidance, which are defined in 4.3.1. Either operational limitations or operational guidance can be used for the following four stability failure modes: excessive acceleration, pure loss of stability, parametric rolling and surf-riding/broaching. For the dead ship condition failure mode, only operational limitations related to areas or routes and season (4.3.1.1 and 4.5.1) can be applied. This means that neither operational limitations related to maximum significant wave height nor operational guidance are applicable because the ship's main propulsion plant and auxiliaries are inoperable. This means that the ship is neither able to avoid heavy weather nor control speed and course.

4.1.4 Operational limitations and operational guidance should provide at least the same level of safety as that provided by the procedures and standards given by the Guidelines for vulnerability criteria in chapter 2 or the direct stability assessment in chapter 3. In particular, the safety level of those loading conditions that fail design assessment requirements in chapter 2 or chapter 3 should become sufficient if all combinations of the sailing condition and sea state that are not recommended by these operational measures are removed from the design assessment.

4.1.5 Whereas the principle in 4.1.4 can be directly used to prepare operational measures ensuring a required safety level, more detailed procedures were developed as described in these Guidelines for convenience of ship designers and Administrations. Using the procedures and standards described herein corresponds to setting a safety level in accordance with the Guidelines for direct stability assessment in chapter 3.

4.1.6 Although the application of operational measures can reduce the likelihood of stability failure to a desired low level, a loading condition for which too many situations should be avoided to achieve the required safety level should not be considered as acceptable. Therefore, from practical and regulatory perspectives, operational measures should not be considered as always sufficient for any loading condition.

4.1.7 In case operational measures are provided for particular failure mode(s) based on these Guidelines, they may be applied instead of the relevant provisions in the guidance provided in MSC.1/Circ.1228.

4.2 Stability failures

4.2.1 The definition of stability failure should be consistent with those used in either the Guidelines for vulnerability criteria in chapter 2 or the Guidelines for direct stability assessment in chapter 3.

4.2.2 The provisions given hereunder apply to all ships, except for ships with an extended low weather deck when considering the dead ship condition failure mode or the pure loss of stability failure mode.

4.3 Operational measures

4.3.1 These Guidelines consider the following ship specific operational measures:

- .1 *Operational limitations* which define the limits on a ship's operation in a considered loading condition, are as follows:
 - .1 *Operational limitations related to areas or routes and season* permit operation in specific operational areas (either geographical areas or specific types of operational areas like sheltered waters) or routes and, if appropriate, the specific season. For the operational area, route and season, the environmental conditions are specified by the wave scatter table and corresponding wind statistics; and
 - .2 *Operational limitations related to maximum significant wave height* permit operation in conditions up to a maximum significant wave height. The environmental conditions are specified by the combination of the wave scatter table related to operational area or route and season, and corresponding wind statistics. The wave scatter table limited to a specific significant wave height is referred to as a *limited wave scatter table*; and
- .2 *Operational guidance* which defines the combinations of ship speed and heading relative to mean wave direction that are not recommended and that should be avoided in each relevant sea state.

4.3.2 The operational measures specified in 4.3.1 require different amount of information and planning in their application, as follows:

- .1 operational limitations related to areas or routes and season do not require weather data during the operation of the ship and thus do not need any specific information and planning;
- .2 operational limitations related to maximum significant wave height need a forecast for the significant wave height and the availability of appropriate routing in a sufficient time before encountering possible storm conditions; and
- .3 operational guidance requires detailed forecast information about wave energy spectrum and wind characteristics, together with means for indicating combinations of ship speed and heading relative to mean wave direction that should be avoided, which should be available for safe routing in a sufficient time before encountering possible storm conditions.

4.3.3 The operational measures specified in 4.3.1 can be combined, e.g. operational limitations can be applied up to a certain significant wave height and operational guidance for greater significant wave heights. When operational limitations are combined with operational guidance, the requirements for operational guidance apply.

4.4 Acceptance of operational measures

4.4.1 Operational limitations and operational guidance should be accepted by the Administration according to these Guidelines.

