

# **Development of intact stability weather criterion applicable to river-sea vessels**

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## **DECLARATION OF AUTHORSHIP**

*I declare that this thesis, “development of intact stability weather criterion applicable to river-sea vessels” and the work presented in it are my own and have been generated by me as the result of my own original research. Where I have consulted the published work of others, this is always clearly attributed. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.*

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## ABSTRACT

### **Development of intact stability weather criterion applicable to river-sea vessels**

Inland vessels, in general are not allowed to navigate in seas and thus there is a need to solve the missing link between minor inland ports to major ports. River-sea vessels are proven models now in many countries to move cargoes in order to solve this missing links in waterway systems. These vessels are intended for inland navigation waterways and suitable for restricted navigation at sea, with significant wave height limited to 2m. For these vessels, 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 local/national statutory Regulations. For stability assessment, these Regulations refer to the IMO code for intact stability, difficult to meet for inland vessels. Also as statutory regulations may not always available, classification rules are expected to include those vessel designs generally prescribed by administrations. The research follows on to define appropriate requirements related to intact stability weather criterion from the study of local meteorological data and the results of the seakeeping analysis. Simulating navigation condition is done using accepted time-series analysis and spectral analysis techniques. The nonlinear relationship between excitation and response of structures is to be done and in this context, wave conditions that produce rare events are to be defined. Through this paper validation of requirements developed is done for roll amplitude and relative wave elevation along with design criteria regarding the evaluation of vessel intact stability.

Keywords: Stability, Weather Criterion, River-sea vessels, Navigation condition, Seakeeping analysis





## 1. INTRODUCTION

River-sea vessels are proven models in many countries to move cargoes from minor ports to major ports. It seamlessly integrates seaborne trade from inland waters to coastal waters and vice versa. The inland waterway has always been a viable alternative for transportation on European corridors. The Netherlands has a number of rivers and canals such as the Rhine, Maas and IJssel rivers and the Amsterdam-Rijnkanaal, all of these accessible to river-sea vessels. The river Humber in England and the Trollhatte canal in Sweden is being navigated by conventional coasters for the movement of goods. These vessels mainly carry bulk loads such as coal, grain, raw building materials and fertilizer. Also we find bulk cargoes such as steel, steel products, sawed timber and paper, with river-sea vessels being employed for transportation purposes. For example it is downstream on the river Rhine that we find transport of steel products taking place, with transport of Scandinavian timber and paper products upstream. Transportation of bulk products such as grain and ore by the means of river-sea vessels has increased.

Liberalised rules are being implemented now-a-days in developing countries like India aimed at boosting coastal shipping. Recently a Kerala-based shipping company in India has launched a river sea container vessel for cargo transport. These vessels are designed for coastal transportation between minor ports in the state. Many companies have started taking initiation to start fixed port-to-port service. It is said that the overall logistics cost is expected to come down by 25-30% once the trade is shifted to coastal transportation for moving goods. Here river sea vessels can ply seamlessly from sea into inland waterways and vice versa. Kerala with a coastline of 590km and 205km of inland waterways is ideally suited for the operation of river-sea vessels especially because of the presence of a major port and 17 intermediary ports.

Water transport system are environment friendly in the sense that it offers less pollution, fuel savings, and reduction of accidents and they are the most economical mode of transportation than road and rail systems. Enhancing the efficiency and sustainability of the same has thus been by far most important step to exploit all the possibilities of the system. Also seaport transshipment is not required for sea-river vessels to be able to connect the hinterland with overseas destinations. Thus a lower transportation costs and a reduced risk of damage of shipment by handling can be reduced on account of the absence of additional transshipment.

In general, inland vessels are not allowed to navigate seas and thus solving the missing links in waterways systems by use of river-sea vessels has a greater significance. For a number of maritime ports, local regulations conditionally allow inland vessels to carry out short sea voyages to connect to mother ships thus allowing to reduce the cost on overall transportation.

Inland vessels have to follow a set of technical requirements, issued by both classification societies and local authorities. To be allowed to perform a sea voyage in restricted sea, an inland vessel has to withstand the additional loads acting on the ship. The more severe wave climate the more severe the wave induced motions and thus it may have to be governed with a set of regulations. These regulations shall be able to limit the loading condition expressed in limits of draft, centre of gravity, stability and hence the roll and pitch motions.

The non-existence of uniformity among the regulations issued by different local authorities will be presented and the research aims to define appropriate requirements related to intact stability weather criterion for the river sea vessels. More over the sea conditions has to be evaluated in detail for different river-sea navigation routes so as to determine the most conservative values for wave conditions. Thus the objective of the study is to develop the intact stability weather criterion applicable to river-sea vessels from the study of local meteorological data and the results of the seakeeping analysis.

### **1.1.Evaluation of vessel stability**

The term stability refers to tendency of a body or system to return to its original state after it has suffered a disturbance. For this it involves calculating centre of gravity of the vessel and centre of buoyancy of hull. The ship remains stable when the centre of buoyancy is lower than centre of gravity of the vessel. When ship is subjected to external disturbance the moment produced by the two forces, ie buoyancy force and weight of the vessel acting through these points makes a couple and produce the moment required to upright the vessel. Now on a ship in general, the disturbance can be either be by wind or wave and the criteria for evaluation of vessel stability should be done such that it ensures the ability of the vessel to withstand these external disturbances.

Most of the ship related accidents is related to ship exposed to extreme weather conditions. In Fig. 1 the causalities occurred on the vessels with wind and sea condition is plotted to show the importance of vessel stability and related incidents. Thus for safe operation of the vessel in adverse climates we should ensure intact stability of the vessels which includes design criteria and weather criterion along with enough safety clearances in terms of hull integrity and slamming criteria. It should be noted that the thesis doesn't present any topic related to the strength of the vessel under these adverse condition because of lack of time.

