Stability and seakeeping of river-sea vessels: Classification rules

Jean-Michel CHATELIER, *Bureau Veritas, DNI*, jean-michel.chatelier@be.bureauveritas.com
Wa Nzengu NZENGU, *Bureau Veritas, DNI / RDT*, wa.nzengu@be.bureauveritas.com
Raffaele COCITO, *Bureau Veritas, DNI / APO*, raffaele.cocito@be.bureauveritas.com

ABSTRACT

River-sea vessels are vessels intended for inland navigation waterways and suitable for restricted navigation at sea. Suitability for restricted navigation at sea should be proven by the compliance with appropriate Rules of a recognized classification society as well as with applicable regulatory requirements. As statutory Regulations are not always available, classification Rules are expected to include those vessel design and equipment topics generally prescribed by administrations. This paper provides an overview of researches carried out by Bureau Veritas Inland Navigation Management aiming to support development of upgraded inland class Rules requirements related to vessel stability and seakeeping. For the sake of illustration of the requirements to be developed, the paper gives the proposed formulation together with the validation results of heave acceleration, vertical wave bending moment, roll amplitude and relative wave elevation, as well as basic considerations regarding the evaluation of the vessel intact stability.

Keywords: *class rules; river-sea navigation; hydrodynamics; seakeeping; stability.*

NOMENCLATURE

D_{ref}	Reference duration [s]
$G(\omega,\beta)$	Directional spreading
GM	Metacentric height [m]
H_s	Significant wave height [m]
k_{xx}	Gyration radius around the longitudinal axis [m]
L	Vessel length [m]
B	Vessel Breadth [m]
C_B	Block coefficient
T_z	Wave mean zero up-crossing period [s]
Δ	Vessel displacement [t]
σ	Relative measure of the width of the peak
γ	Peak enhancement factor
ω	Wave frequency [rad/s]
ω_p	Wave peak frequency [rad/s]
n	Navigation coefficient: $n = 0.85H_S$

1. INTRODUCTION

A solution to existing barriers in sea-inland connection is the development of a waterborne transport chain linking sea and inland waters, realised by vessels (sea-river or river-sea) that bypass seaport terminals and deliver cargo directly to inland destinations. Only river-sea vessels are considered in this paper, i.e. vessels intended for inland navigation waterways and suitable for restricted navigation at sea. Suitability for restricted navigation at sea should be proven by the compliance with:

- applicable regulatory requirements prescribed by the competent authority,
- appropriate vessel design and equipment requirements of a recognized classification society.

An overview of existing applicable Rules and Regulations is given in Section 2. In these requirements, acceptability of the vessel is defined according to the following main approaches:

- probabilistic approach implemented in a risk assessment process defined by the competent authority,
- probabilistic approach implemented in a direct calculation process according to guidance of a recognized classification society,
- compliance with classification rule requirements developed on the basis of a deterministic approach.

In navigation areas not covered by regulatory requirements, classification Rules are expected to include those vessel design and equipment topics generally prescribed by administrations. Today, most of classification prescriptive formulas and criteria dealing with seakeeping applicable to river-sea vessels are derived from seagoing vessels rules. Section 3 provides an overview of research activities carried out by Bureau Veritas Inland Navigation Management, aiming to support development of upgraded inland class Rules requirements related to vessel stability and seakeeping. Proposed requirements are derived from the results of direct simulations conducted on inland vessels operated in restricted sea water stretches characterised by a significant wave height $H_S \leq 2$ m. For the sake of illustration of the requirements to be developed, the paper gives the new formulation together with the validation results of heave acceleration, vertical wave bending moment, roll amplitude and relative wave elevation. Basic considerations regarding the evaluation of the vessel intact stability are given in Section 4.

2. RULES AND REGULATIONS

2.1 *Statutory Rules*

2.1.1 *General*

National Regulations are developed to address those vessels not covered by the international requirements, i.e., those vessels that only operate in their national waters [1]. A country may choose to develop entirely different standards or incorporate, where possible, the international Regulations. For inland navigation vessels intended for operation in territorial sea waters, the most significant topics covered by these Regulations are those regarding vessel sea worthiness, providing the requirements concerning vessel stability and seakeeping. Some examples of national Regulations thoroughly developed in [2] are given hereafter.

2.1.2 *Belgian Regulations*

In Belgium, a Royal Decree [3] governs cargo vessels operating along the Belgian coast at a maximum distance of 5 NM from the coast. To obtain the corresponding certificate, specific requirements are applicable covering fire safety, intact stability, lashing of containers, bilge arrangement, emergency power source, bulwark / handrails, anchors, life-saving appliances, radio communication and navigational equipment. Tank vessels must comply with MARPOL Annex I requirements for double hulls, tank arrangements and damage stability. A hydrodynamic study must be carried out to assess seakeeping ability and the risk of slamming, shipping of water, excessive bending moment or lateral acceleration. The permissible occurrences are once a year for slamming and once in the vessel's lifetime for the other categories, where probability is based on 300 return voyages per year for a 20-year lifetime.