4.4.2 Acceptance of a loading condition for unrestricted operation, limited operation or operation using onboard operational guidance should be performed following these Guidelines in combination with the design assessment requirements according to chapter 2 or chapter 3. A loading condition is considered as:

- .1 *acceptable for unrestricted operation*, if it satisfies the design assessment requirements for all five stability failure modes specified in 4.1.2;
- .2 *acceptable for limited operation*, if it is provided with operational limitations for one or more stability failure modes specified in 4.1.2 for unrestricted operation and satisfies the design assessment requirements for the remaining stability failure modes;
- .3 *acceptable for operation using onboard operational guidance*, if it is provided with operational guidance for one or more stability failure modes specified in 4.1.2 for unrestricted operation and is either provided with operational limitations for unrestricted operation or satisfies the design assessment requirements for the remaining stability failure modes;
- .4 *acceptable for operation in a specified area or on a specified route during a specified season*, if it is provided with operational limitations for one or more stability failure modes specified in 4.1.2 for this area or route and season, and satisfies the design assessment requirements for the remaining stability failure modes;
- .5 *acceptable for limited operation in a specified area or on a specified route during a specified season*, if it is provided with operational limitations for one or more stability failure modes specified in 4.1.2 for a given significant wave height limit for this area or route and season, and either has operational limitations without specification of maximum operational significant wave height for this area or route and season, or satisfies the design assessment requirements for the remaining stability failure modes; and
- .6 *acceptable for operation using onboard operational guidance in a specified area or on a specified route during a specified season*, if it is provided with operational guidance for one or more stability failure modes specified in 4.1.2 for this area or route and season and is either provided with operational limitations for this area or route and season or satisfies the design assessment requirements for the remaining stability failure modes.

4.4.3 Application of the operational limitations related to maximum significant wave height or operational guidance can reduce the stability failure rate to any low level. However, if too many sailing conditions in too many sea states should be avoided for a certain loading condition, such loading condition cannot be considered as acceptable in practical operation. Therefore:

- .1 a loading condition cannot be considered as acceptable if the ratio of the total duration of all situations which should be avoided to the total operational time, is greater than 0.2. In the calculation of this ratio, the situations that should be avoided include those defined by:
 - .1 operational limitations related to maximum significant wave height;
or
 - .2 operational guidance; and

- .2 in the calculation of the ratio in 4.4.3.1, the probabilities of the sea states are taken according to the full wave scatter table. Wave headings are assumed uniformly distributed and the ship forward speed is assumed uniformly distributed between zero and the maximum service speed.

4.4.4 Active means of motion reduction, such as active anti-roll fins and anti-roll tanks, can significantly reduce roll motions in seaway. Therefore, if such devices are not considered in the development and application of the operational measures, the advice to the ship master may be suboptimal or misleading. On the other hand, the safety of the ship with specific reference to aspects addressed by the present Guidelines should be ensured also in cases of failure of such devices. Therefore, it is recommended that the development, application and acceptance of the operational measures is done both with operating and inactive (or retracted, if retractable) anti-roll devices.

4.4.5 Operational guidance can indicate some sailing conditions as safe with respect to roll motion but they may be unattainable due to limits of the propulsion and steering systems of the ship or undesirable due to other problems, such as excessive vertical motions or accelerations and slamming. For example, for parametric rolling in bow waves, roll motions may reduce with increasing forward speed, but high speeds in bow waves could be either unattainable or could lead to excessive vertical motions or loads. Neglecting this contradiction can lead to misleading operational guidance or even put the ship in danger if in some sea state all sailing conditions, acceptable from the point of view of roll motions, are unattainable or dangerous because of other reasons.

4.5 Preparation procedures

4.5.1 *Operational limitations related to areas or routes and season*

4.5.1.1 Operational limitations are prepared following the design assessment procedures in chapter 2 or chapter 3 with modified environmental conditions assumed in operation. The modification of the reference environmental conditions is based on the wave scatter table for a specified area or a specified route during a specified season and corresponding wind statistics, acceptable to the Administration.

4.5.1.2 The environmental conditions applied in the preparation of the operational limitations related to specified areas or specified routes during a specified season should be consistent with the corresponding vulnerability criteria if the preparation is based on the Guidelines for vulnerability assessment in chapter 2. If the preparation is based on direct stability assessment these environmental conditions should be consistent with the Guidelines for direct stability assessment in chapter 3. Other environmental conditions may be applied, as appropriate.

4.5.1.3 For some Level 1 and Level 2 vulnerability assessment procedures, regular wave cases should be defined, based on the wave statistics.

