Draft Interim Guidelines for Operational Measures

Submitted by Germany to Intersessional Correspondence Group on Intact Stability

Background

1 The Sub-Committee, at its fifth session, re-established the Correspondence Group on Intact Stability, under the coordination of Japan.

2 The group was instructed, in particular, to (ref. document SDC 5/15, paragraph 6.15.2) prepare, in their essential aspects, the Interim Guidelines for the preparation of operational limitations and operational guidance, based on documents SDC 3/INF.10, SDC 3/6/7 and SDC 5/6/9 and, in particular, to:

.1 by the end of April 2018, prepare the first draft of the interim Guidelines for the preparation of operational limitations and operational guidance, based on document SDC 5/6/9;

.2 decide on criteria (failure rate or other measures);

.3 provide descriptions of preparation procedure for operational limitations and operational guidance; and

.4 provide interim acceptance threshold.

Proposal

3 It seems appropriate to change the title of the Guidelines as *Guidelines for operational measures* instead of the working title *Guidelines for the preparation of operational limitations and operational guidance*, first, to reflect the contents of the Guidelines (which concern not only preparation but also approval and application) and, second, to allow for more flexibility concerning possible updates of the included options of operational measures in the future.

4 Germany herewith submits a proposal for such Guidelines in Annex 1, which is based on the documents referred to in paragraph 2, for discussion in the Correspondence Group on Intact Stability. In particular, in the present draft,

.1 both probabilistic and non-probabilistic criteria are included as options; the distinguished delegations may decide to keep these options as alternatives or select one of them;

.2 preparation procedures and techniques for probabilistic and non-probabilistic operational guidance are proposed as options for discussion, keeping in mind that they should be discussed and finalised in a harmonised way with the procedures for direct stability assessment;

.3 acceptance thresholds are proposed as suggestions, based on the available accident statistics and assessment results for several ships; they should be discussed and finalised in a harmonised way with the standards for direct stability assessment.

5 This submission consists of the following elements:

.1 Annex 1, containing the proposal for the text of Guidelines for operational measures;

.2 Annex 2, describing definition of the regular wave cases for L1 and L2 vulnerability assessment for a modified wave scatter diagram; this Annex should be removed if it will be decided to move this procedure elsewhere;

.3 Appendix, which is not a part of the Guidelines and contains background information, based on results of a research project conducted in Germany.

6 Whereas all elements of the proposal are open for discussion, we would like to highlight the following high-priority items, for which an early discussion would be especially helpful:

.1 whether operational limitations should be applicable to the dead ship condition stability failure mode: in the proposal it is assumed that, whereas operational restrictions are applicable to all five stability failure modes, operational limitations are not applicable to the dead ship condition stability failure mode because of the impossibility for a ship unable to move or steer to adhere to such limitations;

.2 whether operational limitations and operational guidance can be applied in unrestricted service, i.e. in world-wide operation: although these possibilities are very convenient for both designers and Administrations, their implementation requires definition of environmental data for the world-wide operation;

.3 which terminology is appropriate to distinguish between sufficiently and insufficiently safe combinations of ship speed and course in the operational Guidance: in the present draft, terms “recommended” and “not recommended”, respectively, are used;

.4 whether and if yes, which level 2 vulnerability assessment methods are sufficiently accurate to provide recommendations not only for the wave height but also for the wave period: in the proposal it is preliminary assumed that level 2 vulnerability assessment procedures are sufficiently accurate to provide recommendations for the wave period;

.5 whether second check of level 2 vulnerability criterion for parametric roll failure mode is accurate enough to provide recommendations for the ship forward speed: in the proposal, this criterion is included preliminary to provide recommendations for the ship forward speed, although the results of the research in Appendix show that this criterion is not suitable for forward speed recommendations;

.6 as noted in paragraph 4.2, the evaluation of probabilistic and non-probabilistic criteria for the preparation of operational guidance should be based on the same principles and techniques as those used in the direct stability assessment. Therefore, these principles and techniques should be finalised in a harmonised way with the Guidelines for direct stability assessment;

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ANNEX 1

DRAFT INTERIM GUIDELINES FOR OPERATIONAL MEASURES

1 General principles

1.1 The motivation for these Guidelines is the principle that a sufficient safety level can be most effectively achieved by a combined consideration of design and operation aspects; this requires regulation of operational measures, consistent with the design assessment requirements provided in the Guidelines for vulnerability assessment and Guidelines for direct stability assessment.

1.2 Whereas the principles used in these Guidelines can be applied to consider any operational problems related to ship behavior in seaway, detailed procedures were developed in these Guidelines to cover the following stability failure modes:

.1 pure loss of stability;

.2 parametric roll;

.3 surf riding/broaching;

.4 dead ship condition;

.5 excessive acceleration.

1.3 These Guidelines consider the following operational measures: operational restrictions, operational limitations and operational guidance, which are defined in paragraph 4.1. Whereas any of these measures can be used for the stability failure modes pure loss of stability, parametric roll, surf riding/broaching and excessive acceleration, only operational restrictions can be applied for dead ship condition stability failure since it concerns ships not able to avoid heavy weather.

1.4 Operational measures should be prepared so that they provide the same safety level as the design assessment procedures and standards. In particular, the safety level of those loading conditions that fail design assessment standards should become sufficient if all combinations of the ship speed and wave height, period and direction that are not recommended by these operational measures are removed from the design assessment.

1.5 Whereas the principle in paragraph 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 described by the average stability failure rate not exceeding $2.64 \cdot 10^{-3}$ per ship per year.

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

2 Nomenclature and definitions

2.1 The following nomenclature is used in these Guidelines:

Symbol	Unit	Definition
B_{wl}	m	ship breadth at waterline
d	m	draught of ship at main section
GM	m	metacentric height of ship
h_r	m	height of considered location above assumed roll axis
h_s	m	significant wave height
k_{xx}	m	dry roll radius of inertia with respect to centre of gravity
k_{yy}	m	dry pitch radius of inertia with respect to centre of gravity
k_{zz}	m	dry yaw radius of inertia with respect to centre of gravity
L_{pp}	m	length of ship between perpendiculars
N	-	number of simulations
p_s	-	probability density of sea state, i.e. probability of sea states within the range of significant wave heights and mean zero-upcrossing wave periods of 1 m and 1 s, respectively
r	1/s	rate of stability failures (average number of stability failures per time)
T	s	mean time to stability failure
T_z	s	average zero-upcrossing wave period
v_s	m/s	ship forward speed
φ	deg	roll angle (positive for starboard down)
μ	deg	mean wave direction with respect to ship centre plane: 0^o following waves, 90^o waves from starboard, 180^o head waves
θ	deg	trim angle of ship (positive for bow down)
ω_r	rad/s	natural roll frequency of ship

2.2 General definitions:

.1 *Loading condition* is the condition of loading of the ship, specified, in the scope of these Guidelines, by the draught at main section d, trim θ, metacentric height GM and radii of inertia k_{xx}, k_{yy}, k_{zz};

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

.3 *Scatter table* or *full scatter table* is a table containing probabilities of each range of sea states encountered in the considered operational area or operational route; in these Guidelines, the probabilities contained in a full scatter table are defined to sum up to one;

.5 *Limited scatter table* is a table obtained from the full scatter table by removing all sea state ranges with the significant wave height above a certain limit; in these Guidelines, limited scatter tables are defined to contain the same probabilities as the full scatter table below this limit, i.e. the total probability is not renormalized to one unless this is specifically stated;

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

.7 *Sailing condition* is a short notation for the combination of the ship forward speed v_s and mean wave direction μ with respect to the ship centre plane;

.8 *Situation* is a short notation for sailing condition combined with sea state; thus, a situation is defined in these Guidelines by the ship forward speed v_s, mean wave direction μ with respect to the ship centre plane, significant wave height h_s and mean zero-upcrossing wave period T_z;

.9 *Design assessment requirements*, if not specified otherwise, denote in these Guidelines the criteria and standards for design assessment specified by the Guidelines for vulnerability assessment or Guidelines for direct stability assessment.

3 Stability failure

3.1 These Guidelines can be applied to consider any problem related to ship motions in seaway as found appropriate by the Administration. However, the specific procedures for the evaluation of motion criteria were developed for a specific definition of stability failure, consistent with the design assessment.

3.2 Unless stricter requirements are deemed to be necessary for particular ships or ship types, the following stability failures are recommended as minimum requirements:

.1 *Excessive roll angle*, defined as an exceedance of the minimum of the following roll angles: 40º, angle of vanishing stability in calm water and angle of submergence of unprotected openings in calm water;

.2 *Excessive lateral acceleration*, defined as exceedance of the lateral acceleration of 9.81 m/s^2.

.3 To simplify the evaluation of motion criteria, instead of the requirement in paragraph 3.2.2, an equivalent maximum acceptable roll angle, defined, in degree, as $57.3/(1+h_r\omega_r^2/9.81)$ can be used. For this calculation, the roll axis can be assumed at the midpoint between the waterline and the centre of gravity of the ship.

4 Operational measures

4.1 These Guidelines consider the following operational measures:

.1 *Operational restrictions*, which are related to specific operational areas (either geographical areas or specific types of operational areas like sheltered waters) or routes and, if appropriate, specific season, in which the ship in the considered loading condition can operate. The environmental conditions are specified by the joint probability of the ranges of significant wave height and average zero-upcrossing wave period (scatter table) and corresponding statistics of wind force and gustiness, as approved by the Administration.

.2 *Operational limitations*, which are related to limiting the overall operability of a ship in a specific loading condition in terms of maximum significant wave height. The environmental conditions are specified by the combination of the scatter table, related to the operational area or route and season, and corresponding statistics of wind force, together with the maximum significant wave height at which the ship can operate; the scatter table limited at a specific significant wave height is referred to as a limited scatter table.

.3 *Operational guidance*, which specifies the not recommended combinations of ship speed and wave direction that should be avoided in each relevant sea state.

4.2 The differentiation between the operational measures specified in paragraph 4.1 concerns the amount of control which is required in the application: operational restrictions do not require weather data during the operation of the vessel and thus do not require any specific control; operational limitations need an accurate forecast for the significant wave height and the availability of appropriate routing in a sufficient time before storm; operational guidance requires detailed forecast information about wave energy spectra and wind characteristics, together with an on-board assistant software, indicating combinations of ship speed and wave direction that should be avoided, which should be available for safe routing in a sufficient time before storm.

4.3 The operational measures specified in paragraph 4.1 can be combined: for example, operational limitations can be applied up to a certain significant wave height and operational guidance for greater significant wave heights. In the case of combination of operational restrictions or operational limitations with operational guidance, the requirements for operational guidance apply.

5 Approval of operational measures

5.1 Operational restrictions, operational limitations and operational guidance are approved by the Administrations according to these Guidelines during design approval. In exceptional cases, approval of operational restrictions, operational limitations and operational guidance can be done for specific loading conditions by the port Administration before departure from the port.

5.2 Approval of a loading condition for unrestricted operation, restricted operation, limited operation or operation using on-board operational guidance should be performed following these Guidelines in combination with the Design assessment requirements. A loading condition is considered as

.1 *allowed for unrestricted operation*, if it satisfies the Design assessment requirements for all five stability failure modes specified in paragraph 1.2;

.2 *allowed for unrestricted operation under operational limitations*, if it is provided with operational limitations for one or more stability failure modes specified in paragraph 1.2 for unrestricted area and satisfies the Design assessment requirements for the remaining stability failure modes;

.3 *allowed for unrestricted operation using on-board operational guidance*, if it is provided with an approved operational guidance for one or more stability failure modes specified in paragraph 1.2 (with the exception of the dead ship condition stability failure mode) for unrestricted area and is either provided with operational limitations for unrestricted area or satisfies the Design assessment requirements for the remaining stability failure modes;

.4 *allowed for restricted operation in a specified area or on a specified route during a specified season*, if it is provided with operational restrictions for one or more stability failure modes specified in paragraph 1.2 for this area or route and season and satisfies the Design assessment requirements for the remaining stability failure modes;

.5 *allowed 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 paragraph 1.2 (with the exception of the dead ship condition stability failure mode) for a given significant wave height limit for this area or route and season and either has operational restrictions suitable for this area or route and season or satisfies the Design assessment requirements for the remaining stability failure modes;

.6 *allowed for operation using on-board operational guidance in a specified area or on a specified route during a specified season*, if it is provided with an approved operational guidance for one or more stability failure modes specified in paragraph 1.2 (with the exception of the dead ship condition stability failure mode) for this area or route and season and is either provided with operational limitations or operational restrictions for this area or route and season or satisfies the Design assessment requirements for the remaining stability failure modes.

5.3 Application of operational limitations or operational guidance can reduce the stability failure rate to any low level. However, if too many sailing conditions in too many sea states are not recommended for a certain loading condition, such a loading condition cannot be considered as sufficiently safe in practical operation. Therefore,

.1 A loading condition cannot be considered as allowed if the ratio of the total duration of all situations recommended by operational limitations or operational guidance to the total operational time is less than 0.8.

.2 In the calculation of the ratio in paragraph 5.3.1, the probability density of the sea states is taken according to the full scatter table for the specified operational area or specified route and specified season; wave headings are assumed uniformly distributed between 0 and 360 deg; the ship forward speed is assumed uniformly distributed between zero and full service speed.

5.4 Active means of motion reduction, such as active anti-roll fins and anti-roll tanks, can significantly reduce roll motions in seaway if appropriately used. Therefore, if such devices are not considered in the development and application of the operational measures, the advice to the ship master may be sub-optimal or misleading. On the other hand, the safety of ship should be ensured also in cases of failure of such devices. Therefore, it is recommended that the development, application and approval of the operational measures is done both with operating and switched off anti-roll devices; however, approval of loading conditions considering operational measures according to paragraph 5.2 should be performed with such devices switched off.

5.5 Operational guidance can indicate some sailing conditions as safe from the point of view of 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 roll in bow waves, roll motions reduce with increasing forward speed, but high speeds in bow waves are either unattainable or 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.

5.6 Therefore, it is recommended to take into account the following factors in the operational guidance:

.1 Maximum attainable forward speed in wave directions from head waves to 60 degree off-bow. This speed can be defined from model tests or numerical computations. If such model tests or numerical computations are not available, parametric roll in bow waves can be conservatively evaluated at zero forward speed.

.2 Maximum suitable forward speed in wave directions from head waves to 60 degree off-bow from the point of view of absolute and relative motions, vertical accelerations and slamming. This speed can be defined from model tests or numerical computations or, alternatively, set to 30% of the full service speed in calm water.

.3 In sea states where heading into seaway is necessary to avoid excessive lateral accelerations, the ability of the ship to keep a forward speed in head waves of at least 10% of the full service speed in calm water should be demonstrated by model tests or numerical computations.

6 Preparation procedures

6.1 Operational restrictions

6.1.1 Operational restrictions are prepared following the same principles as the design assessment, by applying the design assessment procedures according to the Design assessment requirements 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, approved by the Administration.

6.1.2 In the preparation of operational restrictions, it is recommended to use the Bretschneider wave energy spectrum and cosine-squared wave energy spreading with respect to the mean wave direction.

6.1.3 For some level 1 and level 2 vulnerability assessment procedures, regular wave cases should be defined based on the wave statistics. Examples of the definition of such regular wave cases for parametric roll and pure loss of stability failure modes are shown in Annex 2.

6.2 Operational limitations

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

6.2.2 Operational limitations are prepared by application of the criteria, procedures and standards defined in the Design assessment requirements.

6.2.3 In the preparation, it is recommended to use the Bretschneider wave energy spectrum and cosine-squared wave energy spreading with respect to the mean wave direction.

6.2.4 For certain level 1 and level 2 design assessment procedures, definition of the corresponding regular wave cases is required; this is done in the same way as for operational restrictions, see examples in Annex 2 for parametric roll and pure loss of stability failure modes.

6.3 General principles of preparation of operational guidance

6.3.1 Operational guidance should indicate all not recommended sailing conditions for each range of sea states in the relevant wave scatter table.

6.3.2 Operational guidance should ensure that the considered condition of loading satisfies the Design assessment requirements after removing from the design assessment all not recommended sailing conditions, assuming that the ship equipped with the operational guidance will not sail in the not recommended situations. To simplify the preparation and approval of operational guidance, three general approaches, recommended for the preparation of operational guidance, are considered below in detail. These options are based on

.1 probabilistic motion criteria and standards (referred to as probabilistic operational guidance);

.2 non-probabilistic motion criteria and standards (referred to as non-probabilistic operational guidance);

.3 simplified motion criteria and standards (referred to as simplified operational guidance).

6.3.3 In the preparation of operational guidance, it is recommended to apply the Bretschneider wave energy spectrum and cosine-squared wave energy spreading with respect to the mean wave direction, unless other recommendations deem appropriate by the Administration.

6.4 Probabilistic operational guidance

6.4.1 This type of operational guidance uses probabilistic criteria, such as probability of stability failure during some time or rate of stability failures, and corresponding probabilistic thresholds to distinguish between recommended and not recommended sailing conditions.

6.4.2 For the rate of stability failures as the safety criterion, not recommended sailing conditions, defined by the ship forward speed v_s and ship heading with respect to the mean wave direction μ, in a sea state defined by the significant wave height h_s and mean zero-upcrossing wave period T_z, are those for which

$$r \cdot w_i > s_1.$$

6.4.3 Here, r, 1/s, is the stability failure rate, w_i is the probability density of the sea state and $s_1 = 10^{-10}$ 1/s is the probabilistic threshold.