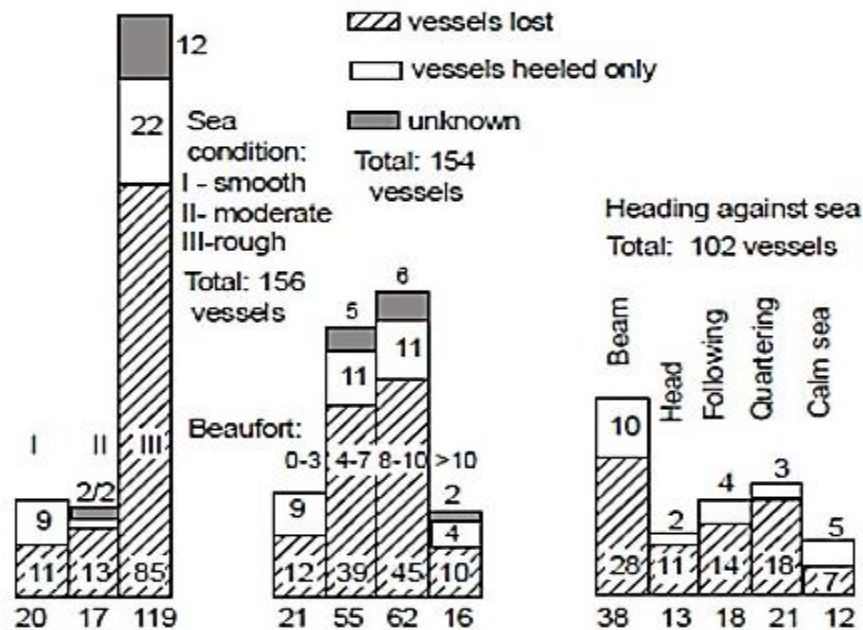


Figure 1 – Sea and wind condition during causality [Courtesy: IMO 1985].

Now for the development of weather criterion a detailed study has to be conducted with regards to stability of the vessels in the vessel loading condition, the fully loaded departure and light ship. Also on this developed criteria, check should be conducted in terms of intact stability criteria, weather criterion and safety clearances. That is starting from body plan, estimation of the vessel loading condition and GZ curve calculation and acceptability of the developed criteria in terms of area under the curve and various other design criteria has to be performed.

The two approaches to develop the stability criteria for a vessel are based on probabilistic approach or another by statistical approach. Now for the research we utilise partially both of these methods to develop weather criterion for river- sea vessels. These two approaches are detailed discussed in the next two sections.

## 1.2. Probabilistic approach

The probabilistic safety assessment is the evaluation of the probability of a critical event or stability failure in environmental conditions which could lead to an accident or loss of life or ship. We know that probability is derived from statistical analysis and this can be in terms of relevant ship motions. Previously the statistical data were obtained with the help of known incidents and accidents. The use of state of art seakeeping softwares only requires an appropriate mechanical model of a ship and the seaway she is exposed to represented by

weather conditions in a realistic scenario. This gives ship motions of all degrees for a fixed period of time..

When the vessel is exposed to severe beam gusting wind of a prescribed mean speed, over a specified exposure time in such scenerio the probability that vessel would attain critical angle of heel, should not exceed an acceptable value. In simple terms use of long term prediction on ship capsizing is done.

But it should be noted that during the life time of the vessels she may ship may find herself in a number of different situations where each situation is characterised by heading and speed, loading condition, sea state and wind force and direction as well as other factors influencing stability. Suppose there are k such situations then coinciding the lifetime probability of capsizing is given by Eq. 1

$$LP_C = \sum_{k=1}^l C_k P_{ck} \quad (1)$$

Where  $P_{ck}$  is the probability of capsizing in the  $k^{\text{th}}$  situation. In our case the above formula can be rewritten as in Eq. 2

$$C_k = \sum_{i=1}^i \sum_{j=1}^j \sum_{l=1}^l \sum_{m=1}^m \sum_{n=1}^n p_i p_{ij} p_{il} p_{im} p_{in} \quad (2)$$

$p_i$  → is probability that the ship is in the  $i^{\text{th}}$  geographical area

$p_{ij}$  → is probability of meeting  $j^{\text{th}}$  weather force in the  $i^{\text{th}}$  area

$p_{il}$  → is probability of meeting  $l^{\text{th}}$  encounter angle relative to wind in the  $i^{\text{th}}$  area

$p_{im}$  → is probability of occurring  $m^{\text{th}}$  loading condition in the  $i^{\text{th}}$  area

$p_{in}$  → is probability of appearance of  $n^{\text{th}}$  additional factor in the  $i^{\text{th}}$  area

The above probabilities could be estimated on the yearly basis of the analysis of the ship's route, statistics of weather conditions and loading conditions. Discrete values of all of the above circumstances have to be chosen and then the number of situations identified. The probabilities of each situation occurring should be then estimated under the condition that the sum of the probabilities has to be equal to one.

### **1.3. Statistical approach**

Analysis of statistical data on stability parameters of capsized ships may be used for establishing stability standards. This is the basis of this approach.

The statistical stability criteria were originally included in resolutions A.167 (ES.IV) and A.168 (ES.IV) of IMO. The criteria was actually developed upon statistical analysis of stability parameters of suffered casualties and ships that were “actually safe”. The following was the steps they have included:

1. Collation, analysis and evaluation of existing national rules or recommendations on stability
2. Evaluation of stability parameters which could be used as stability criteria
3. Collection of stability characteristics of those ships that become casualties or experienced dangerous heeling under circumstances suggesting insufficient stability,
4. Collection of stability characteristics of those ships which were operating with safe experience,
5. Comparative analysis of stability parameters of ships becoming casualties and of ships operated safely,
6. Estimation of critical values of chosen stability parameters
7. Checking formulated criteria against a certain number of existing ships

## 2. METHODOLOGY

In order to develop the intact stability weather criterion applicable to river sea vessels a study of local meteorological data and the results of the seakeeping analysis of existing inland vessels using boundary element based estimation is required. Fig. 3 represent the methodology adopted for the master thesis. Each steps has been explained explicitly on subsequent chapters of this report.