4.5.2 *Operational limitations related to maximum significant wave height*

4.5.2.1 Operational limitations related to maximum significant wave height are developed using design assessment procedures in chapter 2 or chapter 3 for a specific environment, which is defined by cutting the wave scatter table for a specified area or a specified route during a specified season at a specified significant wave height and by corresponding modification of wind statistics.

4.5.2.2 The environmental conditions applied in the preparation of the operational limitations related to maximum significant wave height should be consistent with the corresponding vulnerability criteria, if the preparation is based on the Guidelines for vulnerability assessment in chapter 2. If the preparation is based on the direct stability assessment, these conditions should be consistent with the Guidelines for direct stability assessment in chapter 3. Other environmental conditions may be applied, as appropriate.

4.5.2.3 For certain Level 1 and Level 2 vulnerability assessment procedures, definition of the corresponding regular wave cases is required; this is done in the same way as for operational limitations without specification of maximum operational significant wave height.

4.5.3 General principles of preparation of operational guidance

4.5.3.1 Operational guidance should indicate all sailing conditions that should be avoided for each range of sea states in the relevant wave scatter table.

4.5.3.2 Operational guidance should ensure that the considered loading condition satisfies the design assessment requirements in chapter 2 or chapter 3 after removing from the design assessment all sailing conditions that should be avoided. To simplify the preparation and acceptance of operational guidance, three equivalent approaches, recommended for the preparation of operational guidance, are considered below in detail. These approaches are based on:

- .1 probabilistic motion criteria and standards (referred to as probabilistic operational guidance);
- .2 deterministic motion criteria and standards (referred to as deterministic operational guidance); and
- .3 simplified motion criteria and standards (referred to as simplified operational guidance).

4.5.3.3 Operational guidance should clearly indicate acceptable and unacceptable sailing conditions for each relevant sea state and may be presented in the form of a polar diagram.

4.5.3.4 Other forms different from polar diagrams could be used for displaying operational guidance, provided that equivalent information is included.

4.5.4 Probabilistic operational guidance

4.5.4.1 This type of operational guidance uses probabilistic criteria, such as the probability of stability failure during a specified time or the rate of stability failures, and corresponding probabilistic thresholds to distinguish sailing conditions which should be avoided.

4.5.4.2 Sailing conditions that should be avoided are those for which:

$$r > 10^{-6} \text{ s}^{-1};$$

where r (s^{-1}) is the upper boundary of the 95% confidence interval of the stability failure rate.

4.5.4.3 Procedures and numerical methods applied for the determination of the failure rate as referred to in 4.5.4.2 should satisfy the recommendations of the Guidelines for direct stability assessment in chapter 3.

4.5.4.4 If a certain assumed situation should be avoided, assessment for higher significant wave heights, with other parameters unchanged, is not required. Conversely, if a certain assumed situation does not have to be avoided, assessment for lower significant wave heights, with other parameters unchanged, is not required.

4.5.5 Deterministic operational guidance

4.5.5.1 Using deterministic criteria, such as maximum roll amplitude in a given exposure time, represent a simpler but less accurate approach than using probabilistic criteria. Therefore, in order to provide an equivalent safety level, the thresholds for deterministic criteria are conservatively selected.

4.5.5.2 Deterministic operational guidance can be prepared using only model tests, only numerical simulations or their combination. Numerical methods applied in such simulations should satisfy the recommendations of the Guidelines for direct stability assessment in chapter 3.

4.5.5.3 Sailing conditions that should be avoided are those for which:

$$\alpha \cdot x_{3h} > x_{lim},$$

where $\alpha = 2$ is the scaling factor, x_{3h} is the mean 3-hour maximum roll or lateral acceleration amplitude and x_{lim} is the corresponding stability failure threshold, as defined in the Guidelines for direct stability assessment in 3.2.1.

4.5.5.4 To define the mean 3-hour maximum amplitude, the total recommended duration of a test or simulation is 15 hours at full scale for each considered situation.

4.5.5.5 If a certain assumed situation should be avoided, an assessment for higher significant wave heights, with other parameters unchanged, is not required. Conversely, if a certain assumed situation does not have to be avoided, an assessment for lower significant wave heights, with other parameters unchanged, is not required.

4.5.6 Simplified operational guidance

4.5.6.1 Whereas probabilistic and deterministic operational guidance provides accurate and detailed recommendations for the ship forward speed and course in each sea state, it requires model tests or numerical methods of high accuracy. Therefore, simpler conservative approaches may be used to develop operational guidance for acceptable forward speed and course when it is deemed practicable.