6.4.4 The rate of stability failures can be estimated from numerical simulations of ship motions in seaway as r=1/T, where T is the mean time to stability failure. This time can be estimated as the average of the time until the first stability failure in each of numerical simulations of ship motions in N realisations of the same sea state. The realisations of the same sea state are generated by random selection of frequencies, directions and phases of wave components composing the sea state.

6.4.5 For the numerical simulations of ship motions in waves, numerical methods satisfying the requirements of the Guidelines for direct stability assessment should be used.

6.4.6 The recommended number of sea state relaisations is N=200. Procedures to reduce the number of simulations and time of each simulation to address the problem of rarity can be used as recommended for probabilistic design assessment according to the Guidelines for direct stability assessment.

6.5 Non-probabilistic operational guidance

6.5.1 Whereas using probabilistic criteria provides the best accuracy, it requires significant computational resources and, besides, cannot be developed using model tests. Using non-probabilistic criteria, such as maximum roll amplitude per given time, is much simpler and can be implemented in model tests but is less accurate. To compensate for the inaccuracy when using non-probabilistic criteria, conservative thresholds are necessary to keep the required safety level.

6.5.2 Non-probabilistic operational guidance can be prepared either using only model tests, only numerical simulations or their combination. Numerical methods applied in such simulations should satisfy the requirements of the Guidelines for direct stability assessment.

6.5.3 In a non-probabilistic operational guidance, not recommended sailing conditions, defined by the ship forward speed v_s and ship heading with respect to the mean wave direction μ, in a sea state defined by the significant wave height h_s and mean zero-upcrossing wave period T_z, are those for which

$$\alpha \cdot \varphi_{3h} > s_2.$$

6.5.4 Here, α=2 is the scaling factor, φ_{3h} is the mean three-hour maximum amplitude of roll or lateral acceleration and s_2 is the threshold defined in paragraph 3.2.

6.5.5 To define the mean three-hour maximum amplitude, the total recommended duration of test or simulation is 15 hours for each considered situation. This duration can be divided into several shorter parts. Note that the full duration is required only in marginal cases, whereas for majority of situations, the differentiation between recommendable and non-recommendable is possible after a shorter time. Besides, if a certain situation is evaluated as safe or unsafe, assessment for lower or higher, respectively, significant wave heights with other parameters unchanged are not required.

6.6 Simplified operational guidance

6.6.1 Probabilistic and non-probabilistic operational guidance requires model tests or numerical methods of high accuracy and provides accurate and detailed recommendations for the ship forward speed and course in each sea state. When it deems practicable to use coarse conservative recommendations for forward speed and course, simpler means can be used.

6.6.2 In principle, any simple conservative estimations for the not recommended sailing situations 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 from the Guidelines for vulnerability assessment can be used. Some examples of recommended approaches based on level 1 and level 2 vulnerability criteria are included below:

.1 For the pure loss of stability failure mode, propeller rotation speeds corresponding to the speed in calm-water of $0.752 \cdot L_{pp}^{1/2}$, m/s, are not recommended in following to beam wave directions in sea states for which $\max(c_{1i},c_{2i})=1$, where c_{1i} and c_{2i} are defined according to paragraphs 2.10.3.3 and 2.10.3.4, respectively, of the Guidelines for vulnerability assessment;

.2 For the parametric roll stability failure mode, not recommended in all wave directions and all sea states are forward speeds for which $c_i(v_s,h_s,T_z)$, defined according to paragraph 2.11.3.3.1 of the Guidelines for vulnerability assessment, is equal to 1;

.3 For the surf riding/broaching stability failure mode, propeller rotation speed settings corresponding to the speed in calm-water of $0.94 \cdot L_{pp}^{1/2}$, m/s, are not recommended in following to beam wave directions in sea states for which $c_{HT}>0.005$, where c_{HT} is calculated as

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

where $w_{ij}(h_s,T_z)$ are ... and c_{ij} are...

.4 For the excessive acceleration stability failure mode, wave directions from 30 degree off-bow to 30 degree off-stern are not recommended at all forward speeds in sea states where $w_i c_i>10^{-6}$, where c_i is calculated according to paragraph 2.14.3.2.1 of the Guidelines for vulnerability assessment.

7 Application

7.1 Operational guidance should be provided as easily accessible and understandable information in graphical form, which clearly indicates not recommended 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 not recommended sailing conditions.

7.2 The not recommended sailing conditions are automatically computed from the pre-defined databases of probabilistic, non-probabilistic or simplified safety criteria, stored as functions of the ship forward speed and ship heading with respect to the mean wave direction for sea states specified by significant wave height and mean zero-upcrossing wave period, using as input the actual significant wave height, mean zero-upcrossing wave period, mean wave direction and ship course.

7.3 The effect of 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-upcrossing 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 non-probabilistic operational guidance;

.3 overlaying the non-recommended sailing conditions for each of these wave systems when using simplified operational guidance.

7.4 At a departure from the port, operational limitations or operational guidance should be available for the entire voyage duration until the next port. The ship master should be able to demonstrate that the entire voyage can be conducted satisfying the operational limitations or operational guidance.

7.5 The most actual weather forecast should be available for the entire duration until the end of the voyage in the next port. Detailed time plan for the ship forward speed and course should be permanently ready for the next three days or for the entire duration of voyage, whichever is shorter, based on the latest weather forecast, to allow for sufficient time to change route if necessary.

7.6 The weather forecast data should be available as

.1 significant wave height for operational limitations;

.2 wave energy spectra or, at least, significant wave height, mean zero-upcrossing wave period and mean wave direction for wind sea and swell, for operational guidance.

7.7 As accurate as practicable data should be available for the loading condition at the departure from the port, including draught, trim, displacement, metacentric height, longitudinal position of the centre of gravity, roll, pitch and yaw radii of inertia and the natural roll period. Estimate of the current state of these parameters should be always available during the voyage together with the estimated change of these parameters for the time until the arrival in the next port.

ANNEX 2

WAVE CASES FOR PREPARATION OF OPERATIONAL RESTRICTIONS AND OPERATIONAL LIMITATIONS USING LEVEL 1 AND LEVEL 2 VULNERABILITY ASSESSMENT

1 Wave scatter diagram should have a resolution of at least 1 s for the mean zero-upcrossing wave period and 1 m for significant wave height. For each mean zero-upcrossing wave period in the scatter table,

.1 the *reference wave height* $h_{ref,i}$ is selected as the conditional mean significant wave height; and

.2 the corresponding reference wave period $T_{ref,i}$ is selected as the corresponding mean spectral period: for the Bretschneider spectrum, $T_{mean}=1.0864 \cdot T_z$.

2 The result is a series of reference environmental conditions $T_{ref,i}, h_{ref,i}$ with i=1,…N, where N is the number of wave periods in the wave scatter table.

3 Each reference environmental condition is associated with the probability density w_i, which is obtained from the wave scatter table as the sum of the probabilities of all sea states with the reference wave period $T_{ref,i}$.

4 The sets of N wave cases are selected separately for parametric roll and pure loss of stability starting from the obtained set of reference environmental conditions and using the following equivalence formulae:

.1 For parametric roll: wave length $\lambda_i = 0.5g \cdot T_{ref,i}^2 / \pi$ and wave height $h_i = k_{PR} h_{ref,i}$ with $k_{PR} = 0.7$;

.2 For pure loss of stability: wave length $\lambda_i = 0.5g \cdot T_{ref,i}^2 / \pi$ and wave height $h_i = k_{PL} h_{ref,i}$, where $k_{PL} = 1.4$.

5 The first check of Level 2 vulnerability assessment for parametric roll is carried out using waves defined in paragraph 4.1.

6 Level 1 vulnerability assessment is performed using the following conservative values for the wave steepness parameter:

.1 For parametric roll: $s_w = \max_{i=1,\ldots,N} \left(k_{PR} h_{ref,i} / \lambda_i \right)$;

.2 For pure loss of stability: $s_w = \max_{i=1,\ldots,N} \left(k_{PL} h_{ref,i} / \lambda_i \right)$;

9 Level 2 vulnerability assessments using directly data from the wave scatter table can be applied by substituting the standard wave scatter diagram with the wave scatter diagram associated with the considered operational restrictions or operational limitations.

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APPENDIX

**BACKGROUND INFORMATION TO
DRAFT INTERIM GUIDELINES FOR OPERATIONAL MEASURES**

1 Ships and loading conditions

1.1 Five ships were used in the studies: a cruise vessel, a RoPax vessel and three container ships of 1700, 8400 and 14000 TEU capacity. For each ship, 5 loading conditions were selected: 3 loading conditions with small GM values (relevant for parametric roll, pure loss of stability and stability in dead ship condition) and two loading conditions with big GM values (relevant for excessive accelerations).

1.2 Table 1 summarises the parameters of ships and loading conditions, and Figure 1 shows examples of the calm-water righting lever curves for typical loading conditions with low metacentric height.

Table 1. Ships and loading conditions used in study

Ship	Notation	L_{pp}, m	B_{wl},m	Draft, GM	Loading Condition: 01	02	03	04	05
Cruise Vessel	Cruise	230.9	32.2	d, m	6.9				
				GM, m	1.5	2.0	2.5	3.25	3.75
RoPax Vessel	RoPax	175.0	29.5	d, m	5.5				
				GM, m	3.7	4.5	5.2	5.9	6.6
1700 TEU Container Ship	CV1700	159.6	28.1	d, m	9.5			5.5	
				GM, m	0.5	1.2	1.9	5.75	6.75
8400 TEU Container Ship	CV8400	317.2	43.2	d, m	13.93	14.44	14.48	11.36	
				GM, m	0.89	1.26	2.01	5.0	6.93
14000 TEU Container Ship	CV14000	349.5	51.2	d, m	14.5			8.5	
				GM, m	1.0	2.0	3.0	9.0	12.0

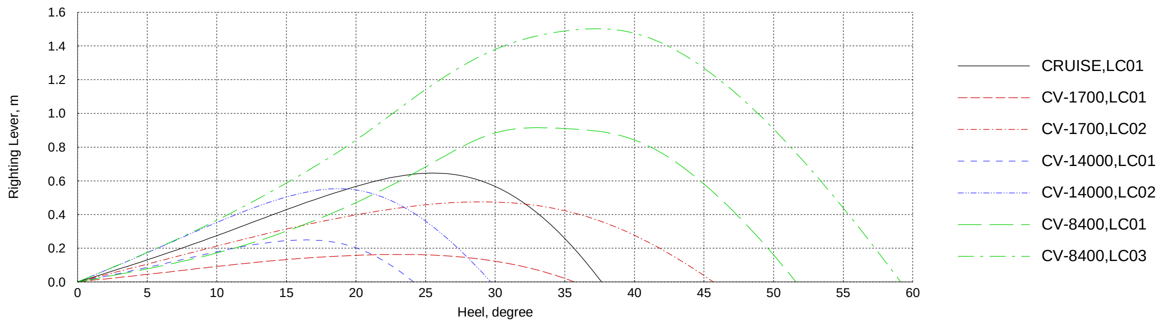

Figure 1. Calm-water righting lever curves for typical loading conditions with low GM

2. Preparation and approval of operational measures and sources of weather data

2.1 An important question is in what phase of ship life cycle operational measures should be produced and approved: in design phase, in port before departure or directly en route.

.1 The first option, pre-computation and approval in the design stage, allows using most comprehensive numerical tools and statistical procedures, qualified staff and dedicated hardware. Besides, this option allows a detailed approval by the Administration. The drawback is that the computations can be performed only for assumed input parameters, most importantly, standard seaway spectra.

.2 The second option, pre-computation before departure from port (by an on-shore provider), allows, in principle, using comprehensive numerical tools and statistical procedures together with qualified staff and dedicated hardware and, in addition, most accurate data about loading condition and the most actual weather forecast available. In principle, operational measures can be verified by the port Administration together with the weather forecast, but this requires development of a corresponding infrastructure. The drawback of this option is the possibility of unforeseen delays in the ship operator time schedule.

.3 The third option, real-time computations during operation, means performing the required computations during operation (on board or on-shore), once accurate weather forecast is available. It allows using the most actual weather and loading condition data. However, when this approach is followed, both numerical tools and statistical procedures employed have to be significantly simplified, so that the advantage of more accurate weather data may be to some degree compensated by the reduced accuracy of numerical tools and statistical procedures.

2.2 Note that when the last option is used, accurate weather forecast and operational guidance (or operational limitations) should be ready in a sufficient time before storm (proposal: 3 days) to allow for route change if safe operation in the foreseen storm is impossible (i.e. if there are no suitable speed-course combinations), taking into account that operational guidance or operational limitations are expected to be required usually for loading conditions that are found vulnerable to stability problems.

2.3 The following sources of environmental data are suitable:

.1 wave scatter tables for operational restrictions but not for operational guidance or operational limitations; and

.2 weather forecast for operational guidance or operational limitations.

2.4 A wave radar provides recommendations only for the instantaneous environmental conditions, thus it seems unsuitable for operational guidance within SGISC (i.e. to provide operational recommendations for loading conditions vulnerable to stability problems), which, however, does not prevent its complementary use to the SGISC instruments.

3 Preparation and approval of operational guidance in design phase

3.1 A drawback of option 2.1.1, pre-computation and approval of operational guidance in the design stage, is that it relies on assumed theoretical wave energy spectra and therefore, deviations of real seaways from this assumption may lead to erroneous operational recommendations. Especially critical situation in this respect is the cross sea, when wind sea and swell have significantly different directions.

3.2 One relevant consideration is that the influence of swell is usually noticeable in small to moderate sea states and relatively small in strong storms (which are dominated by wind sea). Figure 2 shows theoretical relationship between wind speed and wave height of wind sea (solid line), in comparison with hindcast data for two locations in North Atlantic (▲,▼). According to this comparison, the influence of swell is noticeable at small wave heights (indicated by the difference in wave height for a given wind speed between the theoretical relationship and hindcast data) but becomes relatively insignificant in more severe storms. Figure 3, showing the significant wave height of swell plotted vs. the significant wave height of wind sea according to the same hindcast data, confirms this.

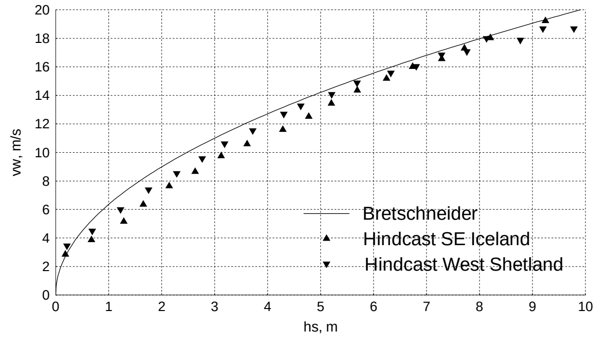

Figure 2. Theoretical relationship between wind speed (y axis) and wave height (x axis), solid line, in comparison with hindcast data for two locations in North Atlantic

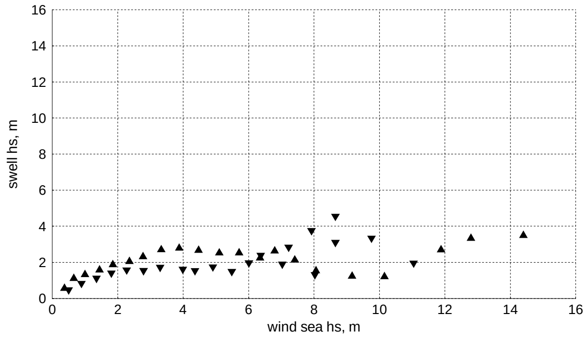

Figure 3. Significant wave height of swell (y axis) plotted vs. significant wave height of wind sea (x axis) for hindcast data shown in Figure 2

3.3 To verify this consideration, world-wide hindcast data from the ERA Interim database were used to estimate the likelyhood of severe cross sea. From the data for one year (about 30 million entries), seaways were selected for which the angle between wind sea and swell was more than 80 deg: for about 0.01% of all data, the heigts of both wind sea and swell were more than 4 m; for about 0.001% of data, more than 5 m, and for 0.0001% of data, more than 6 m. This means that the likelyhood of severe cross sea is negligible.

3.4 To check whether numerical simulations using theoretical wave energy spectra can be applied to approximate roll responses to complex measured wave energy spectra, several cross sea situations were selected from the ERA Interim database. For these situations, two questions were investigated: first, what influence has the overlapping effect of wind sea and swell, i.e. how much the combined response to the two separate (wind sea and swell) wave energy systems differs from the response to the total spectrum and, second, how large is the effect of the approximation of the real wave energy spectrum with a theoretical spectrum.

3.5 To answer these questions, numerical simulations of ship motions in irregular waves were performed for the selected situations for the following modes:

.1 measured wave energy spectrum, including wind sea and swell;

.2 separate wave energy spectra of wind waves and swell, derived from the measured wave energy spectrum. The responses (rate of stability failures) to these two separated spectra were summed; and

.3 approximated wave energy spectra, separately for wind waves and swell. JONSWAP wave energy spectrum with the peak enhancement factor 3.3 and $\cos^2$ wave energy spreading with respect to the mean wave direction was used for approximation. The responses (rate of stability failures) to the separate theoretical spectra were summed.

3.6 In the definition of the separated wave energy spectra of wind sea and swell from the measurements, the significant wave height, mean period and mean direction of the wave energy spectrum, wind sea spectrum and swell spectrum were kept unchanged. The ship course was varied from 0 to 360 deg every 10 deg. Numerical simulations were performed for 200 realisations of each seaway until the first exceedance of 40 deg roll angle.

3.7 This comparison was performed for all ships and loading conditions listed in Table 1, for six forward speeds equally distributed between zero and full speed in calm water. Here, selected results are shown for two situations, Table 2, for 1700 TEU container ship in loading condition LC01 and 14000 TEU container ship in loading conditions LC01 and LC02.