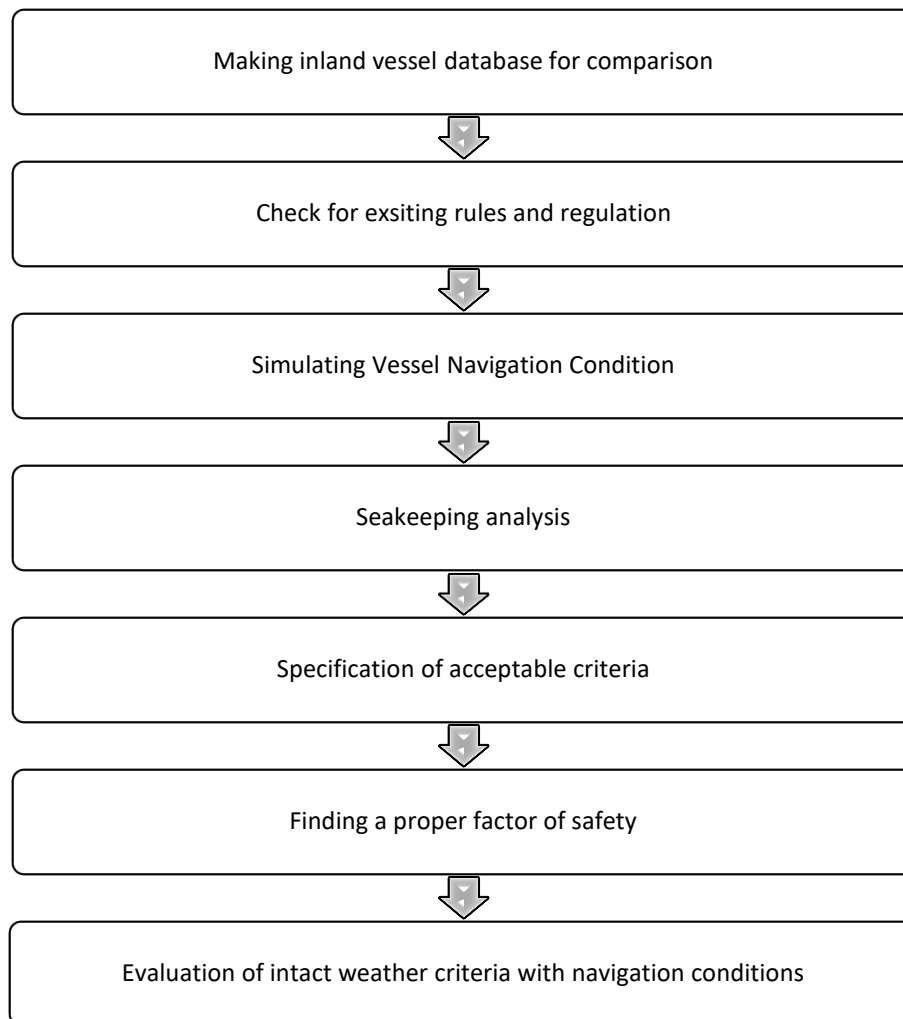


Figure 2 – Methodology of the study

As a starting point a collection of data is done on existing vessels registered with BV with class notation IN ( $0.6 \leq H \leq 2$ ). This include the collection of vessel particulars, intact stability criteria and safety clearances of existing vessels. The hull models of these vessels in terms of lines plan are also collected for the sea keeping analysis and stability analysis in light ship condition and fully loaded departure.

This will be followed by a check on existing rules and regulation associated with stability of river-sea vessels. More concentration will be given to local regulations at different parts of the world. A general comparison of these rules will be made and checked for already developed simple formulation allowing the prediction of weather criterion.

The next step will be identifying the navigation route for the vessel. This is an important step to be undertaken as this has an important role when we discuss hydrodynamic loads on the vessels. Once the navigation route is established a study on the condition of sea will be checked and simulation will be done to identify wave spectrum and thus significant wave height will be established. Together with this wind data will be collected in way of operation and plotted against. Also graphs will be plotted and detail analysis will be done on the spectrums. Data analysis software like Matlab can be used for this analysis.

Direct simulations done on typical vessels according to the sea states can give a prediction of long term wave induced responses and will assist in developing simplified formulas. Thus a seakeeping analysis will be carried out in a boundary element sea keeping analysis software. Vessels operational parameters has to be deduced from collected data's and the short term response for the vessel is plotted as response amplitude operators in the software. Once the analysis is done, we have to extrapolate the results to long term distributions from the short term analysis and then the probability of number of exceedance of a response level should be analysed. This will be followed by the examination of literature to establish formulation for quantifying the above problem. This can be either probabilistic or deterministic as described as in chapters before. Once the formulation is established the long term distribution is analysed to compare the vessel responses under different scenarios.

This will be followed by a check on existing vessels to analyse the acceptability of developed criterion.

### 3. VESSEL UNDER INVESTIGATION

Bureau Veritas has a huge database of inland vessels in stability files, which includes passenger ships, containers, tankers etc. which has been assigned navigation notation from 0m to 2.0m. The study has been performed using a database of 60 vessels for seakeeping and 160 vessels for stability analysis. The Fig. 3 shows the lines plan of a sample fine form inland displacement vessel. For the study, catamarans or any other multihull vessel is not considered. The vessels main dimensions, displacements and other parameters are obtained from the stability software. Propeller and rudder arrangement was not covered in the paper and so is their interaction with vessels seakeeping abilities. The main characteristics of the vessel is give in Fig. 4 and Fig 5.