2.1.3 *French Regulations*

A French Regulation [4], similar to Belgian Royal Decree, applies to container vessels calling at Le Havre from the Seine. The vessels must comply with the Annexed Regulations of the A.D.N. [5], plus additional requirements. A hydrodynamic study must be carried out following the same principle as in Belgium taking the wave particulars of the area into account, although the assumptions regarding the number of voyages per year (100) and occurrences (once a year for all except bending moment and lateral acceleration, which are once in the vessel's lifetime) are different.

2.1.4 *Indian Regulations*

In India, so-called 'river-sea' vessels carrying dry cargo or oil products are allowed to operate along the Indian coast if they comply with national Regulations [6]. They are graded according to four types, depending on service and navigation conditions. Types 1 and 2 are designed for a maximum significant wave height of 2 m and may be considered as improved inland navigation vessels, while types 3 and 4 are regarded as seagoing ships.

2.1.5 *Chinese Regulations*

In China, there are Regulations for inland vessels [7] covering access to the maritime harbours of Shanghai and Hong Kong provided the route is not farther from the shore than 5 km. Inland navigation vessels are graded according to three categories of wave height, which can be up to 2 m (corresponding to probability of exceedance of 5%), while ships allowed to undertake longer voyages between ports within the territorial waters benefit from derogation to IMO conventions.

2.1.6 *Russian Regulations*

In Russia, there are comprehensive Regulations [8] covering all types of inland and river-sea vessels under which water basins are classed in four categories depending on wind-and-wave conditions on the basis of the maximum normative wave height - up to 2 m (corresponding to probability of exceedance of 1%) and even 3 m (corresponding to probability of exceedance of 3%)

2.2 *Class Rules*

The national Regulations mentioned in Section 2.1 entail classification of the vessels according to the Rules of a recognized classification society. The classification Rules for inland navigation vessels can be used in part to ascertain a vessel's suitability to operate in the maritime environment and to ensure the maintenance of proper levels of safety. The Rules of Bureau Veritas applicable to inland navigation vessels already include specific notations based on the maximum significant wave height, which may be up to 2.0 m. The classification Rules would have to be completed by requirements regarding topics not covered by classification such as navigational equipment, life-saving appliances and crew qualification, but also possibly with some other technical requirements for instance with regard to minimum bow height, freeboard, door sills, hatch coamings, etc. to take the actual local conditions into account.

3. SIMPLIFIED FORMULAS FOR LONG TERM RESPONSES PREDICTION

3.1 *Introduction*

Because of the complexity of sea waves and of the dynamic interaction between vessel and waves, the direct calculation of an appropriate design value of wave response for a given vessel is a very complex and time consuming task. Therefore, the main step of the research covered by this paper consists in developing simplified formulas allowing prediction of long term wave-induced responses to be used for the development of upgraded class Rules applicable to river-sea vessels. Simplified formulas are expressed in terms of the principal characteristics of the vessel. They are derived from results of direct simulations conducted on typical inland vessels according to the conditions and procedure described in this section and supported by the research reported in [9] and [10].

3.2 *Vessels database*

This study has been performed using a database made of 60 vessels with main characteristics lying within the ranges given in Tab. 1 and Fig. 1 to Fig. 3. Most of vessels are tankers with a few container vessels.

Table 1: Range of vessels parameters

Parameter	Range
Length (m)	$35 \leq L \leq 135$
Breadth (m)	$5.0 \leq B \leq 22.8$
Draught (m)	$2.2 \leq T \leq 5.2$
Displacement (t)	$405 \leq \Delta \leq 14428$
Block coefficient	$0.82 \leq C_B \leq 0.99$