Table 2. Parameters of wave energy spectra for two situations

Situation	A	B
Significant wave height, m		
total	9.8	8.7
wind sea	4.0	5.4
swell	8.9	6.8
Mean wave period, s		
wind sea	12.4	9.0
swell	10.9	14.3
Mean wave propagation direction, deg		
wind sea	60	213
swell	153	27
shift	93	186

3.8 The results in Figure 4 (situation A) and Figure 5 (situation B) show that the separate simulations for the wave energy spectra of wind sea and swell and summing the resulting rates of stability failures (compare the left and middle columns in Figure 4 and Figure 5) leads to slightly non-conservative results, whereas modelling of wind sea and swell systems using a theoretical spectrum (JONSWAP with γ=3.3 and $\cos^2$ wave energy spreading) leads to slightly conservative results (compare the middle and right columns in Figure 4 and Figure 5). The total effect due to both separate treatment of wind sea and swell and theoretical approximation of wave energy spectra for these wave systems is slightly conservative in situation A and slightly non-conservative in situation B.

3.9 In considered all cases, theoretical modelling of wave systems and overlapping their effect (by summing the failure rate corresponding to each of the systems) leads to practically acceptable recommendations for ship's forward speed and course. Therefore, production and approval of operational guidance in the design phase seems to be an acceptable option.

4 Probabilistic operational guidance

4.1 To prepare a database of ship responses, numerical simulations of motions in waves were conducted for each ship and each loading condition in Table 1. The simulations were performed for six forward speeds, equally distributed from zero to full speed in calm water, for the zero-upcrossing wave periods T_z and significant wave heights h_s covering the North Atlantic wave scatter table, IACS Rec. 34, and for wave directions μ from 0 (following waves) to 180 (head waves) deg every 10 deg. For each combination of forward speed, wave period, significant wave height and wave direction, numerical simulations of the duration of $1.7{\cdot}10^4$ hours (or until the first exceedance event) of ship motions were conducted in 200 realisations of the same sea state; the realisations of the same sea state were generated by random variation of frequencies, directions and phases of wave components composing the sea state.

4.2 From each simulation, the time T_i until the first stability failure was defined. The estimate of the expected time until stability failure was calculated by averaging over N=200 stability failure events as

$$\tilde{T} = \frac{1}{N}\sum_{i=1}^{N} T_i \qquad (1)$$

4.3 The maximum likelihood estimate of the rate r of stability failures (i.e. number of stability failures per time) was calculated as

$$\tilde{r} = 1/\tilde{T} \qquad (2)$$

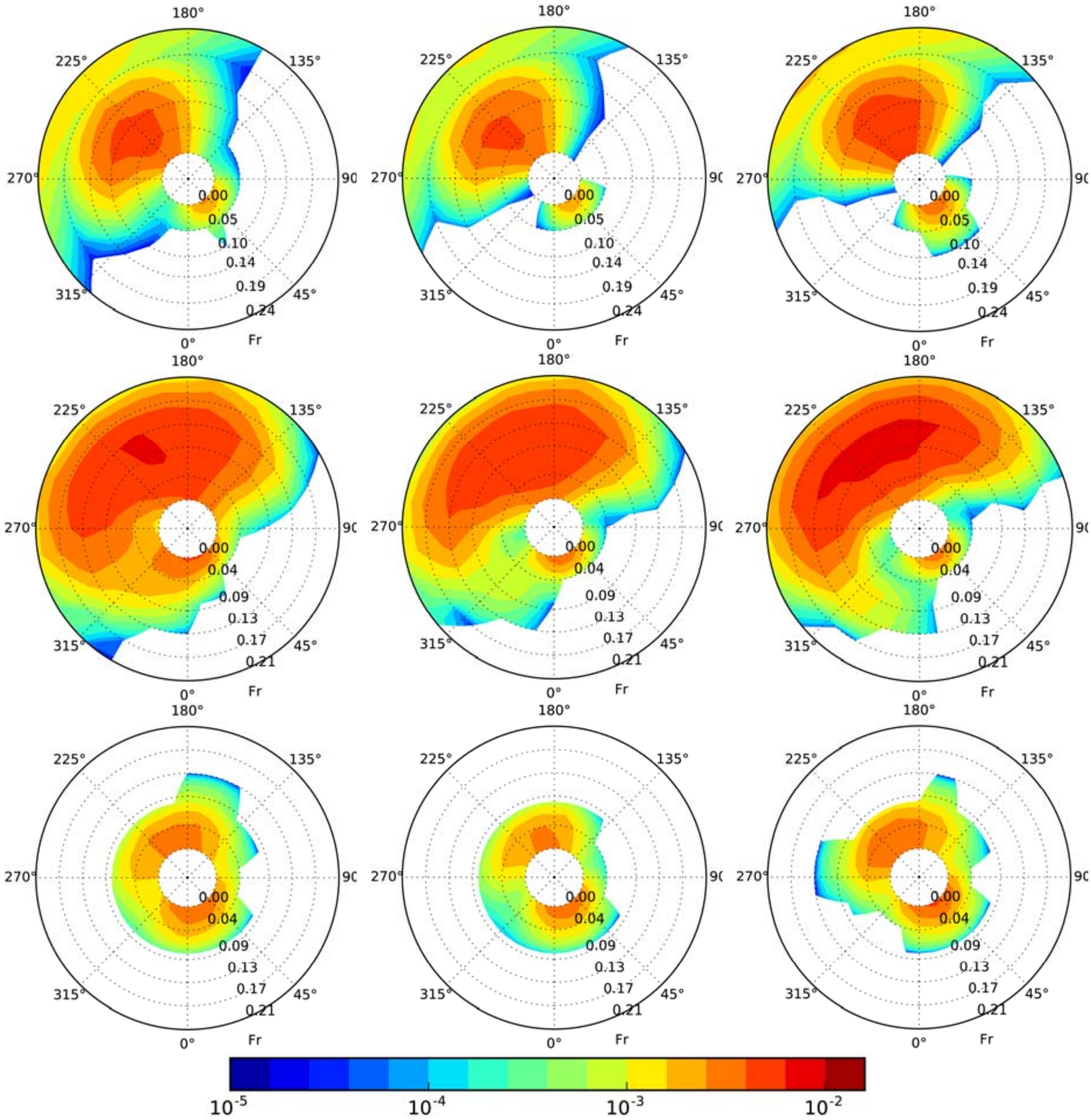

Figure 4. Situation A: colour plot of stability failure rate, 1/s, vs. Fr number (radial coordinate) and ship course (circumferential coordinate) for measured wave energy spectrum (left), summed rate for separate wind waves and swell wave energy spectra (middle) and summed rate for separate wind waves and swell wave energy spectra approximated with JONSWAP spectrum with γ=3.3 and $\cos^2$ wave energy spreading (right) for 1700 TEU container ship in LC01 (top) and 14000 TEU container ship in LC01 (middle) and LC02 (bottom)

4.4 Operational guidance identifies the combinations of ship speed and course that should be avoided for each sea state, specified by the wave height, period and direction. Obviously, operational guidance (as well as operational restrictions and operational limitations) should be developed in such a way that avoiding these combinations ensures the same safety level as for loading conditions satisfying the Design assessment requirements. To assess the safety level provided by an operational guidance, average stability failure rate was calculated after removing all not recommended conditions. To investigate the depedency of results on the forward speed, different forward speeds were first treated separately:

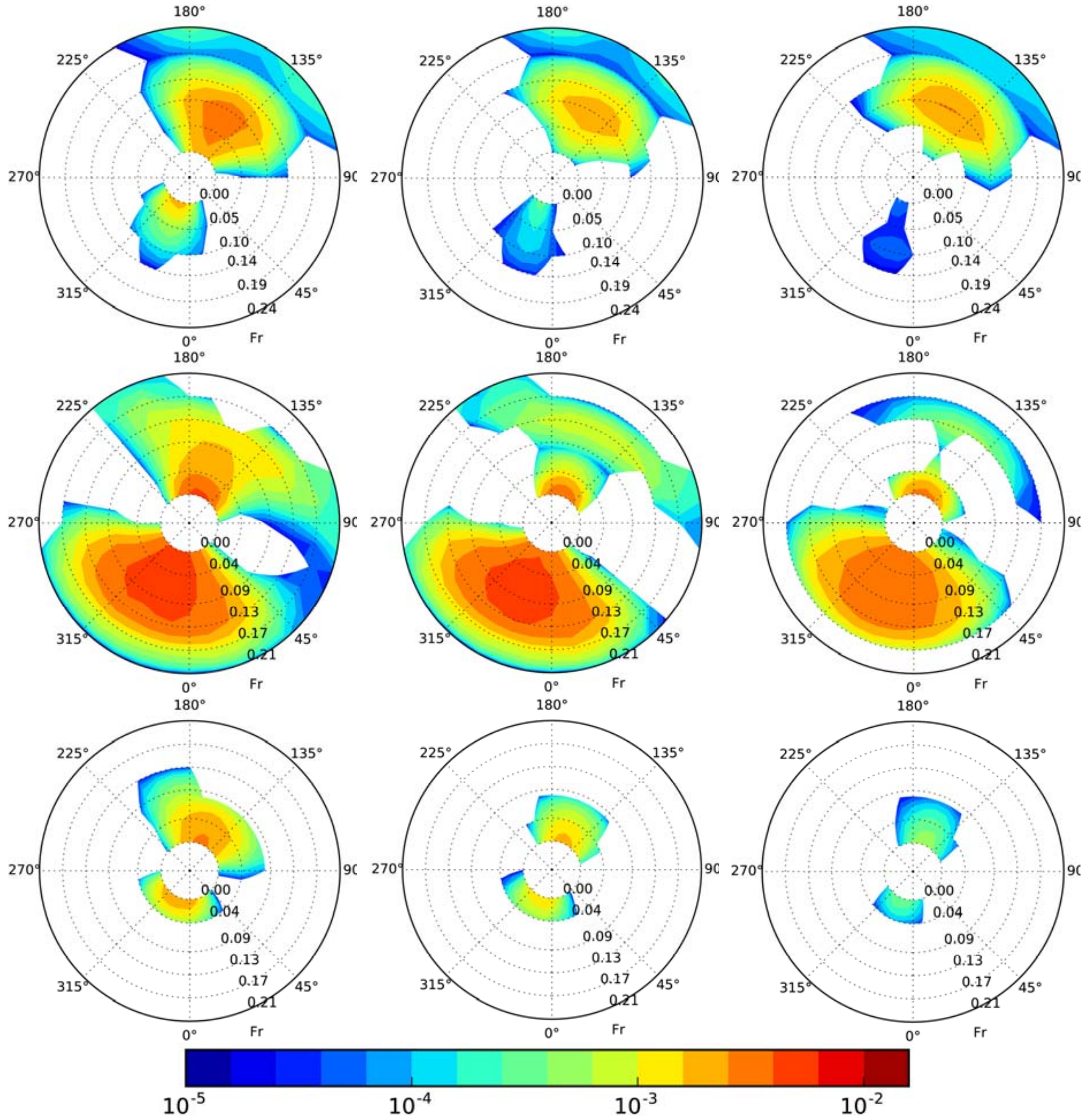

Figure 5. Situation B: colour plot of stability failure rate, 1/s, vs. Fr number (radial coordinate) and ship course (circumferential coordinate) for measured wave energy spectrum (left), summed rate for separate wind waves and swell wave energy spectra (middle) and summed rate for separate wind waves and swell wave energy spectra approximated with JONSWAP spectrum with γ=3.3 and $\cos^2$ wave energy spreading (right) for 1700 TEU container ship in LC01 (top) and 14000 TEU container ship in LC01 (middle) and LC02 (bottom)

$$w_{OG} = \sum_s \sum_\mu r \cdot p_s \Big/ \sum_s \sum_\mu p_s \qquad (3)$$

4.5 In eq. (3), $w_{OG}(\text{ship,LC},v_s)$ is the average stability failure rate conditional on satisfying operational guidance, $p_s(h_s,T_1,\mu\,|\,OG)$ is the conditional probability density of the occurrence of sea state with the significant wave height h_s, mean wave period T_1 and mean direction μ, set to zero if a combination (h_s,T_1,μ) is not recommended by operational guidance and equal to the probability density of sea state occurrence $p_s(h_s,T_1,\mu)$ otherwise; $r(h_s,T_1,\mu;\text{ship,LC},v_s)$

is the average stability failure rate, 1/s, of a given ship in a given loading condition at a given forward speed in the sea state (h_s,T_1,μ). The distribution of the probability density of the occurrence of sea states was defined according to IACS Rec.34 (North Atlantic wave climate).

4.6 For convenience, both the total rate of stability failures and contributions from the various stability failure modes were calculated separately. Note that synchronous rolling in beam waves at non-zero speed is also considered in operational guidance, although it is not addressed directly by SGISC.

4.7 Two probabilistic criteria were tested as possible candidates for differentiators between safe and unsafe sailing conditions: the stability failure rate r and the product $r \cdot p_s$. Figure 6 shows the dependencies of the average rate of stability failures w_{OG} (total rate and contributions from various stability failure modes) on the systematically varied short-term threshold of rp_s, and Figure 7 shows the corresponding dependencies for the systematically varied short-term threshold of r.

4.8 These results prove rp_s as a suitable criterion to be used for operational guidance, because it leads to the same dependencies of the long-term safety level w_{OG} on the rp_s-threshold for all ships, loading conditions and forward speeds until saturation (i.e. when further relaxing of the threshold does not change safety level anymore); at rp_s of about 10^{-5} 1/s, the long-term safety level becomes saturated for all considered ships, loading conditions and forward speeds.

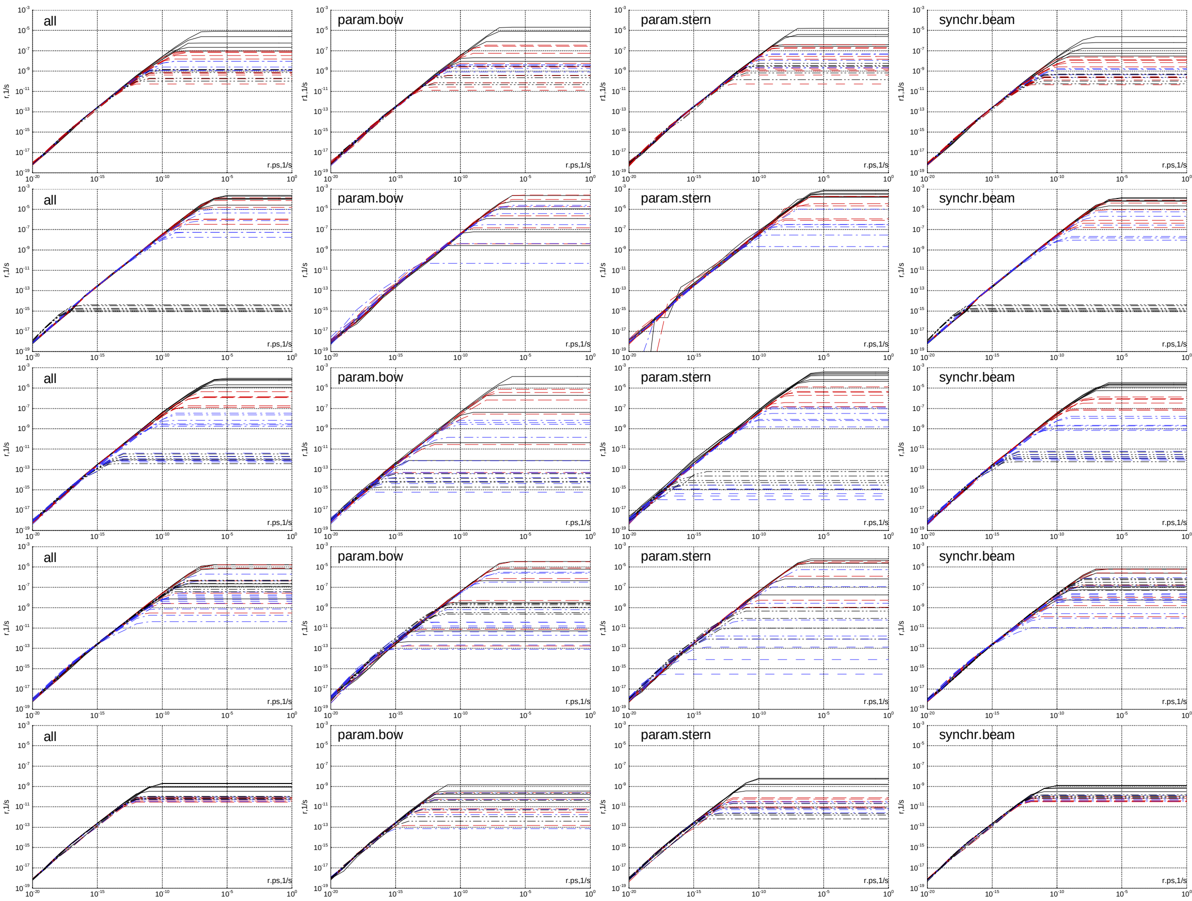

Figure 6. Average rate of stability failures w_{OG} (from left to right: all failure modes, parametric roll in bow waves, parametric roll in stern waves and synchronous roll) depending on rp_s-threshold for (from top to bottom) cruise vessel, CV 14000 TEU, CV 1700 TEU, CV 8400 TEU and RoPax; types and colours of lines differentiate loading conditions, lines of the same type and colour correspond to various forward speeds for same loading condition