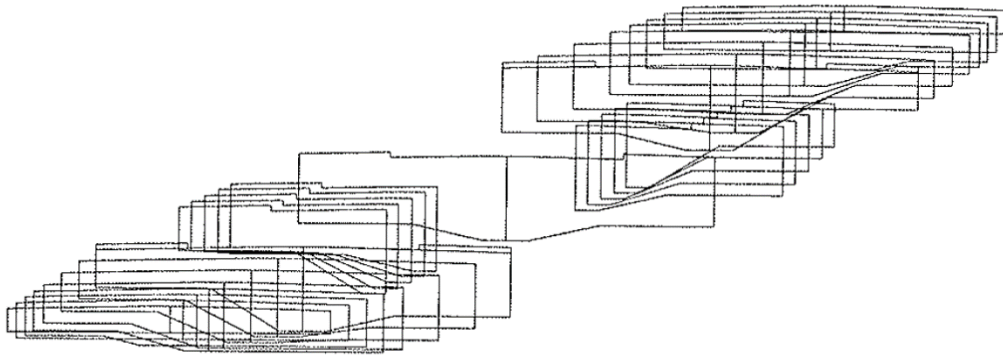


Figure 3 – Lines plan

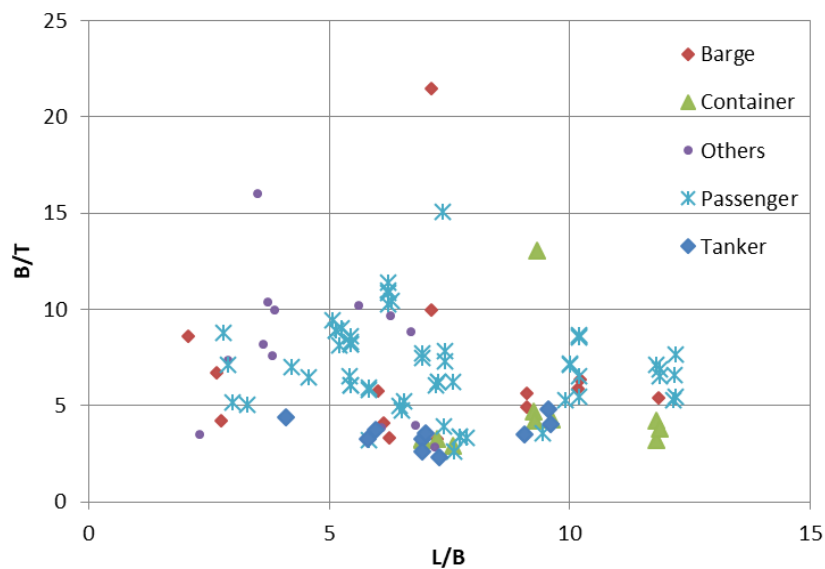
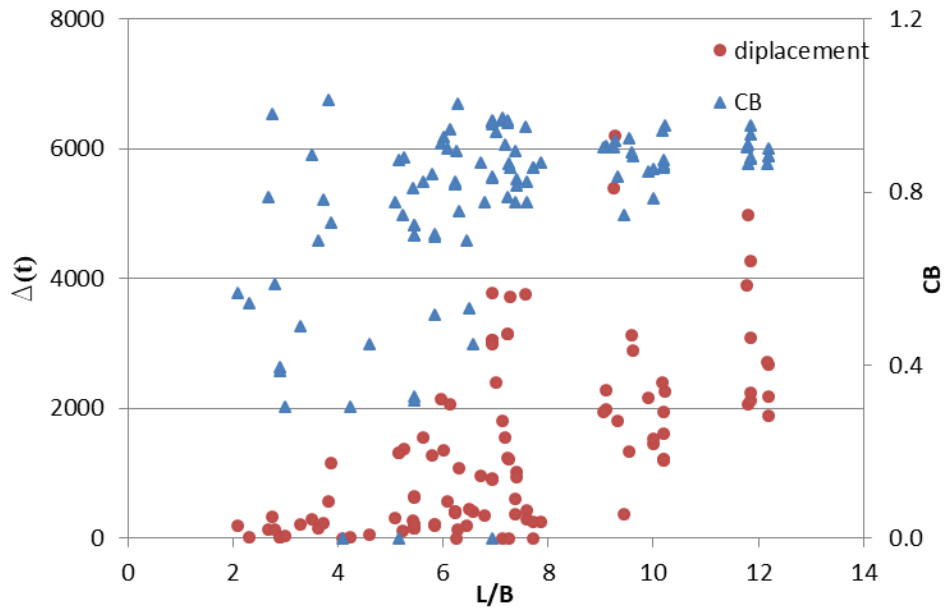


Figure 4 – Range of B/T vs. L/B



Figure 5 – Range of Displacement and  $C_B$  vs.  $L/B$ 

### 3.1.Type of vessels

Instabilities of different nature could arise during the voyage. The type of ship often shows different tendencies for unstable behaviour. The passenger vessels with the weight of her superstructure has a high KG while tankers has low values while free surface effect of liquids inside has to be accounted for.

The basis of every study starts from the analysis of existing vessels. Bureau Veritas has a huge data base for inland vessels with different type of vessels. The database of Bureau Veritas in Argos are given in table. 1 according to their type. It should be noted that these vessels are assigned different navigation notation based on their range of operation.

Table 1. Type of vessels

Type	Numbers
Barge	19
Container Vessel	16
Passenger vessel	80
Tanker	12
Floating structure	4
Others	19

### **3.2.Loading conditions**

For the study two loading conditions are used; fully loaded departure and lightship. The first condition corresponds to a heavy ship with maximum allowable draught while second is related to minimum draught. In these two condition buoyancy distribution along with position of LCB is taken into account to check the real weight distribution and LCG.

### **3.3.Vessel design**

For the seakeeping analysis the value of non-dimensional roll damping coefficient considered is 4% of critical roll damping as typically all inland vessels are equipped with bilge keel. For the calculation of slamming criteria, the most forward part of the keel at 96% of ships length is considered.

## 4. APPLICATION OF CURRENT RULE REQUIREMENTS TO RIVER SEA VESSELS

At present there is no uniformity among the regulations issued by different classification societies and local authorities, which makes it difficult to compare the level of safety achieved by different regulations. This section compares the local regulations and illustrates the possible development and peeks into developed intact stability weather criterion applicable to river-sea vessels

### 4.1 Application of DGS rule to Indian River sea vessels

Indian River Sea vessels are categorized as Type 1 to Type 4 according to their operational profile by the Government of India as per DGS (Director General of Shipping) Order No. 18 of 2013. As per recommendations of the Maritime States Development Council (MSDC), the DGS has already framed technical rules for 2 types of vessels:

- Type I: Vessels engaged in river-sea vessel to shore operations up to a maximum distance of 12 NM beyond IV limits in fair weather only.
- Type II: Vessels engaged in operations between nearby ports during daylight hours in fair weather only.

The Type I and Type II are still not in force. That is officially, one cannot register the vessel as this type. There is still confusion on who would be the registering authority for these vessels. In addition to the above 2 types, this DGS Order envisages further 2 types of vessels with increased voyage duration:

- Type III: Vessels engaged in operations between Indian ports in fair weather conditions where voyage duration does not exceed 24 hours
- Type IV: Vessels engaged in operations between Indian ports in all-weather conditions

According to DG Shipping Order No 18 of 2013 it is mentioned clearly that the “*vessel shall comply with intact stability requirements for cargo ships specified in IMO intact stability code 2008*”, adopted by international Maritime organisation by MSC Res 267(85) as amended/M.S. load line rules. For type III vessels considering the nature of operation during fair weather shall as a minimum comply with following criteria.