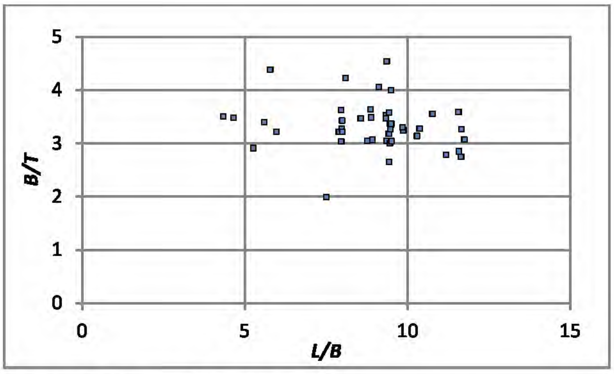

Figure 1: Range of B/T vs L/B

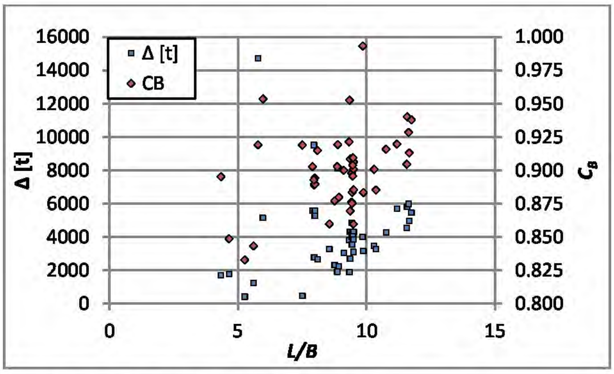

Figure 2: Ranges of Δ and C_B vs L/B

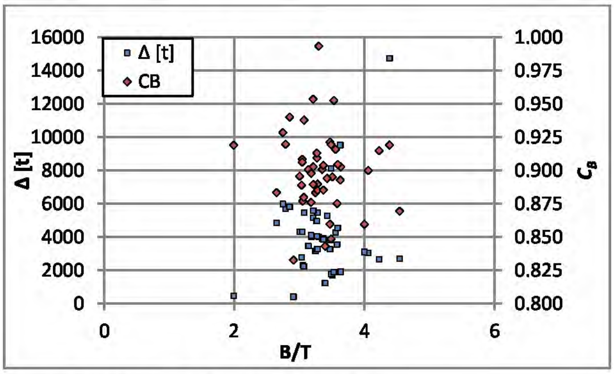

Figure 3: Ranges of Δ and C_B vs B/T

3.3 *Operational parameters*

3.1.1 *Loading conditions*

Simulations for each vessel are carried out in two loading conditions. The first loading condition corresponds to the maximum allowable draught in which the vessel is fully loaded. The second loading condition is related to the minimum draught in which the vessel is ballasted. In these two loading conditions, the real weight distribution is taken into account.

3.1.2 *Roll damping*

As mentioned in [11], a typical ship without roll suppression devices such as bilge keels or the like will have a value of non-dimensional roll damping coefficient less than 5 percent. In this study, 5 percent is adopted when taking account of the fact that most of the river-sea vessels are equipped with bilge keels which increase considerably this non-dimensional damping coefficient. With respect to the non-dimensional damping coefficient of the vessels approved by BV, this value is quite conservative.

3.4 *Environment and simulation parameters*

Simulations are conducted for vessels operated in two navigation areas:

- the Belgian coastal water, according to the vessel course shown in Fig. 4
- the estuary of the river Seine to the harbour Port 2000 (Le Havre) in France, according to the vessel course shown in Fig. 5.

The water depth is taken to be 15 m, for both navigation zones. A constant velocity of 10 knots is adopted for all the vessels, corresponding to Froude number ranging between 0.14 and 0.28.

For the Belgian coast, one-year wave data collected in way of Bol Van Heist buoy, see location in Fig. 4, are used. A three-year wave data in the considered navigation area in France, collected in way of different buoys are considered for simulations. The comparison of wave scatter diagram envelope prevailing in both operating areas is shown in Fig. 6.

Figure 4: Scheldt – Nieuwpoort Route (BE)

Figure 5: La Seine - Port2000 Route (FR)

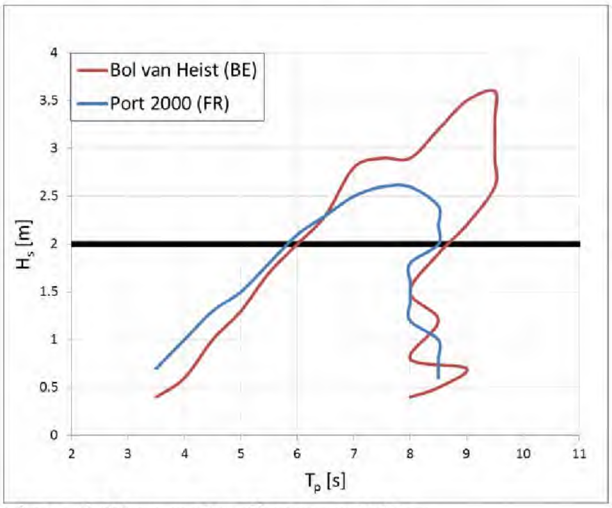

Figure 6: Wave scatter diagram envelope

3.5 *Direct calculation of long term hydrodynamic responses*

3.5.1 *Calculation tool*

The calculation of long term responses has been performed with the software HydroStar version 7.25. Based on the three-dimensional potential flow theory, HydroStar solves the problem of water wave diffraction and radiation around a ship or an offshore structure in deep water as well as in water of finite depth. The method of boundary integral equation (panel method) is used. It had benefited from continuous evolvement, the inspiration of most recent theoretical findings and efficient numerical algorithms. In particular, the advanced algorithms for the Green function - elementary solutions to the first order wave diffraction/radiation problems and application of newly-developed formulations to compute the second order wave loads in an efficient and accurate way. The most advanced features include multi-body hydrodynamics, wave-current-body interaction, coupling of seakeeping with effect of liquid motion in tanks, second-order low frequency and high-frequency QTF in multi-directional waves, mixed panel-stick model and consistent interface of hydro and structure analysis.