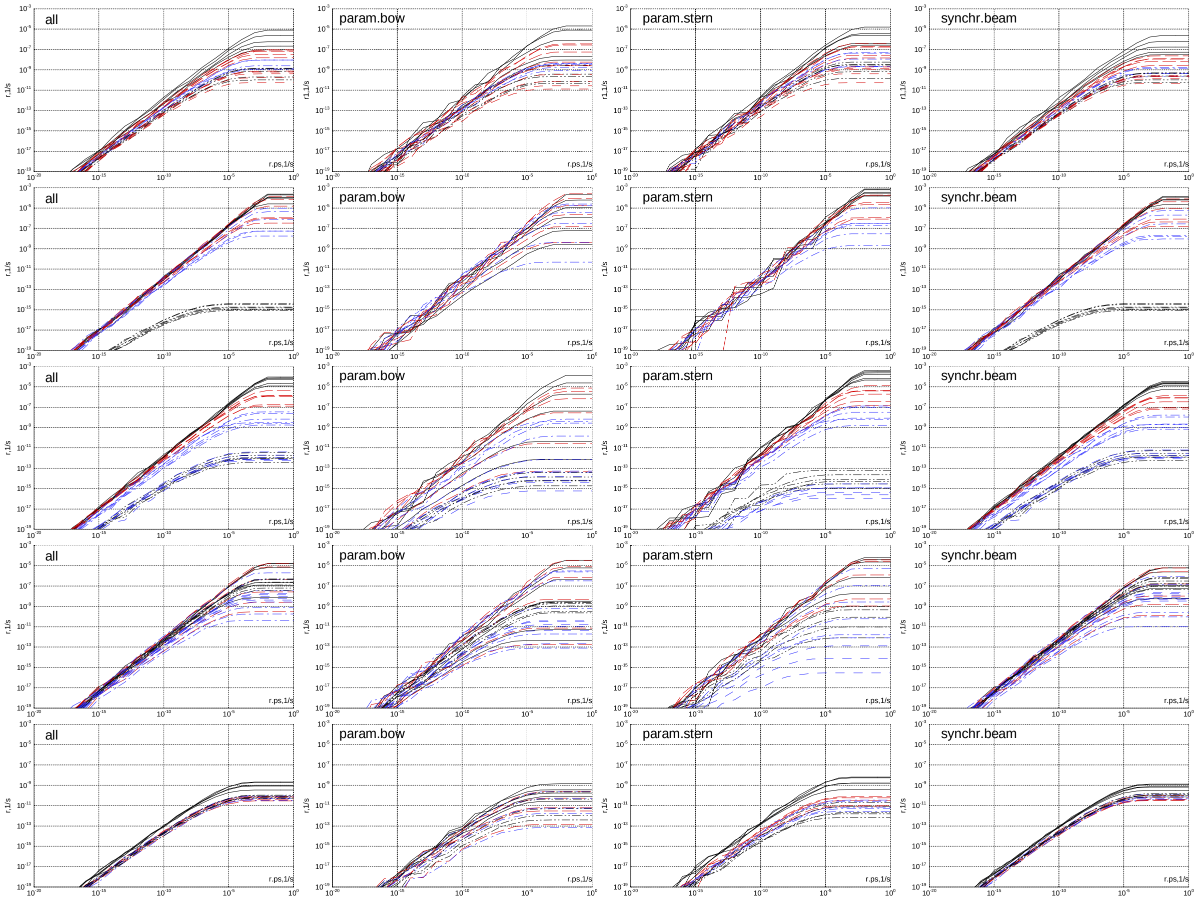

Figure 7. Average rate of stability failures w_{OG} (from left to right: all failure modes, parametric roll in bow waves, parametric roll in stern waves and synchronous roll) depending on r-threshold for (from top to bottom) cruise vessel, CV 14000 TEU, CV 1700 TEU, CV 8400 TEU and RoPax; types and colours of lines differentiate loading conditions, lines of the same type and colour correspond to various forward speeds for same loading condition

4.9 Using directly the the stability failure rate r as a criterion leads to some spreading of the safety level for the same value of the short-term threshold between forward speeds and loading conditions for the same ship and between ships, which means that using r as the safety criterion for operational guidance will lead to spreading of the safety level provided by operational guidance between different ships and loading conditions.

4.10 An appropriately defined approach to operational guidance should provide similar safety level for all loading and sailing conditions, i.e. not allow unsafe sailing conditions while not imposing unnecessary restrictions on safe sailing conditions. To check how the proposed approach influences the safety level of different ships and loading conditions at different forward speeds, Figure 8 (left) shows the results as histograms of the total number of ships, loading conditions and forward speeds (normed by 1) plotted against the resulting safety level w_{OG} (right-hand plot shows the cumulative distributions based on these histograms) for rp_s-criterion, and Figure 9 shows the corresponding results for the r-criterion.

4.11 These figures indicate that using the rp_s-criterion effectively removes cases with insufficient safety level, whereas cases that were safe enough without operational guidance are not influenced. As a result, all cases influenced by operational guidance achieve very close safety level.

4.12 Using r as a criterion for operational guidance provides a similar, while slightly poorer, quality to using rp_s.

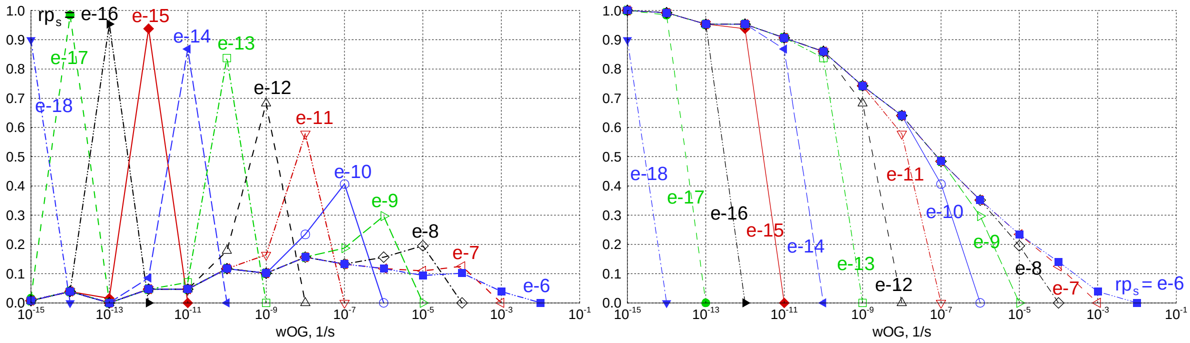

Figure 8. Left: histograms (number of ships, loading conditions and forward speeds normed on 1) having long-term safety level w_{OG}, 1/s (x axis) for various rp_s-threshold values (indicated in plot). Right: cumulative distributions derived from these histograms.

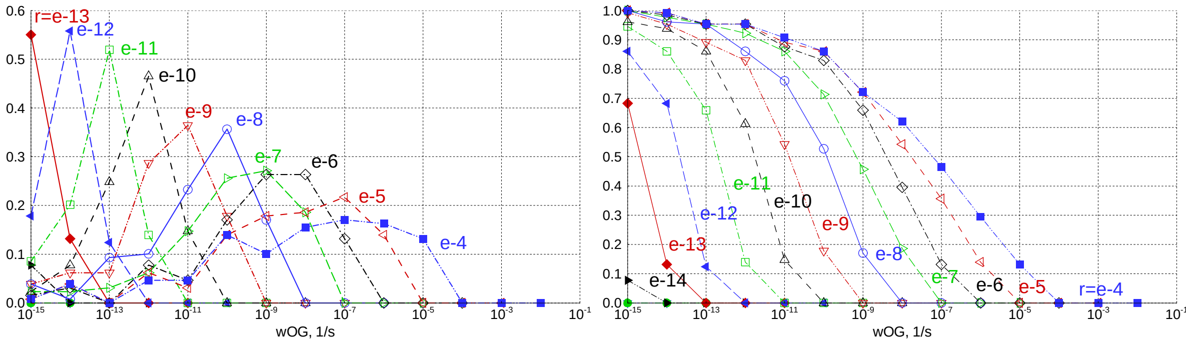

Figure 9. Left: histograms (number of ships, loading conditions and forward speeds normed on 1) having long-term safety level w_{OG}, 1/s (x axis) for various r-threshold values (indicated in plot). Right: cumulative distributions derived from these histograms.

5 Non-probabilistic operational guidance

5.1 Whereas operational guidance based on probabilistic criteria rp_s and r works well, its preparation requires significant computational resources. Hence, it was investigated whether operational guidance based on a simpler, non-probabilistic, criterion is a possible solution. Such non-probabilistic operational guidance is much simpler in production and approval than a probabilistic one and, besides, it can be developed using model tests. A drawback may be, however, that non-probabilistic operational guidance does not ensure consistent safety level across various ships, loading conditions and sailing conditions, thus it is difficult to ensure consistency with direct stability assessment.

5.2 On the other hand, if direct stability assessment is performed using design situations method, its results cannot be used for production of operational guidance anyway, thus operational guidance will require specific computations which are based on a different concept. Moreover, if operational guidance is simple enough in production, it may be feasible to develop it without performing direct stability assessment, i.e. directly for loading conditions failing to fulfill vulnerability assessment requirements of level 1 or level 2.

5.3 Another consideration is that although inevitably big inaccuracy of a non-probabilistic operational guidance must be compensated by its conservativeness (to keep a suitable safety level), excessive conservativeness of operational guidance is a smaller problem than excessive conservativeness of direct stability assessment: usually, operational practices are based on more conservative requirements than design assumptions.

5.4 The approach is based on the same idea as in the probabilistic operational guidance, eq. (3); the difference is that instead of a probabilistic criterion (stability failure rate r or product rp_s above), a non-probabilistic criterion is used to differentiate between safe and unsafe sailing conditions. Studies towards the development of non-probabilistic direct stability assessment methods showed that from all compared non-probabilistic criteria (standard deviation of roll angle, average roll amplitude, significant roll amplitude and 3-hour maximum roll amplitude), the latter provides the best results in direct stability assessment compared to the others; therefore, it was also used as a criterion in the non-probabilistic operational guidance.

5.5 To compute the expected maximum 3-hour roll amplitude, numerical simulations were performed in 50 realisations of the same sea state, generated by random variation of the frequencies, directions and phases of components modelling seaway. A difficulty in the application of non-probabilistic criteria is occurrence of capsizings in some realisations: in such cases, the maximum 3-hour roll amplitude could not be defined and therefore, the mean 3-hour maximum roll amplitude could not be calculated. To indicate such cases, the mean 3-hour maximum roll amplitude was set to 60 deg in plots (because in situations where capsizings did not happen, mean 3 hour maximum roll amplitude never achieved 60 deg).

5.6 Figure 10 shows the dependencies of the average rate of stability failures w_{OG} (total and due to various stability failure modes) on the systematically varied threshold of the mean 3 hour maximum roll amplitude. The results indicate significant scatter of the dependencies of w_{OG} on the non-probabilistic threshold between ships, loading conditions and forward speeds; saturation happens at about 30 deg of mean 3-hour maximum roll amplitude for all considered ships, loading conditions and forward speeds.

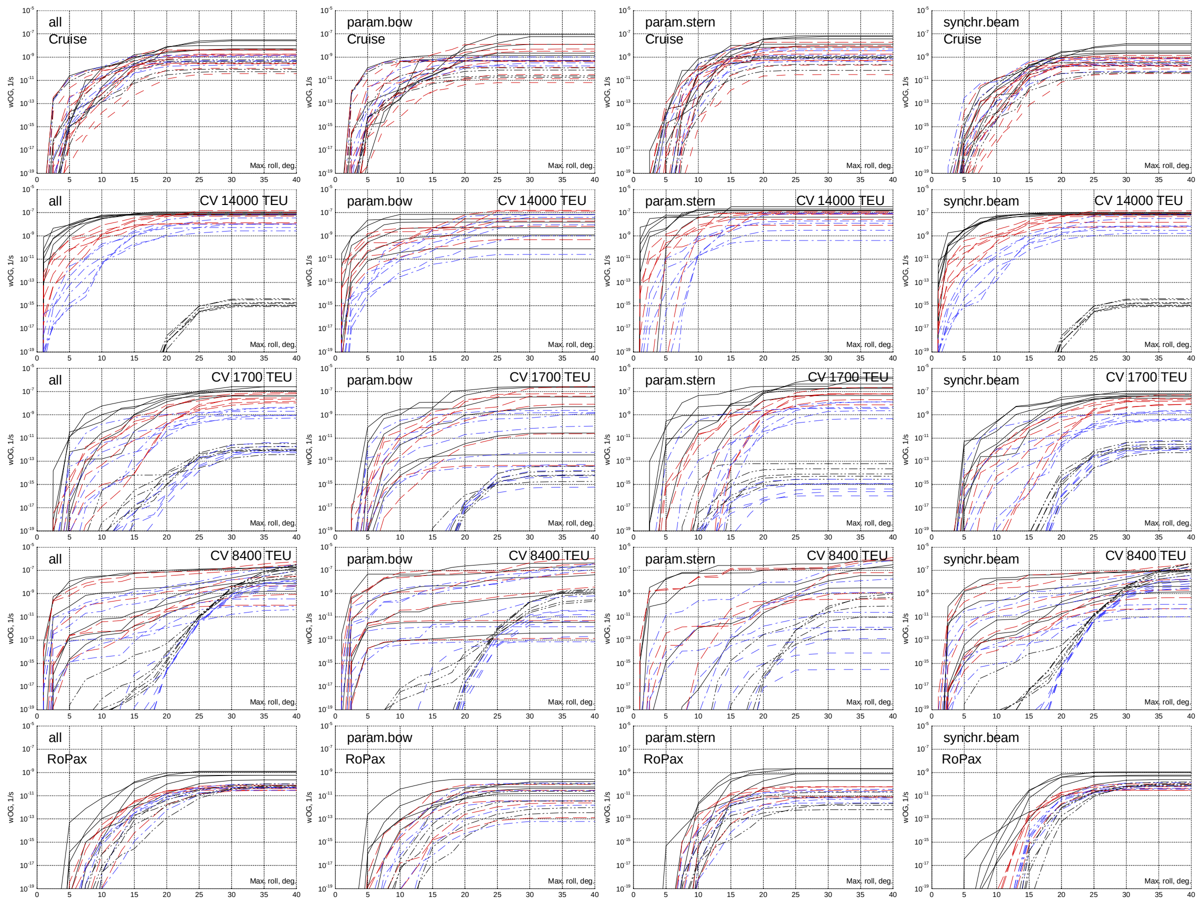

Figure 10. Average rate of stability failures w_{OG} (from left to right: all failure modes, parametric roll in bow waves, parametric roll in stern waves and synchronous roll) depending on threshold of mean 3-hour maximum roll amplitude for (from top to bottom) cruise vessel, CV 14000 TEU, CV 1700 TEU, CV 8400 TEU and RoPax; types and colours of lines differentiate between loading conditions, lines of the same type and colour correspond to various forward speeds for the same loading condition

5.7 To check how non-probabilistic operational guidance influences the safety level of different ships and loading conditions at different forward speeds, Figure 11 (left) shows histograms of the total number of ships, loading conditions and forward speeds normed by 1, plotted against the achieved safety level w_{OG} for various values of the threshold for the mean 3-hour maximum roll (right plot shows the cumulative distributions based on these histograms). Note that the results for the threshold values of 40 and 60 deg are very similar (note that cases with 60 deg maximum roll amplitude mean here such cases where at least one capsize happened in 50 simulations of 3 hour duration each).

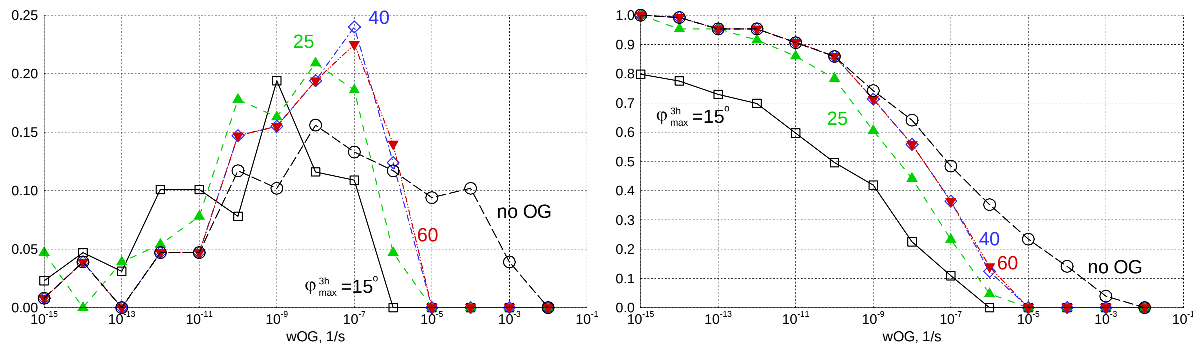

Figure 11. Left: histograms of total number of ships, loading conditions and forward speeds (normed on 1) having long-term safety level w_{OG}, 1/s (x axis) for various values (indicated in plot) of threshold of mean 3 hour maximum roll amplitude. Right: corresponding cumulative distributions.

5.8 The non-probabilistic approach does not allow to fully exclude cases with insufficient safety level: in fact, strengthening of threshold from 60 to 25 deg influences little the average rate of stability failures at and below 10^{-7}. The safety level of all cases influenced by operational guidance is broadly spreaded.

6 Definition of thresholds

6.1 To differentiate between recommendable and not recommendable combinations of the ship forward speed and course in each sea state, appropriate long-term standard (safety level) should be defined, from which the corresponding short-term acceptance thresholds for rp_s, r and φ_{3h} can be derived using the available assessment results.