- The initial metacentric height shall not be less than 0.3m
- The righting lever (GZ) shall be at least 0.20meters

- The area under the righting lever (GZ) curve shall not be less than 0.09 meter-radians up to an angle of flooding or 40° whichever is less.

## 4.2 Belgium Royal Decree of 2007

The Belgian Royal Decree of 2007 allows inland vessels meeting certain requirements to perform a limited, non-international sea journey. According to Belgian royal decree for sea-going inland vessels, the stability requirements imposed by the decree closely mirror the criteria prescribed by the IMO International Code on Intact Stability (IMO, 2008). The requirements for the righting lever curve and the weather criterion are the equivalent to sea going ships, despite the fact that the estuary route is short and very close to the coast, where calmer met-ocean conditions can be expected. Moreover, inland vessels are only allowed to start a sea voyage when the wave height does not exceed a certain value. The operational limit is expressed by a significant wave height which cannot be exceeded. For this, calculation of the boat response under the influence of wave conditions that are considered representative of the wave climate in the area concerned is to be done. This study ensures a probability less than a predefined value for a number of adverse events. The vessel also must meet the wind criteria defined in paragraph 3.2.2 of IMO Resolution A749.

Also in detail, behaviour of the vessel in waves is implemented by risk analysis in the annex of the decree. It defines the operational limit for navigation in the restricted navigation area according to the prediction of the climate of waves, determination of significant wave amplitude, outlines the calculation method of the vessel's responses in dominant wave function and describes the wave climate and how to represent them. It also stipulates the use of linear theory to calculate the spectrums of responses in frequency domain. The study must be presented to characterize the sea keeping quality, deck wetness, slamming and other accelerations with regards to a selected point

## 4.3 French Regulations

For French regulations requirement related to container ship is available for *Le Havre (Port 2000)*. The law stipulates the risk analysis to be done for slamming, green water shipping and roll angle as in 'Belgium royal decree'. The risk analysis conducted determines the conditions of navigation admissible for the boat provided in the decree. The probability of exceedance is estimated for the following quantities also

- The longitudinal vertical bending moment of the boat
- Torsional torque (except for vessels with continuous watertight deck);
- The lateral acceleration component at the centre of gravity

The value of wind pressure,  $P$  when calculating weather criterion can be taken as 300Pa rather than 504Pa for sea going vessels as per IMO criterion.

#### **4.4 United Nations Economic Commission of Europe**

As per United Nations Economic Commission for Europe the navigation range is differentiated as three zones namely, zone 1, zone 2 and zone 3. These zones are differentiated by average of height of 10% of total number of waves having the greater heights measured between wave trough and crest. Also the navigation ranges are clearly marked by navigation area in the annex I of the “Recommendations on harmonized Europe-wide technical requirements for inland navigation vessels”. Criteria for checking the stability of vessels are laid out as general principles in terms of initial metacentric height and weather criterion. The permissible heeling moment for all external forces for all required loading conditions shall be determined by means of static or a dynamic stability curve in accordance with the values of permissible angle of heels with given criteria. The vessel shall satisfy the weather criterion if, under the most unfavourable loading condition, the permissible moment produced by dynamic inclinations of the vessel is equal to or greater than the heeling moment resulting from the dynamic pressure of the wind. When calculating the dynamic pressure of wind for zone 1 vessels which has  $H_{1/3}$  less than 1.57m the heeling moment resulting from the dynamic pressure of wind  $M_{wd}$  shall be calculated taking the specific wind pressure  $P_{wd}$  given in the supplementary requirements. The critical angle shall be taken to be the angle of heel at which water begins to fill the vessel through unsecured openings in the side plating or on the deck. The maximum angle may not extend further than the upper edge of the side coaming of the cargo hatch or the upper edge of the expansion trunks of tankers. The value for the amplitude of roll of a flat-bottomed vessel with a bilge radius of 0.05 B can be determined from the formula given in this section.

In 2011 special provisions applicable to river-sea navigation vessels adopted by ECE Working Party on Inland Water Transport. The zones and conditions of sea navigation has been established as Zone RS 2.0, Zone RS 3.0, Zone RS 3.5, Zone RS 4.5 and Zone RS 6.0 with wave height up to 2;m 3m, 3.5m, 4.5m, and 6m respectively. Here the vessels stability is regarded as sufficient as regards weather criterion if, at combined effect of wind and rolling the

requirements. These requirement is in terms of initial metacentric height corrected for the free-surface effect of liquid cargo and shall be at least 0.15 m for all types of vessels at any options of loading.

#### 4.5 IMO international code on intact stability

The statutory requirements for river-sea vessels are to be in accordance with Resolution MSC 267(85) - Adoption of the international code on intact stability, 2008. So a closer look at the IMO criteria is done in below section.

Weather criterion, i.e. severe wind and rolling criterion, regards with the ability of a ship to withstand the combined effects of beam wind and rolling. The following has to be demonstrated for a vessel to follow the rule.

- The ship is subjected to a steady wind pressure acting perpendicular to the ship's centreline which results in a steady wind heeling lever ( $l_{w1}$ );
- From the resultant angle of equilibrium ( $\varphi_0$ ), the ship is assumed to roll owing to wave action to an angle of roll ( $\varphi_1$ ) to windward. The angle of heel under action of steady wind ( $\varphi_0$ ) should not exceed  $16^\circ$  or 80% of the angle of deck edge immersion, whichever is less
- The ship is then subjected to a gust wind pressure which results in a gust wind heeling lever ( $l_{w2}$ )
- Under these circumstances, area b shall be equal to or greater than area a, as indicated in Fig 4.

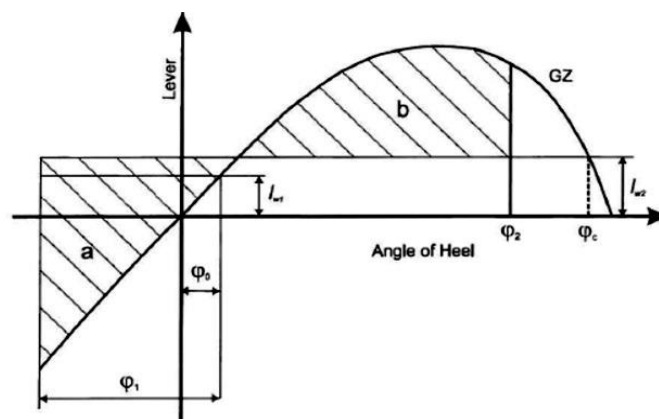


Figure 4 – Severe wind and rolling criteria [Courtesy: IMO].