3.5.2 *Wave spectrum*

Statistics of the sea states during one year at the buoy Bol van Heist such as significant wave height, peak period, wave direction and spectral energy are provided by the Belgian Authorities. By use of JONSWAP spectrum model (1) with $\gamma = 1$, it is seen that the modelled spectral energy fits very well the measured one.

$$S_w(\omega) = \\ = \frac{\alpha g^2}{\omega^5} exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right]\gamma^{\left[exp\left(-\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}\right)\right]} \quad (1)$$

An example of the comparison between modelled wave spectrum energy and measured one for one sea state is shown in Fig. 7.

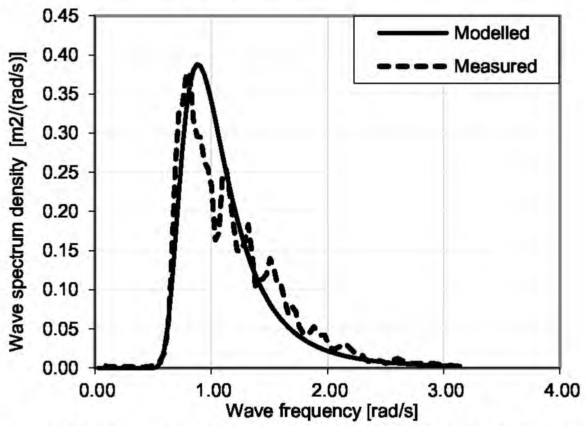

Figure 7: Comparison between modelled and measured wave spectrum energy

Sea states in the navigation zone toward/from Port 2000, in which JONSWAP spectrum model with $\gamma = 1.8$ is used are provided by the French Authorities then used as input data for the spectrum analysis in this study.

3.5.3 *Long term statistics*

A short term analysis is performed for each sea-state in a list of sea states observed during a reference duration D_{ref}. The long term distribution is obtained by cumulating the results from the short term analysis in order to obtain an extreme value at a probability of exceedance of 10^{-8} for vertical wave induced bending moment and at a probability of exceedance of 10^{-5} for local loads and motions. The method implemented consists in counting, over all sea-states up to $H_S = 2$ m, of all maxima of the response (i. e. each response cycle). It can be written as:

$$n_{ex}(X) = \sum_{ss=1}^{ss=N_{ss}} n_{ss}\,(1 - P(X)) \quad (2)$$

where N_{SS} is total number of sea-states; $n_{ex}(X)$ is expected number of exceedance of a response level X, over a reference duration D_{ref}; $P(X)$ is probability distribution for the sea-state ss:

$$P(X) = 1 - \exp\left(-\frac{X^2}{8m_0}\right).$$

n_{ss} is number of response cycles for a sea-state ss:

$$n_{ss} = \frac{D_{ref}}{T_z} Prob(ss),$$

where $Prob(ss)$ is the probability of occurrence of the sea-state ss.

X is range of response in double amplitude. The reference duration D_{ref} is calculated based on an assumption that the vessel of interest navigates during 85% of his 20-year lifetime.

3.5.4 *Comparison of vessels responses between the two navigation areas considered*

Due to similarity of the scatter diagram envelope up to $H_S = 2$ m (see Fig. 6), the values of vessels responses obtained for the 2 navigation areas covered by this study are very close as emphasized, for instance, in Fig. 8 and Fig. 9 for heave acceleration and roll amplitude respectively.

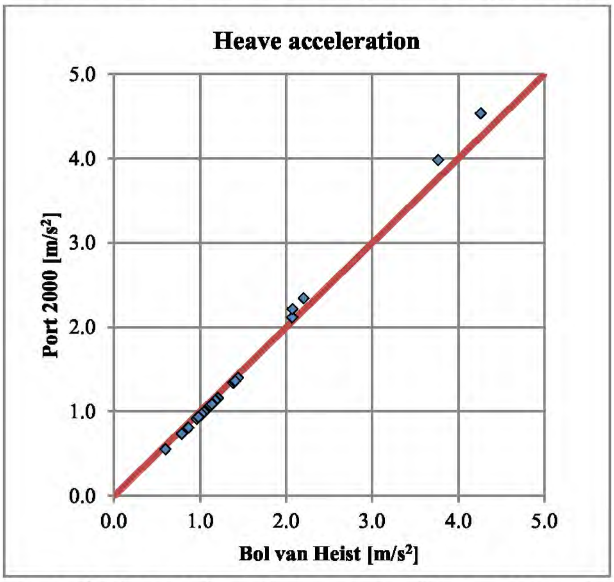

Figure 8: Comparison of responses – Heave acceleration (H_S = 2 m)