6.2 To define the long-term standard, data from FSA studies for container vessels (ref. document MSC 83/INF.8), LNG carriers (MSC 83/INF.3), crude oil tankers (MEPC 58/INF.2), cruise ships (MSC 85/INF.2), RoPax (MSC 85/INF.3) and general cargo vessels (MSC 88/INF.8) were used.

6.3 Losses due to foundering are reported only for container ships and general cargo vessels ($9.78\cdot10^{-4}$ and $5.10\cdot10^{-3}$ losses per ship per year, respectively). Since SGISC address not only total losses but also other stability failures, another relevant figure is the average frequency of accidents due to heavy weather, which is reported for container ships and LNG carriers as $2.64\cdot10^{-3}$ and $3.20\cdot10^{-3}$ accidents per ship per year, respectively. The lower of these figures is used here to define the thresholds for recommended sailing conditions: these thresholds should provide at least the same safety level.

6.4 The figure $2.64\cdot10^{-3}$ stability failures per ship per year corresponds to the mean time to stability failure of $1/2.64\cdot10^{-3}$=378.8 years for one ship. To relate this number to the computations performed here, note the following:

.1 In the computations, worst possible loading condition is sought for each ship: in reality, ships rarely sail in such loading conditions. To take this into account, a factor 0.1 is applied to the above time to stability failure.

.2 Assume time in port as 20% of the total design life, thus a further factor 0.8 is applied.

.3 Computations are performed here for the rather severe North Atlantic wave climate, whereas the results of FSA relate to the world-wide service. To consider a reduced time in heavy sea in reality due to this difference, apply a further reduction factor 0.2.

.4 In the computations it is assumed that a ship randomly encounters sea states according to their occurrence frequencies in the wave scatter table; in reality, however, ships use routing and heavy-weather avoidance. This is accounted for by another reduction factor 0.2.

.5 Applying the factors described in paragraphs 6.4.1 to 6.4.5 to the time to stability failure of 378.8 years gives the time to stability failure of 1.2 years, or $3.8 \cdot 10^7$ s per ship that should be ensured by operational measures under the assumptions used here (this corresponds to required $w_{OG}=2.6 \cdot 10^{-8}$ 1/s).

6.5 To select the short-term thresholds, Figure 12 and Table 3 show the long-term stability failure rate w_{OG}, averaged over all speeds, depending on the varied rp_s- (left), r- (middle) and φ_{3h}- (right) thresholds; the results indicate 10^{-10} 1/s and 10^{-6} 1/s as appropriate thresholds for rp_s and r, respectively.

6.6 To illustrate the difficulty of the definition of the required short-term threshold for the mean 3 hour-maximum roll amplitude φ_{3h}, Table 4 shows the mean time (in hours) to stability failure, following from the rp_s-threshold of 10^{-10} 1/s; note that for the short-term threshold for r of 10^{-6} 1/s, the mean time to stability failure is about 280 hours for each sea state.

6.7 These values mean that the required exposure time for many relevant sea states significantly exceeds computational or model testing capabilities. They also mean that extrapolation of the exceedance rate over roll amplitude is unfeasible: such extrapolation needs to go too far, whereas the dependency of the exceedance probability on roll amplitude is unpredictable, Figure 13, and strongly depends on the form of the righting lever curve, stability failure mode and wave height, period and direction.

6.8 One practical alternative is to find a simple empirical formula for the φ_{3h}-threshold based on its relation with the safety level. Figure 12, right, shows the long-term stability failure rate w_{OG}, averaged over all forward speeds, vs. short-term φ_{3h}-threshold for sample ships and loading conditions, and Table 3 shows the resulting threshold values. Figure 14, comparing these values with the calm-water capsize heel angle, shows that the threshold can be approximated as half of the calm-water capsize heel (generally, as half of the heel angle defining stability failure). Although this definition appears not conservative in some cases, note that the results of probabilistic assessment used to define thresholds are conservative due to conservative extrapolation of stability failure rate over wave height: this does not matter for the definition of r- and rp_s-thresholds but influences the definition of φ_{3h}-threshold.

6.9 Another way is to use a relation following from the Rayleigh distribution of roll amplitudes, i.e. $\alpha \cdot \varphi_{3h} \leq \varphi_{sf}$, where φ_{sf} defines the stability failure, $\alpha=\{\ln(T/T_r)/\ln(T_{3h}/T_r)\}^{0.5}$ (but not less than 1), $T=p_s/10^{-10}$, T_r is the natural roll period and T_{3h} is 3 hours in seconds; Figure 15 shows that this approximation is suitable for synchronous roll in beam waves and conservative for parametric roll.

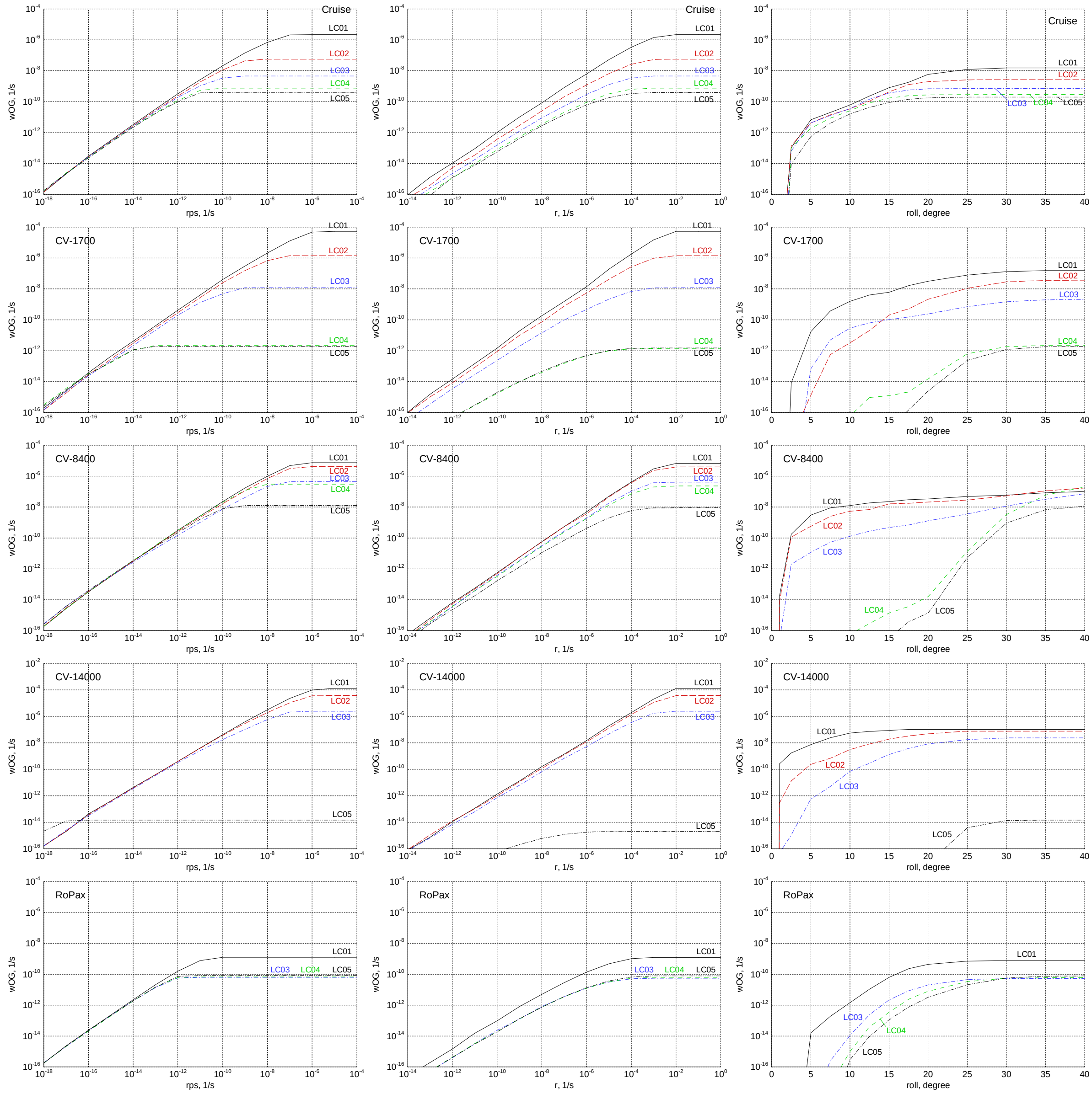

Figure 12. Long-term stability failure rate w_{OG} (averaged over all forward speeds) vs. short-term rp_s- (left), r- (middle) and φ_{3h}- (right) thresholds for different ships (rows) and loading conditions (different lines)

Table 3. Definition of short-term threshold for operational guidance

Ship	Loading condition	rp_s, 1/s	r, 1/s	φ_{3h}, °
Cruise vessel	01	$1.3 \cdot 10^{-10}$	$4.7 \cdot 10^{-6}$	-
	02	$4.2 \cdot 10^{-10}$	$9.7 \cdot 10^{-5}$	-
1700 TEU container ship	01	$6.5 \cdot 10^{-11}$	$1.7 \cdot 10^{-6}$	20.7
	02	$1.1 \cdot 10^{-10}$	$5.9 \cdot 10^{-6}$	29.7
8400 TEU container ship	01	$1.2 \cdot 10^{-10}$	$5.2 \cdot 10^{-6}$	20.6
	02	$1.8 \cdot 10^{-10}$	$6.1 \cdot 10^{-6}$	23.6
	03	$5.4 \cdot 10^{-10}$	$1.6 \cdot 10^{-5}$	34.8
	04	$2.7 \cdot 10^{-10}$	$2.5 \cdot 10^{-5}$	33.6
CV-14000 container ship	01	$6.3 \cdot 10^{-11}$	$1.7 \cdot 10^{-6}$	7.7
	02	$7.1 \cdot 10^{-11}$	$2.1 \cdot 10^{-6}$	17.9
	03	$1.7 \cdot 10^{-10}$	$5.4 \cdot 10^{-6}$	-
Selection		10^{-10}	10^{-6}	s. text

Table 4. Expected time to stability failure, hours, corresponding to $rp_s=10^{-10}$ 1/s

h_s,m/T_z,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	19.5	20.5	21.5	cum. h_s,%
21.5										2	2	2								100
20.5								2	4	4	6	4	2	2						100
19.5							2	6	12	15	15	12	6	4	2					100
18.5							6	19	39	50	46	33	17	8	4	2				100
17.5						2	19	66	127	158	135	89	46	19	8	2				100
16.5						10	68	222	401	465	378	231	114	46	17	6	2			100
15.5					2	37	241	721	1211	1306	997	579	270	106	37	12	4			100
14.5					10	141	826	2255	3490	3499	2500	1368	606	226	73	21	6	2		100
13.5					37	521	2714	6728	9558	8872	5916	3040	1271	449	139	39	10	2		100
12.5				4	149	1850	8549	19109	24786	21215	13154	6331	2492	835	247	66	15	4		100
11.5				14	586	6310	25677	51404	60534	47564	27319	12274	4541	1439	403	102	23	6	2	100
10.5				64	2251	20610	73169	130216	138368	99296	52612	21989	7620	2274	604	145	33	8	2	100
9.5			2	293	8335	64130	196555	308351	293636	191381	93113	36065	11672	3275	822	187	41	8	2	100
8.5			10	1316	29643	188800	493673	676208	572641	336844	149720	53513	16119	4242	1003	218	44	8	2	99
7.5			54	5733	100554	521111	1146676	1356439	1012485	533659	215424	70716	19749	4857	1080	222	42	8	2	98
6.5			322	24242	322189	1331483	2426389	2447049	1593243	746090	271632	81429	20986	4805	1003	195	35	6	2	95
5.5		2	1927	98437	961333	3092058	4576869	3874012	2172126	894226	291080	79115	18704	3968	774	141	25	4		90
4.5		29	11483	378318	2612429	6343403	7441018	5180330	2459753	877866	252498	61607	13248	2585	469	81	14	2		82
3.5		336	67398	1341645	6223835	10946988	9836167	5474477	2149059	651393	162654	35085	6773	1202	201	31	6			69
2.5	2	4159	380887	4164313	12017671	14370011	9375594	3985204	1243154	309113	64986	12058	2039	322	48	8	2			49
1.5	62	56539	1902020	9598645	14926494	10743858	4582654	1356960	310031	58789	9743	1464	204	27	4					26
0.5	2514	258034	1670195	2288538	1223833	359473	71188	10820	1375	154	15	2								3

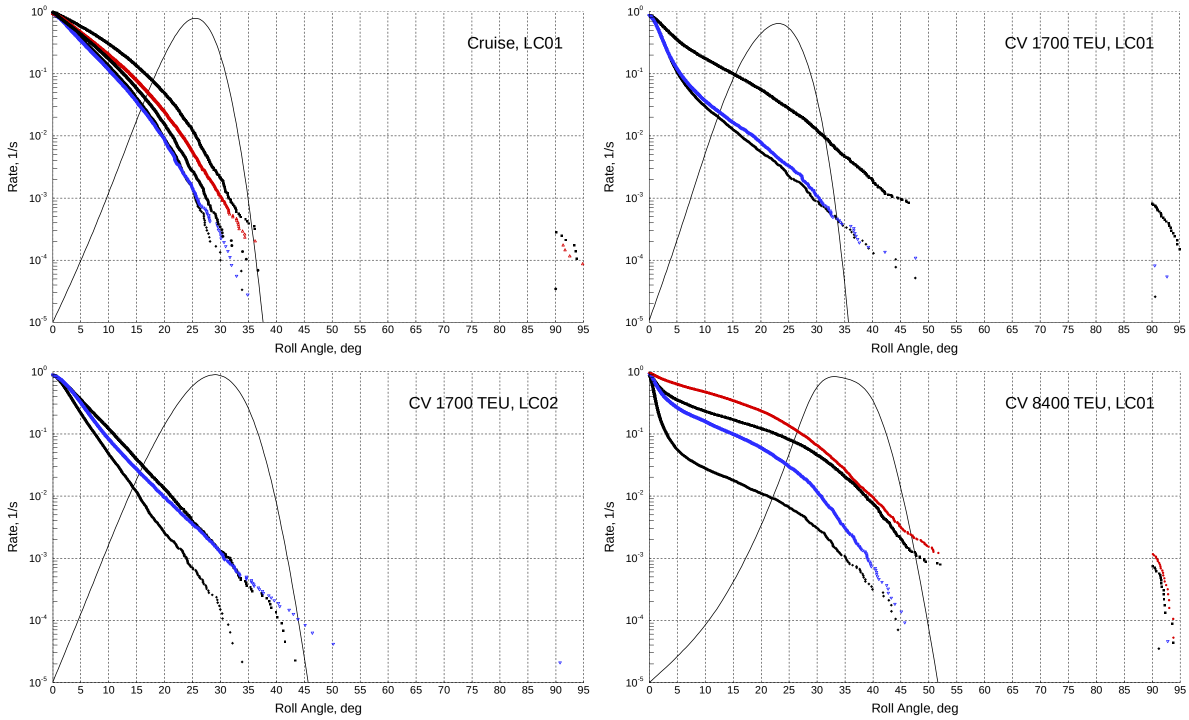

Figure 13. Cumulative distributions of exceedance rate vs. roll amplitude for (from left to right then top to bottom) cruise vessel in loading condition LC01 (examples of parametric roll in head and following waves and synchronous roll in beam waves), 1700 TEU container ship in LC01 (parametric roll in head and following waves) and LC02 (synchronous roll in beam waves) and 8400 TEU container ship in LC01 (parametric roll in head and following waves)