In the figure  $\varphi_1$ , angle of roll to windward due to wave action can be found according to Eqn. 3

$$\varphi_1 = 109. k. X_1 . X_2 . \sqrt{r} . s \quad (3)$$

Where  $k$  is a coefficient dependent on the relative area of bilge keels,  $X_1$  depends on the beam to draught ratio,  $X_2$  is a function of the block coefficient  $C_B$ , and  $s$  is a function of the roll period  $T_\phi$  which can be expressed by Eq. 4

$$T_\phi = \frac{2 \cdot C \cdot B}{\sqrt{GM_T}} \quad (4)$$

$$\text{Where } C = 0.373 + 0.023 \cdot \frac{B}{T} - 0.043 \cdot \frac{L_W}{100} \quad (5)$$

Also in the Fig. 4,  $\phi_2$  is the angle of down-flooding or  $50^\circ$  or  $\phi_c$  (angle of second intercept between wind heeling lever  $l_{w2}$  and GZ curves), whichever is less

The wind heeling levers  $l_{w1}$  and  $l_{w2}$  can be calculated using Eqn. 6 and Eqn.7 respectively.

$$l_{w1} = \frac{P \cdot A \cdot Z}{1000 \cdot g \cdot \Delta} \quad (\text{m}) \quad (6)$$

$$l_{w2} = 1.5 \cdot l_{w1} \quad (\text{m}) \quad (7)$$

Where the values are

$P$  = wind pressure of 504Pa. The value of  $P$  used for ships in restricted service may be reduced subject to approval of administration

$A$  = Projected lateral area of the portion of the ship and deck cargo above the WL ( $\text{m}^2$ )

$Z$  = vertical distance from the centre of  $A$  to the centre of the underwater lateral area or approximately to a point at one half the mean draught (m)

## 4.6 Classification rules

### 4.6.1 Bureau Veritas

According to regulations by BV, character IN(Hs) indicates the vessel on inland navigation waters and within brackets the significant wave height  $H_s$  which she can operate. Bureau Veritas deals with River-sea vessels operating in significant wave height greater than 1.2m in estuary plus section in part D of rules for inland navigation vessels. The range of navigation notation will be completed by navigation notation Estuary plus, if:

- The significant wave height exceeds 1.2m or
- The vessel is operated on restricted maritime stretches of water, or

- The vessel is operated on large lakes.

With inland navigation notation Estuary plus the vessels has to pass the design criteria where the vessel has to comply with GZ curve requirements. Also the vessel has to pass minimum righting lever, angle of maximum righting lever, minimum angle of down-flooding and initial metacentric height. Now the objective of the work is to develop the weather criterion and to establish the requirements for the estuary plus vessel notation.

#### ***4.6.2 Russian Registry of shipping***

Russian River Register formulates intact stability and weather criterion in alternative way but relays more or less on same theory. Stability of a ship by the main criterion is considered to be sufficient when it withstands dynamically applied wind pressure on still water or at waves. This can be understood from the Eqn. 8 or Eqn. 9.

$$M_{heel} < M_{herm} \quad (8)$$

$$K = M_{perm} / M_{heel} \geq 1 \quad (9)$$

The heeling moment applied to a ship due to the dynamic wind pressure is calculated by Eqn.10, in kN/m

$$M_{heel} = 0.001 \cdot p \cdot S \cdot z \quad (10)$$

Here p is the assumed rated gust wind pressure, in Pa; S, the windage area of the ship at average draught to actual waterline, m<sup>2</sup> and z, reduced heeling lever arm at simultaneous heel and lateral drift of the ship. Assumed wind pressure is taken from a relationship between height of windage centre and design dynamic wind pressure for different classes of ships.

The maximum permissible moment  $M_{perm}$ , shall be equal to  $l_{perm}$  (which represents the maximum permissible moment corresponding to the angle of capsizing of the ship, m) multiplied by the weight of the ship D, kN, at the draught. It should be noted that IMO regulations are used for dynamic stability in case of passenger vessels with control on gust wind.

#### **4.7 Interpretation of rules.**

For understanding the basis of IMO rules, the basis of criteria through which the rule was derived is to be checked. The stability standard known as weather criterion adopted by IMO as resolution A.562, is based on a number of simplifying assumptions.



- The ship attains a stationary angle of heel  $\phi_0$  due to side wind loading. The wind loading here is represented by lever  $l_{w1}$ . This is not dependent on the heel angle but is a resultant of a wind of 26m/s. In this situation the wind heeling arm is maximal. In this simplest model the wind generates a force  $F_v$ , that acts in the centroid of the lateral projection of the above-water ship surface, and has a magnitude given by the Eqn. 11

$$F_v = P.A \quad (11)$$

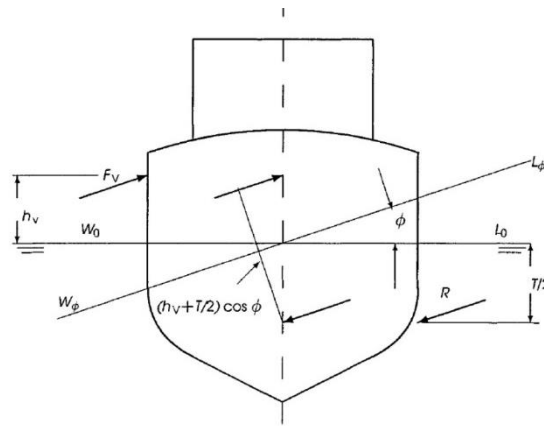


Figure 5 – Wind heeling arm.