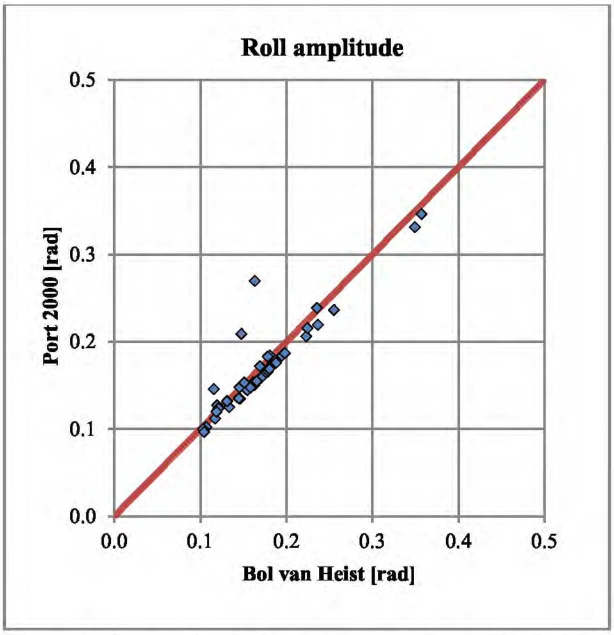

Figure 9: Comparison of responses – Roll amplitude (H_S = 2 m)

3.6 *Development of simplified formulas*

3.6.1 *General*

The long term response in the formulas to be developed is in single amplitude. Motions and accelerations are considered with regards to the centre of gravity.

3.6.2 *Wave parameter*

The study carried out by Hauteclocque and Derbanne [12] shows that in the existing BV Rules [13] and [14], the wave parameter H_W is used to figure out the influence of the vessel's length in its responses. Envelope formula for any given ship response X in single amplitude, can be written as follows:

$$X = H_W * L^{(k-1)} * \Gamma_S * f_{nl} * f_r, \quad (3)$$

where Γ_S is shape function, depending on the ship shape and mass properties; f_{nl} is non-linear factor; f_r is calibration factor; k is dimension number.

3.6.3 *All motions, with the exception of roll*

Using the procedure described in [12], the accelerations prediction formulas for sway, surge, heave pitch and yaw have been developed according to the following steps:

- The long term ship responses X obtained by the direct calculation are divided by $L^{(k-1)}$ (for k, see Table 2).
- The obtained values are scaled by γ which is a constant for each entity so that the maximum value of wave parameter H_W is equal to 1.
- The wave parameter is obtained in the following form:

$$H_W = \gamma \frac{X}{L^{(k-1)}} \quad (4)$$

- The wave parameter shape fitted to match the wave parameter values from direct calculation shown in Fig. 11 for each response, is given by formula (5):

$$H_W = \frac{n}{1.7}\left(\frac{L}{33.7}\right)^{-3} \quad (5)$$

- The non-linear factor $f_{nl} = 1$
- The calibration factor $f_r = 1$
- The dimension number k is given in Tab. 2.

Table 2: Dimension number

Entity	*k*
Linear acceleration	3
Angular acceleration	2

- Finally, the shape function Γ_S for each response is determined by the curve fitting on direct calculation.

$$F(P_L) = c_0 \prod_{p_i \in P_L} {p_i}^{c_i}$$

with $P_L = \{L/B, L/T, B/T, C_B \dots\}$

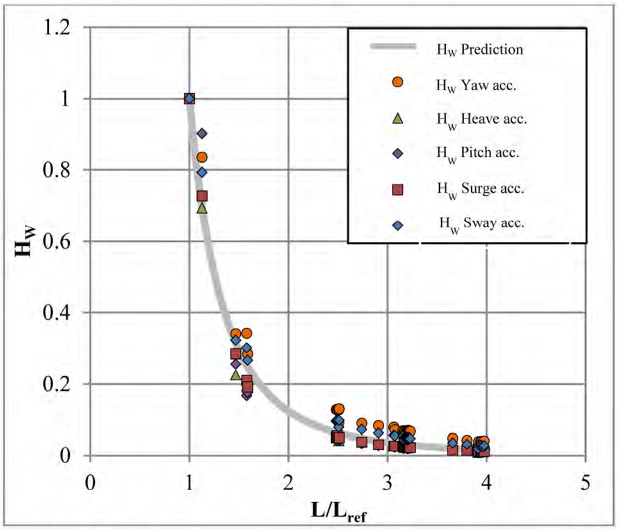

Figure 11: Wave parameters (H_S = 2 m) - Prediction vs direct calculation

The accuracy of the developed prediction formulas is given in Tab. 3.