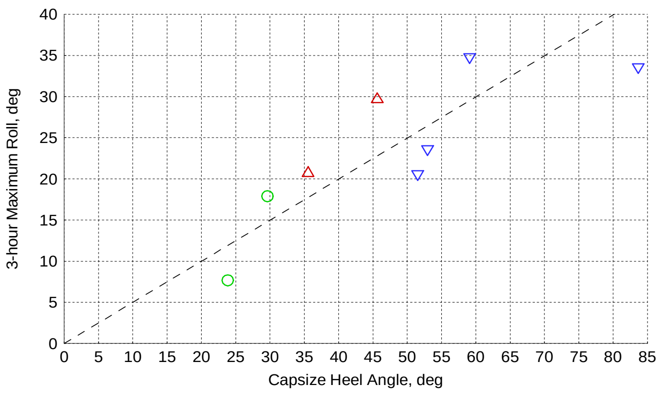

Figure 14. φ_{3h}-threshold vs. calm-water capsize heel angle

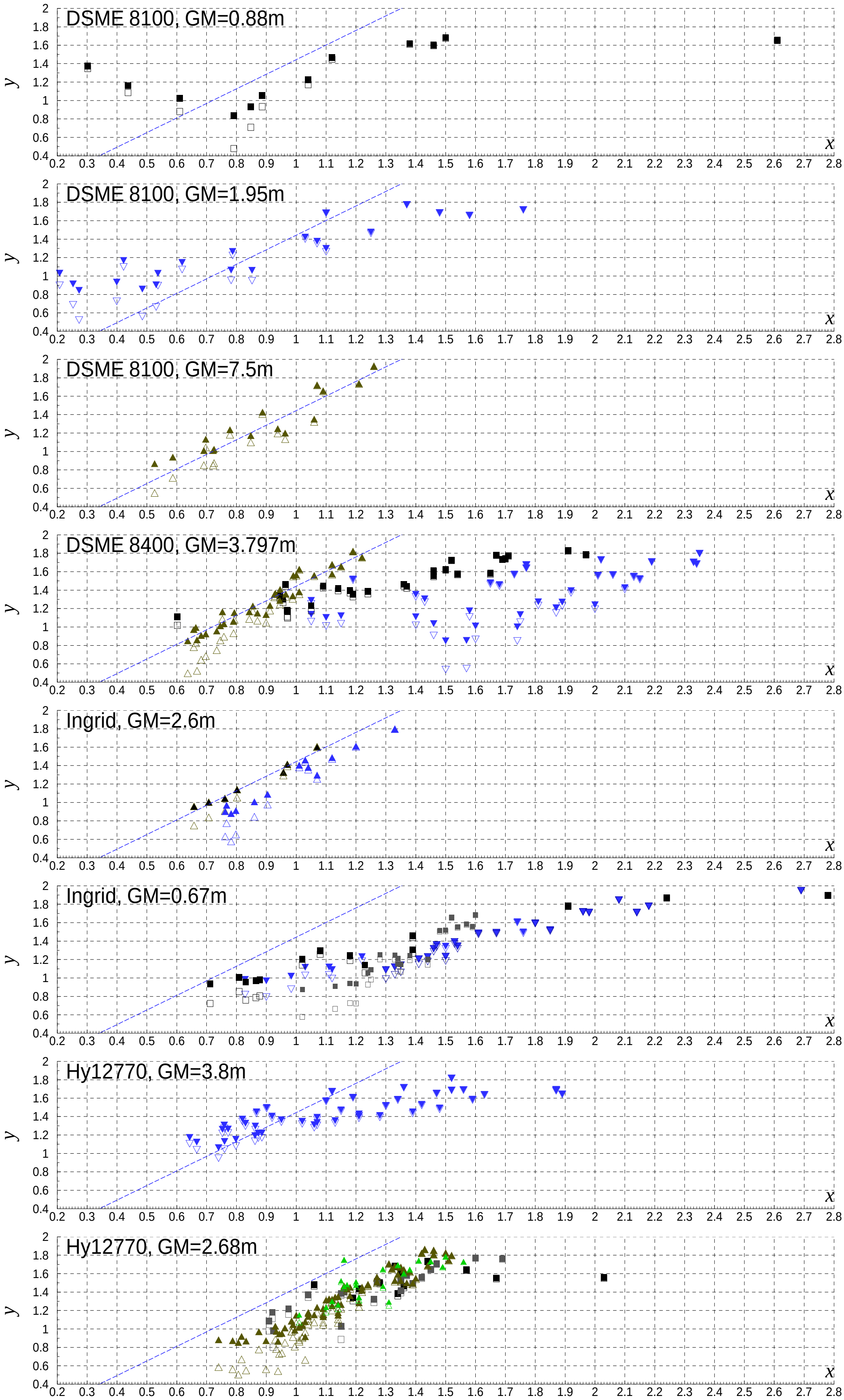

Figure 15. $\ln(-\ln r)$ vs. $\ln\left\{(\varphi_{3h}-\overline{\varphi})/\sigma_{\varphi}\right\}$ for parametric roll in stern-quartering (■,□) and bow (▼,▽) waves and synchronous roll (▲,△); blue dashed lines show Rayleigh distribution

6.10 Figure 16 shows examples mean 3 hour-maximum roll amplitude, its double value and maximum roll amplitude, defined from 15 hour simulations of several typical parametric and synchronous roll situations, vs. significant wave height, and Figure 17 shows the corresponding results using factor α. The results indicate that doubling φ_{3h} produces slightly more conservative results than using factor α, and both provide the limiting significant wave height of 1 to 2 m less than that leading to capsizing in 3 hours.

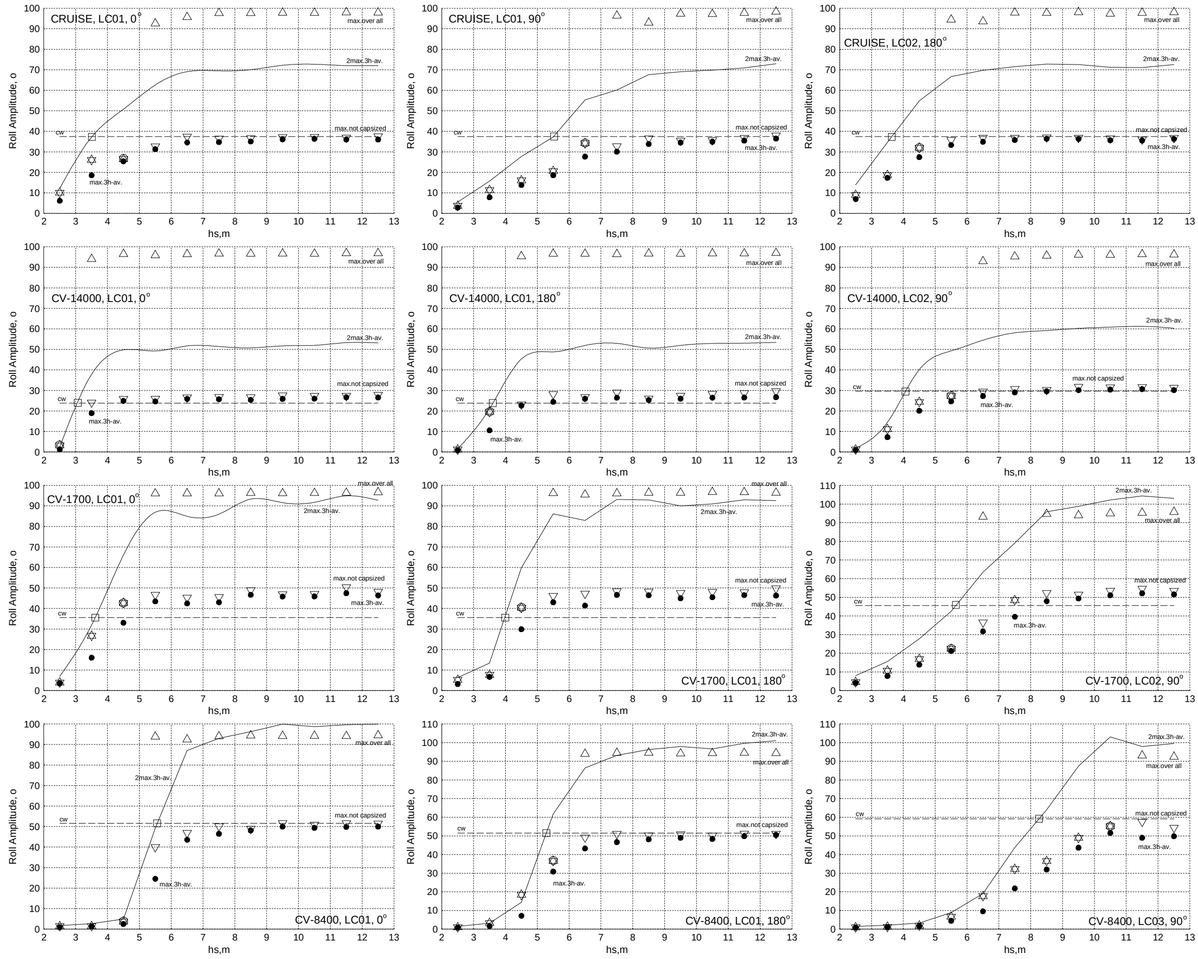

Figure 16. Mean 3-hour maximum roll amplitude defined excluding capsizing events (●), its double value (solid line), maximum roll amplitude taking (△) and not taking (▽) into account capsizes and calm-water capsize heel (horizontal dashed line) vs. significant wave height for parametric roll in following (0^o) and head (180^o) waves and synchronous roll in beam (90^o) waves: for several ships and loading conditions

6.11 Table 5 shows conservative and non-conservative errors (defined as the percentage of the number of situations with conservative or non-conservative errors from the total number of situations) of non-probabilistic operational guidance based on $2\varphi_{3h}$-criterion vs. probabilistic operational guidance based on rp_S-criterion; Figure 18 compares the resulting non-recommended sailing situations (shown in red).

7 Simplified operational guidance

7.1 Operational guidance provides detailed recommendations regarding ship's forward speed and course and therefore, requires accurate methods (numerical or experimental) of the level corresponding to direct stability assessment. However, sometimes coarse conservative recommendations for the forward speed and course, provided by simpler means, are sufficient for the ship owner and acceptable for the Administration.

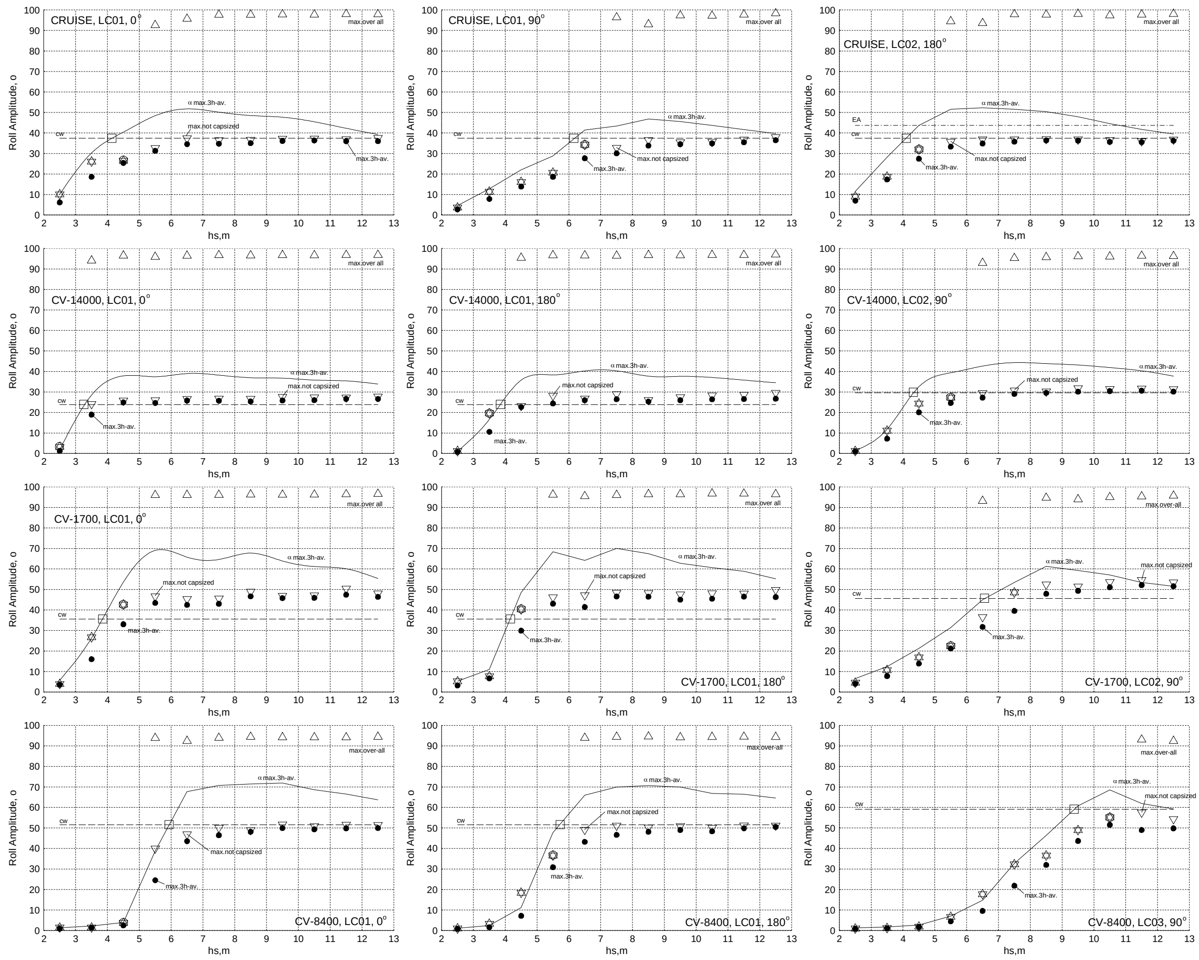

Figure 17. Mean 3-hour maximum roll amplitude (●), its value multiplied with factor α (solid line), maximum roll amplitude taking (△) and not taking (▽) into account capsizes and calm-water capsize heel (horizontal dashed line) vs. significant wave height for parametric roll in following (0º) and head (180º) waves and synchronous roll in beam (90º) waves for several ships and loading conditions

Table 5. Percentage of conservative and non-conservative errors of non-probabilistic operational guidance compared to probabilistic operational guidance

Ship	Cruise	CV 1700 TEU		CV 8400 TEU	
LC	LC01	LC01	LC02	LC01	LC03
Non-conservative	2.4	1.6	2.5	3.5	2.1
Conservative	4.1	9.9	5.6	1.6	0.0

7.2 For example, level 1 or level 2 criteria from the Guidelines for vulnerability assessment can be used for some failure modes:

.1 for the pure loss and surf-riding/broaching stability failure modes, operational limitation (i.e. maximum recommended significant wave height) defined with level 2 vulnerability criteria can be efficiently combined with the forward speed limit according to level 1 vulnerability criteria in following and stern-quartering seaways at greater significant wave heights;

.2 for excessive accelerations, where the level 2 vulnerability assessment is performed at zero forward speed, forward speed effect can be added to level 2-based operational limitations in a conservative way.

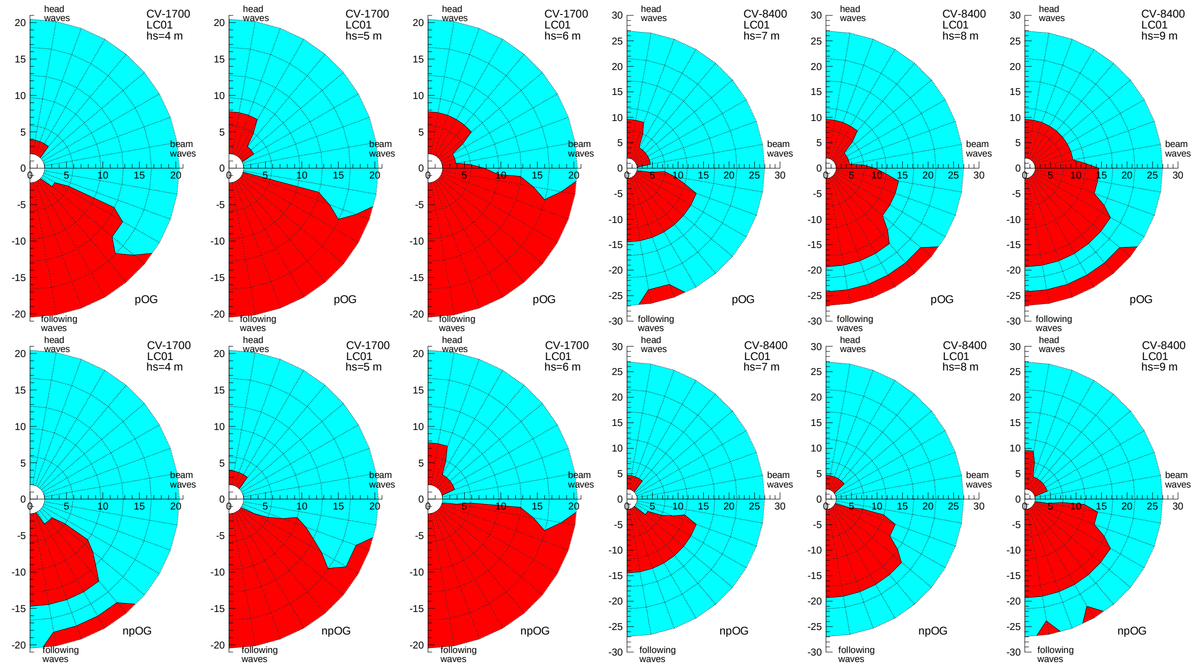

Figure 18. Examples of probabilistic (top) and non-probabilistic (bottom) operational guidance in axes ship speed (in knots, radial coordinate) – mean wave direction (circumferential coordinate) at different significant wave heights (columns) for 1700 TEU (three left columns) and 8400 TEU (three right columns) container ships

7.3 Check 2 of level 2 parametric roll criterion provides dependency of roll motion characteristics on the forward speed, hence it is useful to check whether this dependency is sufficiently accurate for a simplified operational guidance. Here, the sensitivity of this criterion to changes in forward speed is compared with direct stability assessment results.

7.4 According to this criterion, a loading condition is considered not vulnerable to parametric roll stability failure mode if $C_2 = \frac{1}{7}\left\{\sum_{j=1}^{3} C_2^H(Fr_j) + C_2^H(0) + \sum_{j=1}^{3} C_2^F(Fr_j)\right\} < 0.06$, where $C_2^H(Fr_j)$ and $C_2^F(Fr_j)$ refer to sailing in head and following waves, respectively, at a Froude number Fr_j and are calculated for each of Fr_j as a sum over all N sea states of a scatter table as $C_2^{H,F} = \sum_{i=1}^{N} w_i c_i$; w_i is the normed probability density of a sea state i and c_i=1 when roll amplitude exceeds 25° and 0 otherwise.

7.5 To verify whether criteria $C_2^{H,F}$ can be used for forward speed recommendations, their dependency on the forward speed for all sample ships in all loading conditions was compared with the dependency on forward speed of the mean rate of stability failures due to parametric roll obtained from direct stability assessment separately in head (denoted as w_{PR}^H) and following (w_{PR}^F) waves.

7.6 For comparison, 40, 25 and 15° heel angles were used as definition of stability failure. Figure 19 shows w_{PR}^H (left y axis) and C_2^H (right y axis) vs. Fr (x axis) for 15 (left), 25 (middle) and 40 (right) deg definitions for different loading conditions (differentiated with lines of the same type: those with symbols refer to direct assessment result w_{PR}^H and those without symbols to check 2 of level 2 result C_2^H) of sample ships (each ship corresponds to one row). Figure 20 shows corresponding results for parametric roll in following waves.