Under the influence of this force the ship tends to heel as shown in Fig. 5, a motion opposed by the water with a force,  $R$ , equal in magnitude to  $F_v$ . To simplify calculations an assumption that  $R$  acts at half-draught,  $T/2$  is taken. The two forces,  $F_v$  and  $R$ , form a torque that inclines the ship until the heeling moment equals the righting moment. This is equated by the IMO rules to find the lever  $l_{w1}$ . The wind pressure,  $P$  is related to the wind speed,  $V_w$ , by Eq. 12

$$P = \frac{1}{2} C_w \rho V_w^2 \quad (12)$$

Where  $C_w$  is an aerodynamic resistance coefficient and  $\rho$  is the air density.

- Around this angle the ship is assumed to perform resonant rolling motion due to side wave action, as a result of which it reaches a momentary maximum angle  $\phi_1$  on the weather side
- As at this position the ship is most vulnerable in terms of weather-side excitations, it is further assumed that the ship is acted upon by a gust wind represented by a lever which will be  $l_{w2} = 1.5 \times l_{w1}$ . Which can be translated into an  $\sqrt{1.5}$  increase of the wind

velocity, assumed to affect the ship for a short period of time but at least equal with half of the natural period under the assumption of resonant ship response.

- The requirement for stability formulates as follows: should the ship roll freely from the off-equilibrium position  $\varphi_1$  with zero angular velocity, the limiting angle  $\varphi_2$  to the lee-side calculated on the basis of the condition  $b > a$  as shown in fig. 5 should not be exceeded during the ensuing half-cycle. This limiting angle is either the angle where significant openings are down-flooded, the vanishing angle  $\varphi_2$ , or the angle of 50 deg, which can be assumed as an explicit safety limit, whichever of the three is the lowest.

The basic principle of weather criteria is energy balance between beam wind heeling and righting moments with a roll motion taken into account. It is required that the energy due to restoring is larger than that due to wind heeling moment. The rule also assumes that ship has a steady heel angle due to steady wind with a resonant roll motion in beam winds. Then as a worst case, the ship is assumed to suffer gusty wind when she rolls toward windward. In case of resonant roll, roll damping moment and wave excitation cancels out. Thus, the energy balance between restoring and wind heeling energy can be validated around upright condition. Also as no resonance mechanism exists near the angle of vanishing stability, the effect of wave excitation moment could be approximated to be small.

Due to the very low flooding angles of inland vessels, it is almost impossible for such vessels to comply with the IMO requirements on stability. More over the local regulations (Royal decree of France and Belgium) formulates restrictions on probability of slamming, green water shipping etc. Also it stipulates that the roll angle should not exceed  $2/3^{\text{rd}}$  of flooding angle or  $15^\circ$ . A modification of the stability requirements for inland vessels at sea, which takes into account both the typical structure of such vessels and thus more controlled environmental conditions is required.

## 4.8 Comparison of Rules

Rule requirements for restricted navigation has been discussed in previous section. Now a detailed analysis is carried out in regards to the stability criterion already existing for inland navigation and will be checked with IMO criterion as given in previous section. A general comparison of rules for a river-sea vessel and inland vessel can be summarised as in the Table. 2. This can be further illustrated from the Fig. 6 shown below. The difference in the values can be attributed to fact that sea going vessels face harsh climate as opposed to inland vessels.

Table 2. Comparison of rules of seagoing vessel and inland vessel.

Specifications	Seagoing vessel	Inland vessel
Area under GZ	0.055m.rad. up to 30°	0.024 m.rad. up to 27°
Initial Metacentric height $GM_{initial}$	0.15m	0.10m
Righting lever, GZ	0.2m	0.12m

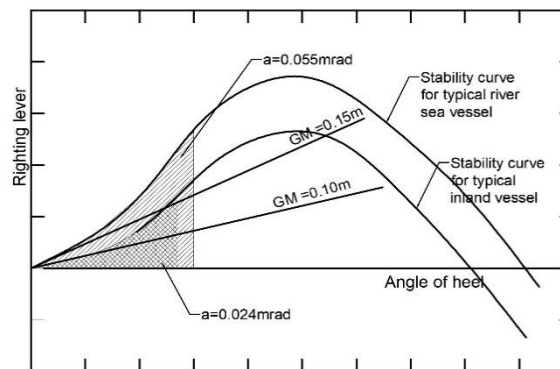


Figure 6. Comparison of rules of seagoing vessel and inland vessel.

## 5. NAVIGATION CONDITION

### 5.1 Navigation conditions across world.

For the assessment of the stability of a ship, the determination of the weather environment she is exposed to and the length of time she spends in the environment is to be identified. For short term analysis, to perfectly gauge the stability, it is required to have a period of 1-3 hours. Therefore once the routes are fixed, assessment should be done to forecast representative environmental parameters in the vicinity of prescribed routes. Accomplishing this is a difficult task. Consider a harsh climatic zone such as Japan, which is located in middle latitudes and frequently visited by extra tropical cyclones, so it is subject to major changes in weather and sea conditions. The coastal areas around Japan have been the place where marine casualties occur with great frequency. The Fig. 7 shows the marine causality occurred in coastal area of Japan. On the other hand there are waters where the significant wave height usually doesn't cross 0.6m, this being said no body of water is immune to roughness, even lakes can sink a ship.

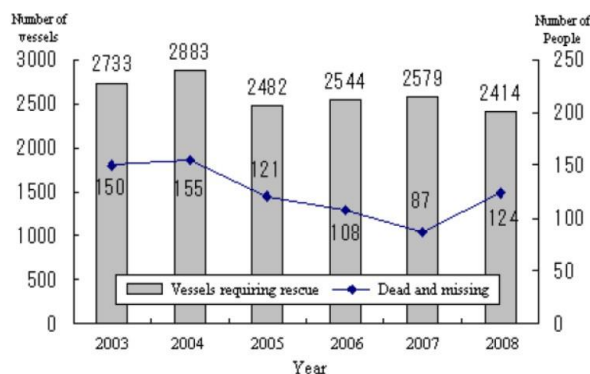


Figure 7 – Marine casualties in territorial waters in Japan [Courtesy: For the safety of navigation in Japanese coastal waters].

Now we shall see a detailed summary of the wave height and wind velocity of typical coastal area around the world.

1. Winter: - The mean wind velocity is 15 to 20 knots and the mean wave height is 1.5 to 2 metres. High-wave regions are widely distributed. The mean wave height in these regions is more than 2.5 metres.
2. Spring: - The mean wind velocity is 10 to 17 knots and the mean wave height is 1 to 1.8 metres. High-wave regions, where the mean wave height is about 2 metres.