Table 3: Accuracy of proposed formulas

Response	Standard error	Mean error
a_{sway}	0.03	1.41 %
a_{surge}	0.01	-0.27 %
a_{heave}	0.12	-1.05 %
a_{pitch}	0.01	-1.53 %
a_{yaw}	0.00	3.44 %

Formula (6) shows an example of formula developed to predict heave acceleration. The predicted value is plotted versus direct calculation value for $H_S = 2$ m as shown in Fig. 12.

$$a_{heave} = \\ = 2.78\, H_W\, L^2 \left(\frac{L}{B}\right)^{0.61} \left(\frac{T}{L}\right)^{0.38} C_B{}^{-1}\, 10^{-3} \quad (6)$$

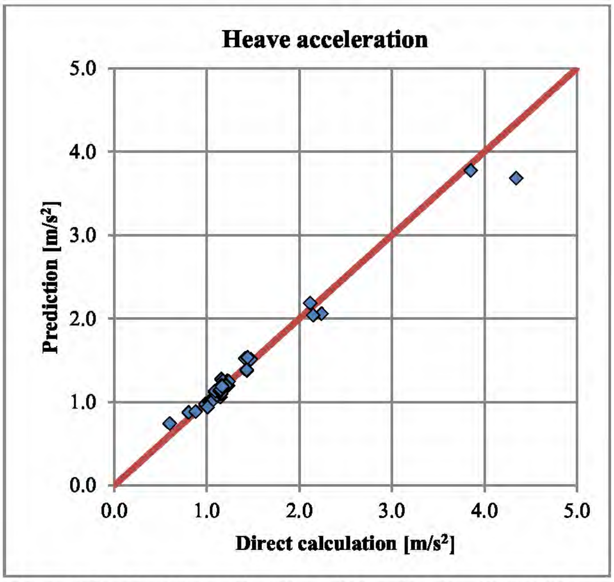

Figure 12: Heave acceleration (H_S = 2 m) - Prediction vs direct calculation

3.6.4 *Roll motion*

The wave parameter H_W is given for roll motion as:

$$H_W = \frac{n}{1.7} \quad (7)$$

The extreme value of roll amplitude, in rad, is predicted by formula (8) and plotted against direct calculation value in Fig. 13 for $H_S = 2$ m.

$$A_R = H_W \left(\sqrt{\frac{GM}{k_{xx}}} + 2.15\right) \frac{1}{\sqrt[3]{\Delta}} \quad (8)$$

The roll acceleration may be calculated using formula (9)

$$a_R = A_R \left(\frac{2\pi}{T_R}\right)^2 \quad (9)$$

where T_R is roll period given by formula (10).

$$T_R = 2.3 \frac{k_{xx}}{\sqrt{GM}} \quad (10)$$

The accuracy of the developed prediction formulas is shown in Tab. 5 for roll amplitude and roll acceleration.

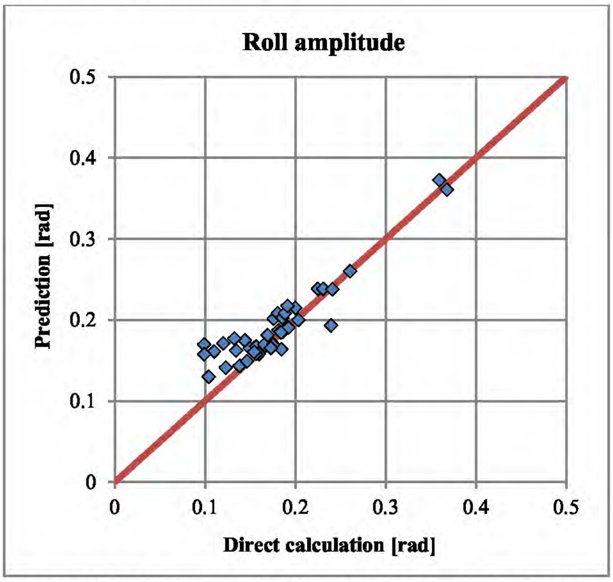

Figure 13: Roll amplitude (H_S = 2 m) - Prediction vs direct calculation

3.6.5 *Vertical wave bending moment*

The absolute value of the vertical wave bending moment, M_W is given by formula (11) and plotted against direct calculation value in Fig. 14 for $H_S = 2$ m.

$$M_W = 0.021\, H_W\, L^2\, B\, (C_B + 0.7) \quad (11)$$

Formula (11) has been derived from BV Inland Rules [13] by implementation of a unique formula (12) for the wave parameter H_W applicable to all vessels sizes.

$$H_W = n\, (10.5 - 0.023L) \quad (12)$$

The accuracy of the developed prediction formula is shown in Tab. 5.