4.5.6.2 In principle, any simple conservative estimations for the sailing conditions that should be avoided in each relevant sea state, can be used if they are shown to provide a superior safety level compared to the design assessment requirements. In particular, Level 1 or Level 2 vulnerability criteria of the Guidelines for vulnerability assessment in chapter 2 can be used. Some examples of recommended approaches based on Level 1 and Level 2 vulnerability criteria are included below:

- .1 For the excessive acceleration stability failure mode, all forward speeds should be avoided in all sea states where $C_{S,i} > 10^{-6}$, where $C_{S,i}$ is defined according to 2.3.3.2.1 of the Guidelines for vulnerability assessment. The transfer function $a_y(\omega)$ defined in 2.3.3.2.2 is multiplied by the absolute value of the sine of the wave heading angle μ and calculated by replacing the wave frequency ω_j with wave encounter frequency ω_{ej} .

- .2 For the pure loss of stability failure mode, nominal ship forward speed of the ship of $0.752 \cdot L^{1/2}$ m/s or greater, should be avoided in following to beam wave directions in sea states for which $\max(C1_i, C2_i) = 1$, where $C1_i$ and $C2_i$ are defined in 2.4.3.3 and 2.4.3.4, respectively, of the Guidelines for vulnerability assessment.
- .3 For the parametric rolling stability failure mode, forward speed, for which $C_{S,i}(v_s, H_s, T_z)$, defined according to 2.5.3.3.1 of the Guidelines for vulnerability assessment, is equal to 1, should be avoided in all wave directions and all sea states.
- .4 For the surf-riding/broaching failure mode, either:
- .1 nominal ship speed of $0.94 \cdot L^{1/2}$ (m/s), or greater, should be avoided when the wavelength, based on mean wave period, is greater than 80% of the ship length, the significant wave height is greater than 4% of the ship length L (m) and the heading angle μ (deg) from the wave direction is less than 45 degrees; or
- .2 alternatively, the critical nominal ship speed provided by the Level 2 vulnerability criteria (see 2.6.3.4.2) or above should be avoided in following to beam wave directions in sea states for which $c_{HT} > 0.005$, where c_{HT} is calculated as:

$$c_{HT}(H_s, T_z) = \sum_{i=1}^{N_\lambda} \sum_{j=1}^{N_a} w_{ij}(H_s, T_z) C2_{ij}$$

where $w_{ij}(H_s, T_z)$ and $C2_{ij}$ should be calculated based on the level 2 vulnerability criteria in 2.6.3.2, but with the diffraction component of the wave force taken into account.

4.6 Application

4.6.1 Operational guidance should be provided as easily accessible and understandable information in graphical form which clearly indicates unacceptable sailing conditions for a given sea state, as well as the relevant stability failure modes. Automatic alert systems can be used for the cases when sailing conditions are close to or within the areas of unacceptable sailing conditions.

4.6.2 Unacceptable sailing conditions are derived from the pre-defined databases of probabilistic, deterministic or simplified safety criteria, stored as functions of the ship forward speed and ship heading with respect to the mean wave direction for relevant sea states. These sea states are specified by using as input the actual significant wave height, mean zero-crossing wave period, mean wave direction and ship course.

4.6.3 The effect of non-parallel wave systems (cross sea) can be reproduced using these pre-defined databases by combining separate responses to the wind sea and swell which correspond to the significant wave height, mean zero-crossing wave period and mean wave direction of each of these wave systems by:

- .1 summing the rate of stability failures for each of these wave systems when using probabilistic operational guidance;

- .2 summing the maximum responses to each of these wave systems when using deterministic operational guidance; and
- .3 overlaying the unacceptable sailing conditions for each of these wave systems when using simplified operational guidance.

The procedure described above is meant to be a practical approximation tool for addressing cross sea conditions starting from pre-calculations based on simpler standard sea states. However, such a procedure is an approximate one and sea states encountered in the ship's operation can be characterized by complex spectra combining multiple wind sea and swell systems. Therefore, particular caution is recommended to be exercised during operation when making use of operational guidance developed according to the described procedure, if the sea state is characterized by complex combinations of wind sea and swell systems.

4.6.4 The master should ensure that the ship, at any time during the voyage and considering the available weather forecasts, satisfies the operational limitations related to maximum significant wave height or operational guidance.