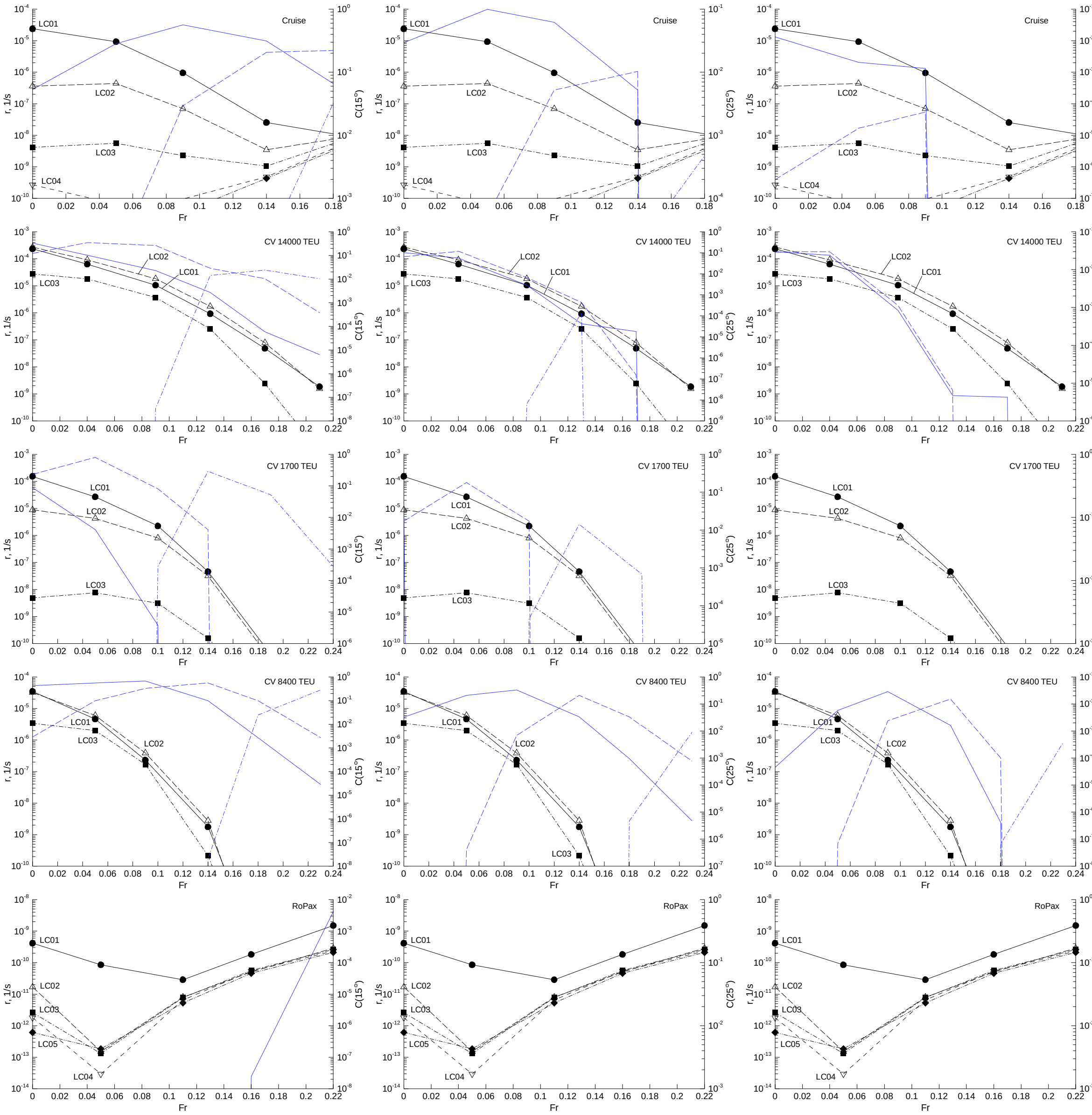

Figure 19. Parametric roll in head waves: direct assessment result w_{PR}^{H} (left y axis) and check 2 of level 2 result C_2^H (right axis) vs. Fr (x axis) for 15 (left), 25 (middle) and 40 (right) degree definition of stability failure for all loading conditions; each line corresponds to one loading condition: black lines with symbols refer to w_{PR}^{H}, same type blue lines without symbols to C_2^H

7.7 The results indicate that check 2 of level 2 parametric roll criterion produces in general good results at low GM; with increasing GM, the agreement worsens: this criterion indicates that large roll amplitudes move to higher forward speed or disappear, thus parametric roll becomes not dangerous at low forward speeds, whereas direct simulations indicate persistent danger of parametric roll at low forward speeds (with the exception of RoPax, for which failure rate due to parametric roll is always very small). The agreement between check 2 of level 2 and direct simulation improves for 40^o heel angle as a failure criterion instead of 25^o and worsens for 15^o.

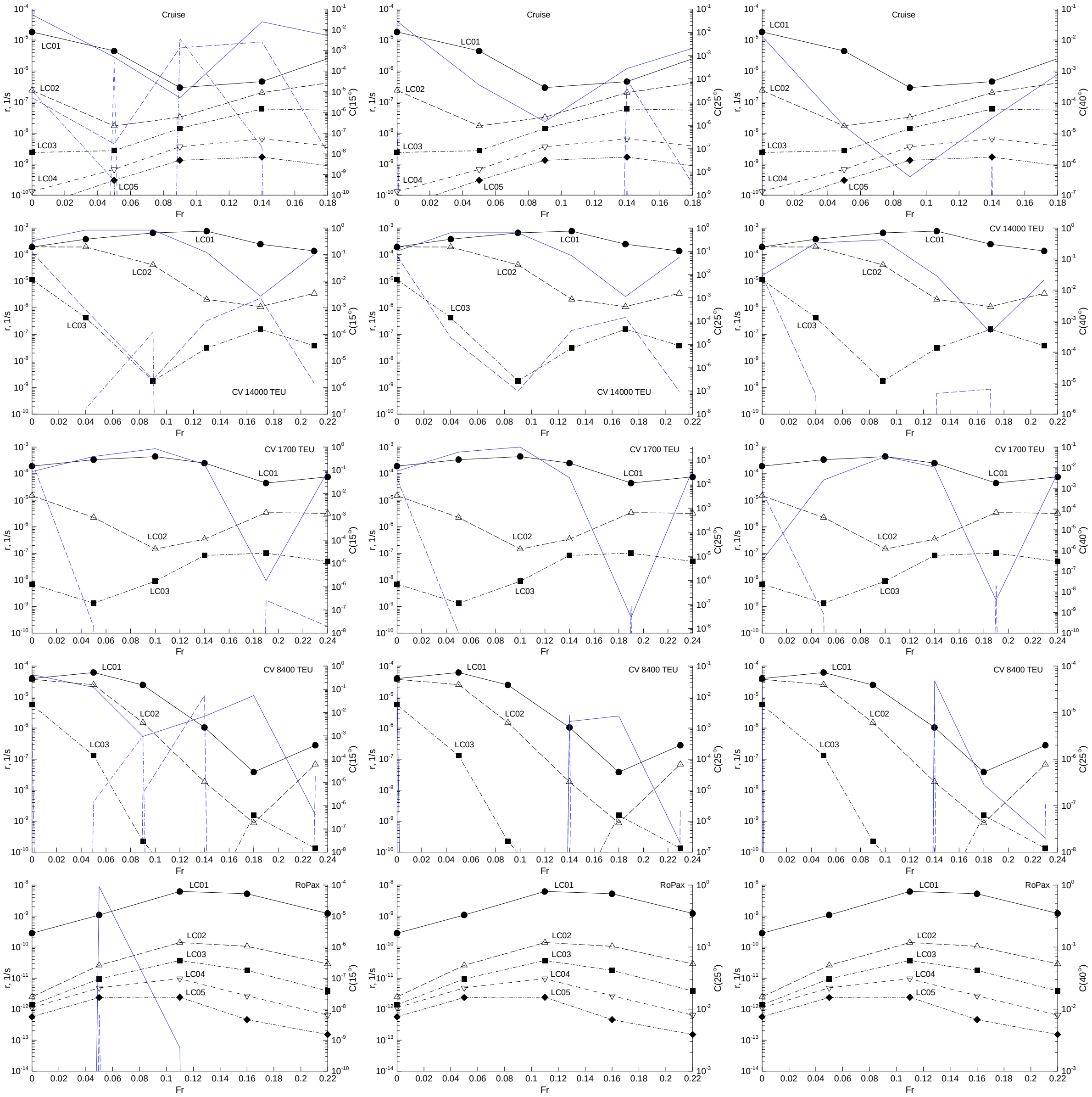

Figure 20. Parametric roll in following waves: direct assessment result w_{PR}^{F} (left y axis) and check 2 of level 2 result C_2^F (right axis) vs. Fr (x axis) for 15 (left), 25 (middle) and 40 (right) degree definition of stability failure for all loading conditions; each line corresponds to one loading condition: black lines with symbols refer to w_{PR}^{F}, same type blue lines without symbols to C_2^F

7.8 To check the reason for this difference, Figure 21 and Figure 22 show failure rate due to parametric roll in head waves together with roll amplitude according to check 2 of level 2 criterion depending on Fr for 8400 TEU container ship, for which the differences between check 2 of level 2 and direct assessment in Figure 19 and Figure 20 are the largest, in three loading conditions with the smallest GM values at three significant wave heights and various mean wave periods. The figures indicate that the dependency of roll motions on forward speed differs between check 2 of level 2 criterion and direct simulations.

7.9 These results suggest that, first, using check 2 of level 2 parametric roll criterion to provide forward speed recommendations requires further validation and eventually improvement of this criterion; and, second, that direct stability assessment for parametric roll in head waves can be conducted at zero (or as small as practicable) forward speed.

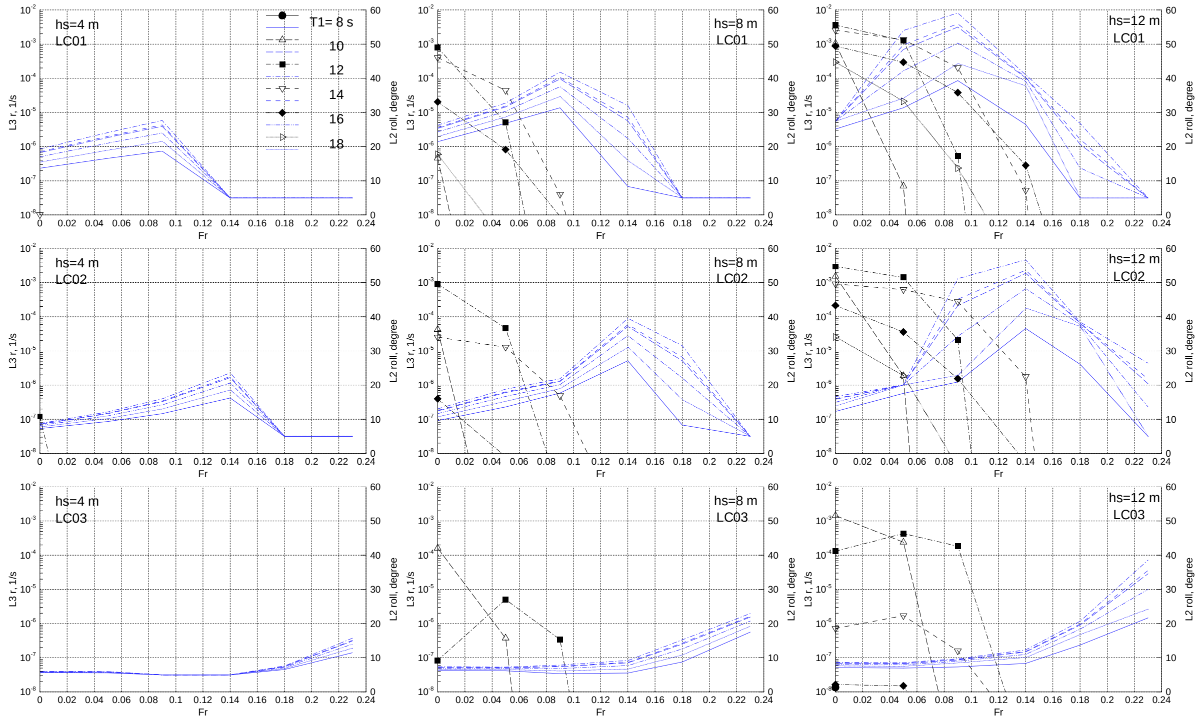

Figure 21. Failure rate due to parametric roll in head waves (left y axis, black lines with symbols) and roll amplitude from check 2 of level 2 PR criterion (right y axis, blue lines without symbols) vs. Fr (x axis) for 8400 TEU container ship in three loading conditions (each row corresponds to one loading condition) at significant wave height of (from left to right) 4, 8 and 12 m; different lines correspond to different wave periods

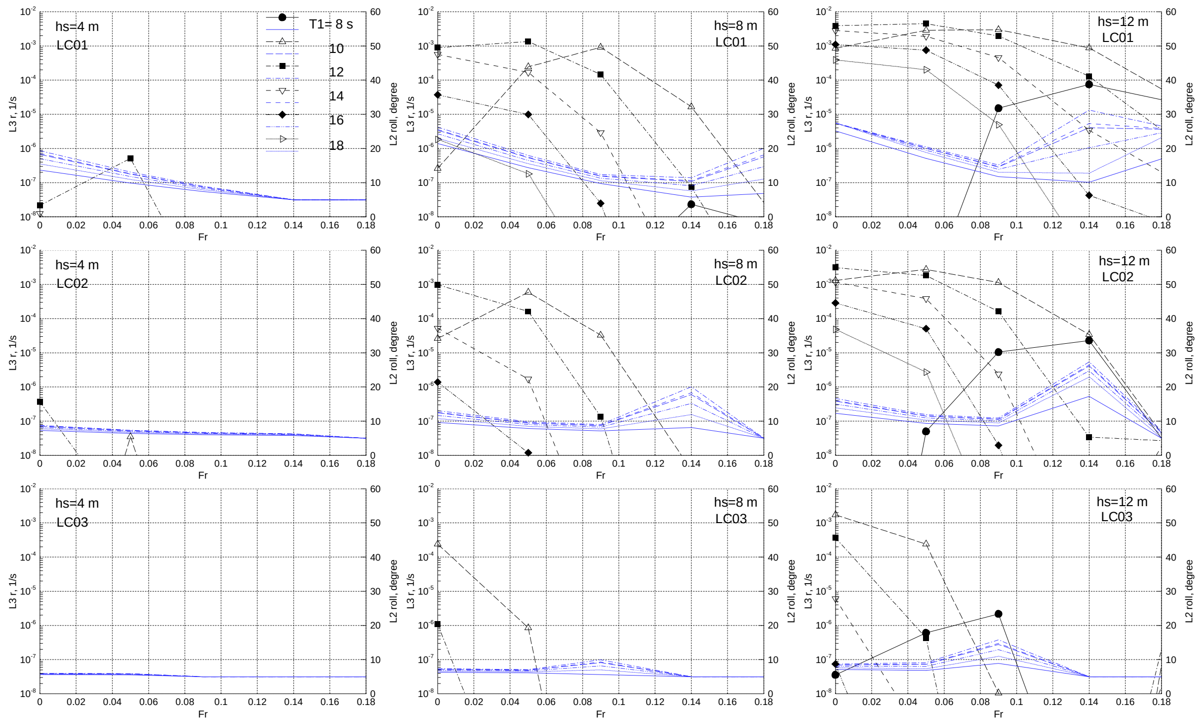

Figure 22. Failure rate due to parametric roll in following waves (left y axis, black lines with symbols) and roll amplitude from check 2 of level 2 PR criterion (right y axis, blue lines without symbols) vs. Fr (x axis) for 8400 TEU container ship in three loading conditions (each row corresponds to one loading condition) at significant wave height of (from left to right) 4, 8 and 12 m; different lines correspond to different wave periods

7.10 Model test results in Figure 23 confirm that in irregular waves, low forward speeds are more critical for parametric roll in head waves than higher forward speeds, even if resonance condition suggests that higher forward speed should be more critical (compare with Figure 24 which relates to parametric resonance in regular head waves).