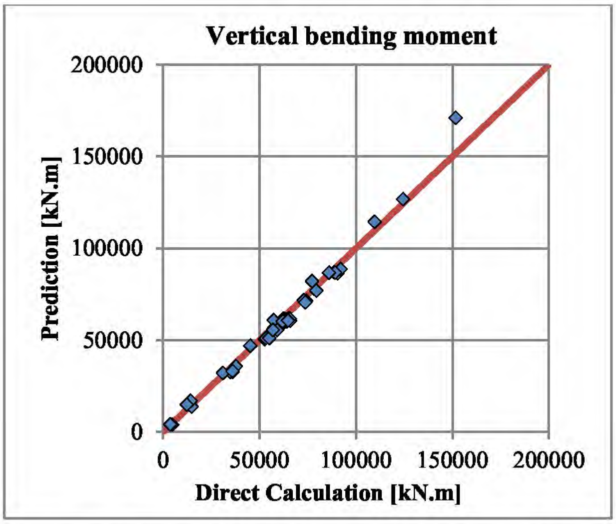

Figure 14: Vertical bending moment (H_S = 2 m) - Prediction vs direct calculation

3.6.6 *Relative wave elevation*

The wave parameter H_W is given for relative wave elevation as:

$$H_W = \frac{n}{1.7} \quad (13)$$

The extreme values of relative wave elevation, h_1 at different positions along the vessel are predicted by the formulas given in Tab. 4 and plotted against direct calculation values in Fig. 15 for $H_S = 2$ m.

The accuracy of the developed prediction formulas is given in Tab. 5 for relative wave elevation at location $x = 0.50$ L.

Table 4: Relative wave elevation

Location	h_1 [m]
$x = 0\ (h_{1,AE})$	$0.89\ h_{1,M}$
$0 < x < 0.35\ L$	$h_{1,AE} + \frac{h_{1,AC} - h_{1,AE}}{0.35}\frac{x}{L}$
$x = 0.35\ L\ (h_{1,AC})$	$1.02\ h_{1,M}$
$0.35\ L < x < 0.50\ L$	$h_{1,AC} + \frac{h_{1,M} - h_{1,AC}}{0.15}\left(\frac{x}{L} - 0.35\right)$
$x = 0.50\ L\ (h_{1,M})$	$4.7\ H_W\ \frac{\Delta^{0.16}}{L^{0.4}}$
$0.50\ L < x < 0.75\ L$	$h_{1,M} + \frac{h_{1,FC} - h_{1,M}}{0.25}\left(\frac{x}{L} - 0.50\right)$
$x = 0.75\ L\ (h_{1,FC})$	$1.04\ h_{1,M}$
$0.75\ L < x < L$	$h_{1,FC} + \frac{h_{1,FE} - h_{1,FC}}{0.25}\left(\frac{x}{L} - 0.75\right)$
$x = L\ (h_{1,FE})$	$17.5\ H_W\ \frac{1}{\sqrt[3]{L}}$

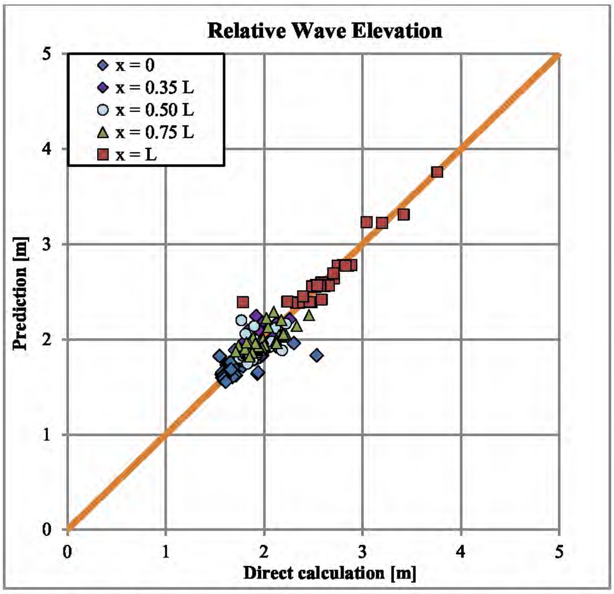

Figure 15: Relative wave elevation (H_S = 2 m) - Prediction vs direct calculation

Table 5: Accuracy of proposed formulas

Response	Standard error	Mean error
A_{roll} [rad]	0.03	4.89%
a_{roll} [rad/s^2]	0.03	8.94%
M_W [kN.m]	4102	-1.67%
$h_1(x = 0.5L)$ [m]	0.12	-0.18%

4. EVALUATION OF VESSEL STABILITY

4.1 *Adequate intact stability*

The vessel intact stability will be assessed according to the International Code on Intact Stability set out in the annex to the IMO Resolution MSC.267(85) [15], but using different parameters values as explained in Section 4.2.

4.2 *Beam wind combined with rolling*

4.2.1 *Wind pressure*

Wind data (maximum wind speed, V_{MAX} and mean wind speed, V) collected in way of Westhinder station on the Belgian coast (see location on Fig. 4) are plotted against significant wave height in Fig. 16. This figure also shows that the ratio V_{MAX}/V varies around 1.22. This ratio shows a good agreement with the increase of 50% in the heeling arm due to gust wind in comparison with steady wind as required in [15]. However, attention should be drawn to the fact that, depending on the geographical configuration of a considered operating area, the ratio of V_{MAX} to V may be higher.