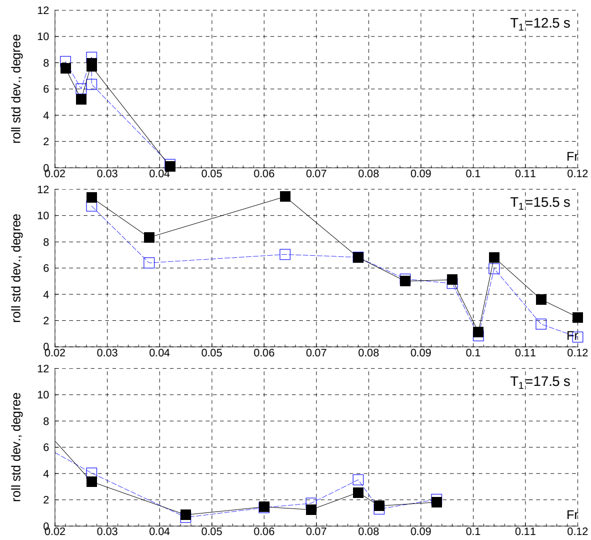

Figure 23. Measured (■) and computed (□) RMS of roll angle (y axis) in irregular head waves vs. Fr (x axis) and wave period (one wave period per plot)

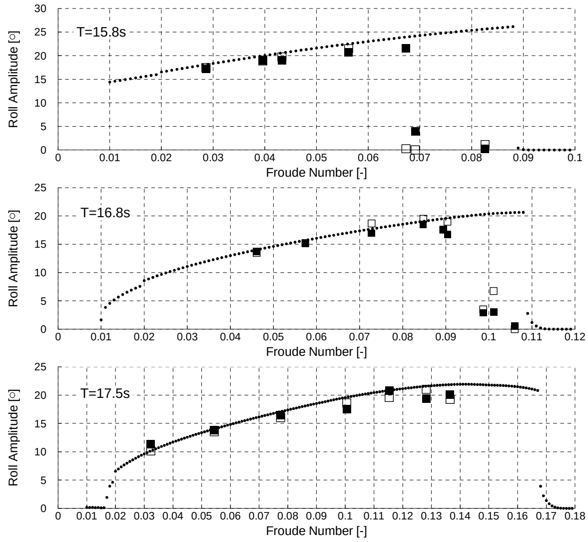

Figure 24. Measured (□,■) and computed (•) roll amplitude (y axis) in regular head waves vs. Fr (x axis) and wave period (one wave period per plot)

8 When operational limitations or operational guidance may not be sufficient

8.1 Obviously, application of operational limitations or operational guidance can reduce the mean stability failure rate to any specified level; thus, any loading condition of any ship can be made "sufficiently safe" using sufficiently strict operational limitations or operational guidance. However, if too many combinations of ship speed and course in too many sea states should be excluded as unsafe for some loading condition, it cannot be considered as safe in routine practical operation. Thus, if the total amount of safe sailing conditions becomes too small for some loading condition, it cannot be considered as allowed even when operational limitations or operational guidance is provided.

8.2 It follows from these considerations that a suitable criterion to distinguish between those loading conditions for which operational limitations or operational guidance is a suitable measure from those which cannot be allowed even with operational limitations or operational guidance, is the total duration of recommende sailing conditions (defined by wave height, period and direction and forward ship speed) according to operational limitations or operational guidance as percentage from the total operational life at sea; such percentage is frequently referred to as operability.

8.3 Similarly to other criteria, the standard for operability can be defined from case studies. Figure 25 shows the average stability failure rate w_{OG} depending on the applied rp_S-threshold, operability plotted as a function of rp_S-threshold and the average stability failure rate plotted as a function of operability for different ships, loading conditions and forward speeds. For rp_S-threshold equal to 10^{-10} 1/s and the maximum acceptable long-term mean stability failure rate of $2.6 \cdot 10^{-8}$ 1/s, the minimum value of operability over all considered ships and loading conditions is about 0.7. Removing the worst case leads to the value 0.8 as appropriate for the operability standard to eliminate loading conditions for which operational limitations or operational guidance is not a sufficient alternative.

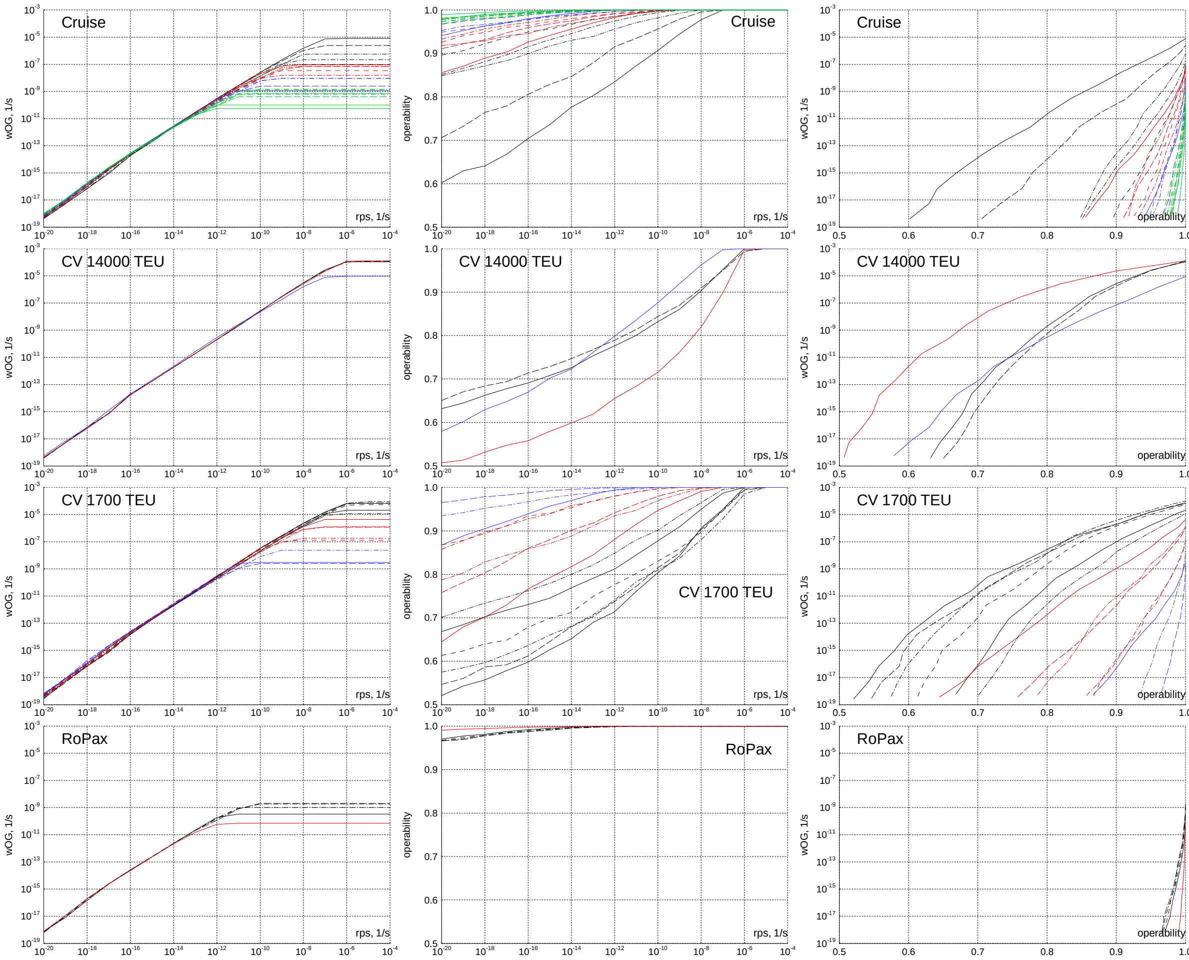

Figure 25. Left: mean long-term stability failure rate w_{OG} vs. rp_s-threshold, middle: operability vs. rp_s-threshold, right: mean stability failure rate vs. operability for (from top to bottom) cruise vessel, CV 14000 TEU, CV 1700 TEU and RoPax; curves of the same colour refer to the same loading condition, curves of the same style refer to the same forward speed

8.4 Figure 26 shows similar dependencies for a non-probabilistic operational guidance: mean long-term stability failure rate w_{OG} depending on the short-term threshold of the mean 3-hour maximum roll amplitude, operability as a function of the threshold of the mean 3-hour maximum roll amplitude and mean long-term rate of stability failures as a function of operability for different ships, loading conditions and forward speeds.

9 Influence of propulsion, steering and seakeeping

9.1 So far, propulsion and steering abilities of a ship, as well as such seakeeping problems as excessive vertical motions and accelerations and excessive loads at high forward speed in bow waves, have not been considered in design assessment and operational measures concerning dynamic stability. For some stability failure modes, this can lead to non-conservative errors in design assessment or misleading operational recommendations. In particular,

.1 For pure loss of stability and surf-riding/broaching stability failures, which are relevant in stern waves, consideration of propulsion and steering abilities and seakeeping problems is not critical for dynamic stability.

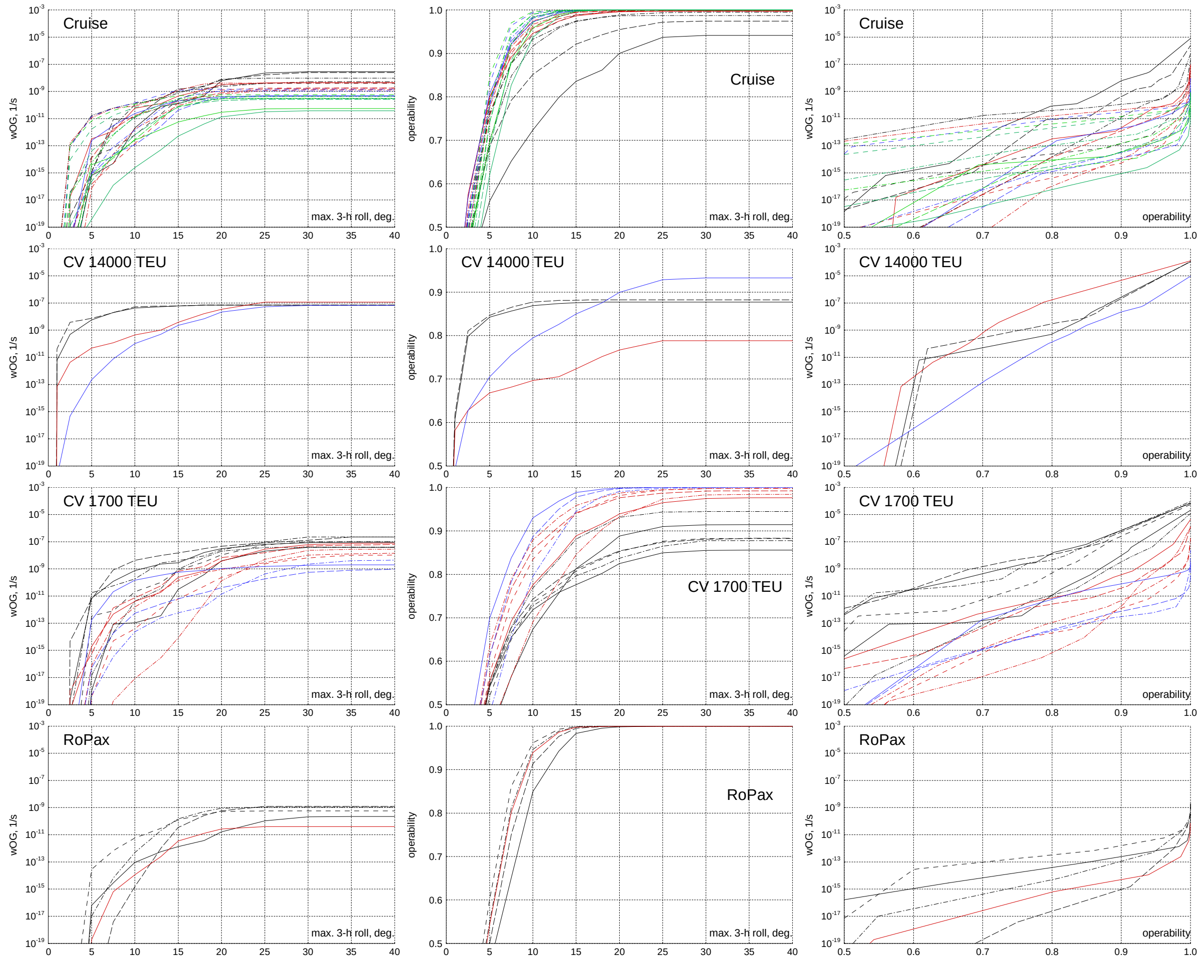

Figure 26. Left: mean long-term stability failure rate w_{OG} vs. threshold of mean 3-hour maximum roll amplitude; middle: operability vs. short-term threshold of mean 3-hour maximum roll amplitude; right: mean stability failure rate vs. operability for (from top to bottom) cruise vessel, CV 14000 TEU, CV 1700 TEU and RoPax; colours and line styles differentiate loading conditions and forward speeds, respectively

.2 Dead ship condition stability failure is relevant only at zero forward speed in beam seaway, therefore these problems are also not critical.

.3 For excessive acceleration stability failure, achievable forward speed in beam seaway rather moderately influences roll motion (due to decreasing roll damping with decreasing forward speed); this does not influence the design assessment (which is performed at zero forward speed) but has a moderate influence on operational guidance. More important issue for the operational guidance is the course-keeping ability in bow seaways: if the ship is not able to avoid excessive roll motions because it cannot steer into seaway, this needs to be considered in the operational guidance.

.4 For parametric roll in bow waves, neglecting propulsion, steering and seakeeping abilities can lead to over-estimation of ship's safety in the design assessment (if safe but unattainable ship's speed and course combinations contribute as possible) and to dangerous situations in terms of operational guidance (when attainable ship's speed and course combinations in a storm are not recommended, whereas all recommended combinations are found unattainable only in the storm).

9.2 Figure 27 shows colour plot of roll amplitude depending on forward speed and course together with the line of maximum attainable speed (solid black line) and line of maximum available steering effort (yellow dashed line) for the 8400 TEU container ship in three loading conditions. In bow waves, majority of forward speeds that lead to small roll motions are unattainable due to added resistance in seaway. Note that this observation is confirmed by experience: all parametric roll accidents in bow waves happen at a low forward speed.

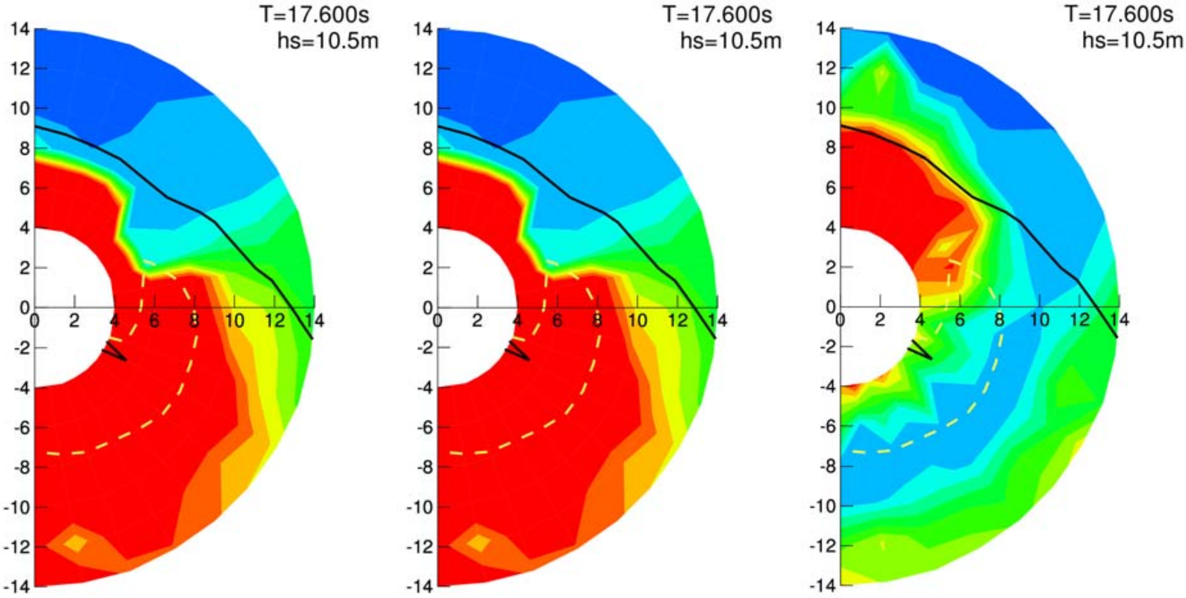

Figure 27. Colour plot of mean 3 hour maximum roll amplitude depending on forward speed (m/s, radial coordinate) and wave direction (circumferential coordinate, head waves at the top) for 8400 TEU container ship in loading conditions (from left to right) LC01, LC02 and LC03 together with line of maximum attainable speed (black solid line) and maximum available steering effort (yellow dashed line)

9.3 To estimate the influence of propulsion ability on parametric roll in head waves, average (over all significant wave heights and wave periods) rate of parametric roll stability failures in head waves was calculated with and without considering maximum attainable speed in head waves. In both cases, the forward speed was applied that minimises the stability failure rate, but in the calculations taking into account propulsion ability, the range of speeds was restricted by the requirement that the required engine power should not exceed the available power. Figure 28 shows the result as the rate of stability failures considering speed limit plotted depending on the rate of stability failures without considering speed limit.

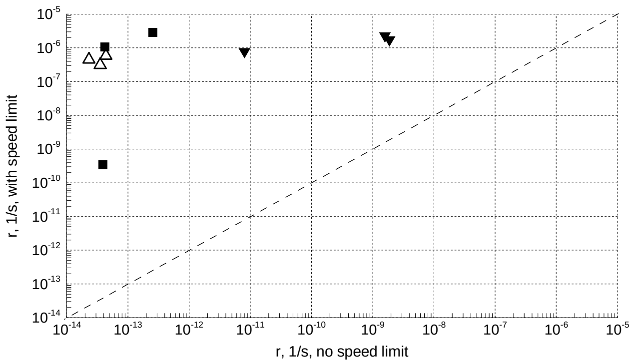

Figure 28. Rate of parametric roll stability failures in head waves considering (y axis) and not considering (x axis) attainable forward speed for three container ships (different symbols) in three loading conditions each

9.4 The results show that the rate of stability failures increases by several orders of magnitude if propulsion ability is considered. This means,

.1 in terms of stability assessment, that assessment at zero forward speed in head waves is a realistic assumption; and

.2 in terms of operational guidance, that propulsion ability should be considered in operational guidance to prevent from misleading operational recommendations.

9.5 The attainable forward speed can be defined from model tests or numerical computations; alternatively, a simple empirical formula can be established.