In Fig. 17 are plotted against significant wave height the pressure induced by the mean wind speed calculated using formula (14) and the value of wind pressure prescribed by the European directive 2006/87/EC [16] for inland vessels stability assessment, P = 250 Pa. In the range of significant wave height considered, this pressure remains higher than the values derived from measured speed and, therefore, may be recommended as default value of steady wind pressure, where appropriate data are not available.

$$P = \frac{1}{2}\rho V^2 \tag{14}$$

where P is dynamic pressure, in Pa; ρ is air density, ρ = 1.25 kg/m^3 at 10°C; V is mean wind speed, in m/s at 10 m.

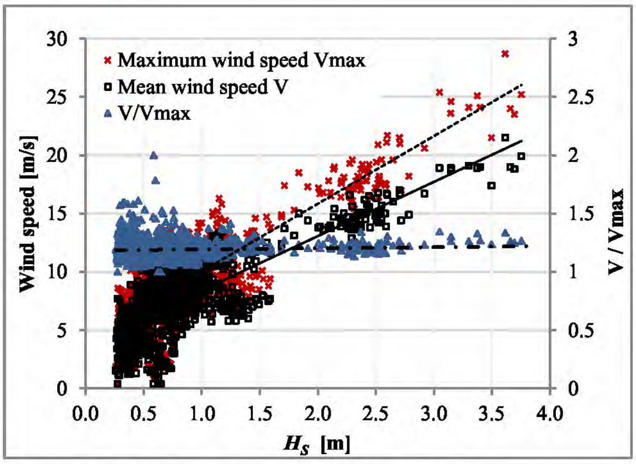

Figure 16: Wind speed – at station Westhinder

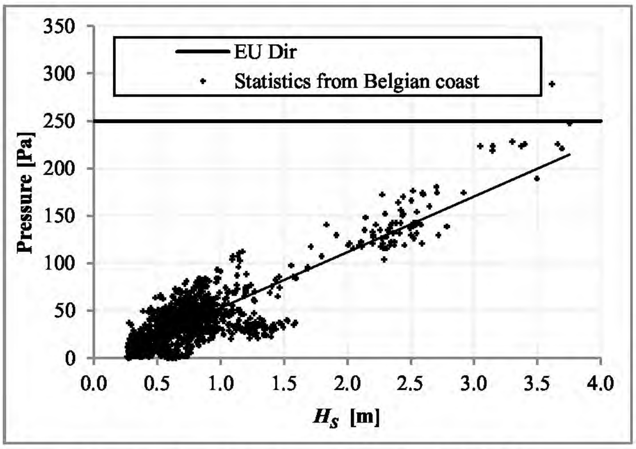

Figure 17: Wind pressure vs H_S at station Westhinder

4.2.2 *Angle of roll to windward due to wave action*

The angle of roll to windward due to wave action is calculated as follows:

$$\theta_1 = \theta_R + \theta_0 \tag{15}$$

where θ_R is roll angle:

$$\theta_R = \frac{180}{\pi} A_R \tag{16}$$

θ_0 is angle of heel under steady wind, A_R is roll amplitude determined according to paragraph 3.6.4.

4.3 *Maximum allowable roll angle*

The roll angle θ_R calculated according to (16) is to be limited as follows [3]:

$\theta_R \leq \min(2\theta_f/3\ ;\ 15°)$,

where θ_f is the angle of heel in degree, at which openings in the hull, superstructures or deckhouses which cannot be closed weathertight immerse. In applying this criterion, small openings through which progressive flooding cannot take place need not be considered as open.

4.4 *Safety clearance*

The safety clearance is to be not less than the relative wave elevation determined according to paragraph 3.6.6. According to the Directive 2006/87/EC [16] the safety clearance is defined as the distance between the plane of maximum draught and the parallel plane passing through the lowest point above which the vessel is no longer deemed to be watertight.

5. CONCLUSIONS

Suitability for restricted navigation at sea of inland vessels should be proven by the compliance with appropriate Rules of a recognized classification society as well as with applicable regulatory requirements. In navigation areas not covered by regulatory requirements, classification Rules are expected to include those vessel design and equipment topics normally covered by statutory Regulations. This paper provides a short review of existing Rules and Regulations applicable to river-sea vessels as well as an overview of researches carried out by Bureau Veritas aiming to support development of upgraded inland class requirements related to vessel stability and sea-keeping. The main contribution of the works covered by this paper may be summarised by the following:

- systematic direct simulations conducted on inland vessels operated in restricted sea water stretches characterised by a significant wave height $H_S \leq 2$ m
- development of upgraded class prescriptive formulas allowing to predict vessel hydrodynamic responses
- proposal of basic considerations regarding the evaluation of the vessel intact stability.

Requirements to be proposed will be intended to be applicable to inland vessels complying with the database investigated for any restricted sea navigation where $H_S \leq 2$ m. Further investigation of vessel responses on other navigation areas remains to be performed for their validation.

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