3. Summer: - The mean wind velocity is 9 to 13 knots and the mean wave height is 0.8 to 1.5 metres. This is the calmest season of the year. High-wave regions where the mean wave height is about 2 metres can only be observed in some sea areas.
4. Autumn: - The mean wind velocity is 13 to 18 knots and the mean wave height is 1.3 to 1.9 metres. This is the season after winter when waves are most turbulent. High-wave regions, where the mean wave height is over 2.5 metres, can be observed in the sea areas. In some places, the wave height reaches as much as approximately 3 metres.

This can show the very uncertainty which can be seen in navigation areas around coastal areas. The best way to simulate the sea state will be to get data from the buoys located in coastal areas to understand the behaviour of seas. The Fig. 8 shows the wave height distribution (in y axis) in cm in time domain (in x-Axis obtained from Bol van heist in Belgium).

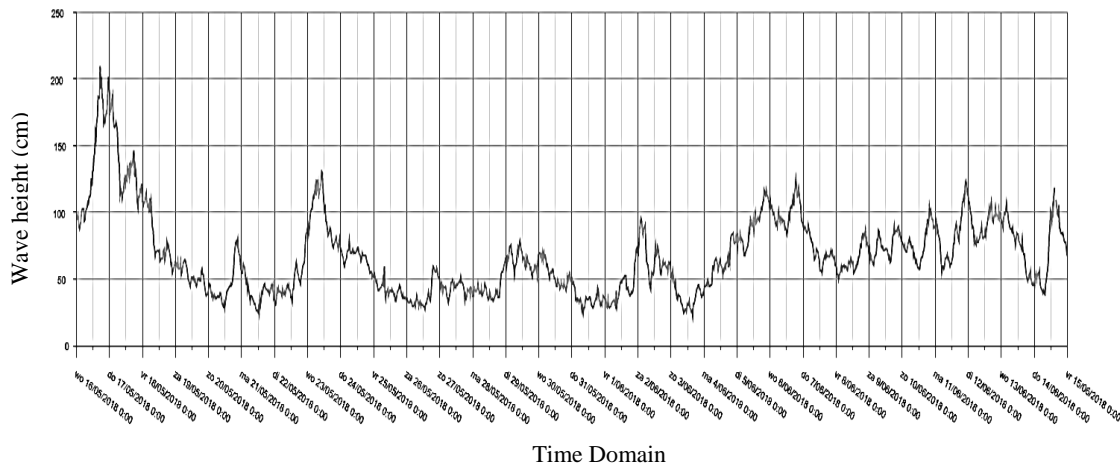


Figure 8 – Wave amplitude from Bol Van Heist buoy in time domain. [Courtesy: <https://meetnetvlaamsebanken.be/Measurement>]

## 5.2 Sea state representation

The characteristics of coastal water determine the ability of a ship to navigate in that waters, the most important characteristics of sea is the wave climate and wind climate. To determine wave climate in a coastal zone it is recommended to combine the in situ measurements and wave modelling. When we model the sea condition for potential solver it is only possible to use a wave model and on other hand in situ measurements are needed to validate and drive this wave model.

The first step for any study on collection of data on wave will be measured results from wave data buoys around the world. Many national or international oceanic and atmospheric administration's maintains a network of data buoys to monitor oceanographic and meteorological data off coasts and ocean. Wave data analysis involves application of accepted time-series analysis and spectral analysis techniques to time-series measurements of buoy motion. Usually measured directional wave data time series consist of digitized data representing one of the following types of data sets.

- Vertical acceleration, pitch, and roll measured using a sensor.
- Buoy acceleration from a single-axis accelerometer.

A measured time series can be analysed as a single record or as a number of data segments. Data segmenting with overlapping segments decreases statistical uncertainties while it also increases spectral leakage since, for shorter record lengths in each segment, fewer Fourier frequencies are used to represent actual wave frequencies. It should be noted that the some newest systems doesn't require data segmenting.

### 5.2.1 Fourier Transformation and spectra

Fourier transforms can be calculated by FFT algorithms. Usage of a simple algorithm can be used for this purpose. An FFT is a discrete Fourier transformation is given in Eqn. 13 that provides the following frequency domain representation,  $X$ , of a measured time series,  $x(n\Delta t)$ , with  $N$  data points digitized at a time interval,  $\Delta t$ , is divided into  $J$  segments of length  $L$ .

$$X(j, m \Delta\varphi) = \Delta t \sum_{n=0}^{L-1} x(j, n\Delta t) e^{-i \frac{2\pi mn}{L}} \quad (13)$$

Here  $m=0, 1, 2, 3, \dots$  and  $\Delta\varphi = \frac{1}{L\Delta t}$ .

Power spectral density estimates for the  $j^{\text{th}}$  segment are given by Eqn. 14.

$$S_{xx}(j, m\Delta\varphi) = \frac{|X(j, m\Delta\varphi)|^2}{L\Delta t} \quad (14)$$

Final spectral estimates are obtained by averaging the results for all segments by Eqn. 15

$$S_{xx}(m\Delta\varphi) = \frac{1}{J} \sum_{j=1}^J S_{xx}(j, m\Delta\varphi) \quad (15)$$

### 5.2.2 JONSWAP spectrum

The JONSWAP spectrum was established during a joint research project, the “Joint North Sea Wave Project” and is represented in literature by Hasselmann & al. The spectrum represents wind generated seas with fetch limitation. Thus JONSWAP wave spectrum is never fully developed. It continues to develop through non-linear, wave-wave interactions even for very long times and distances. Hence an extra and somewhat artificial factor was added to the Pierson-Markowitz spectrum in order to improve the fit to their measurements. The spectrum can be represented by the Eqn. 16

$$S_{\omega}(\omega) = \frac{5}{16} H_S^2 \omega_p^4 \omega^{-5} \exp \left[ -\frac{5}{4} \left( \frac{\omega}{\omega_p} \right)^{-4} \right] \gamma \quad (16)$$

Here  $\gamma$  is the peak enhancement factor and thus it will function as to increase the peak of the spectrum so as to fit the measured spectrum. The fig. 8 below shows the various values of  $\gamma$  and the corresponding peaks obtained.

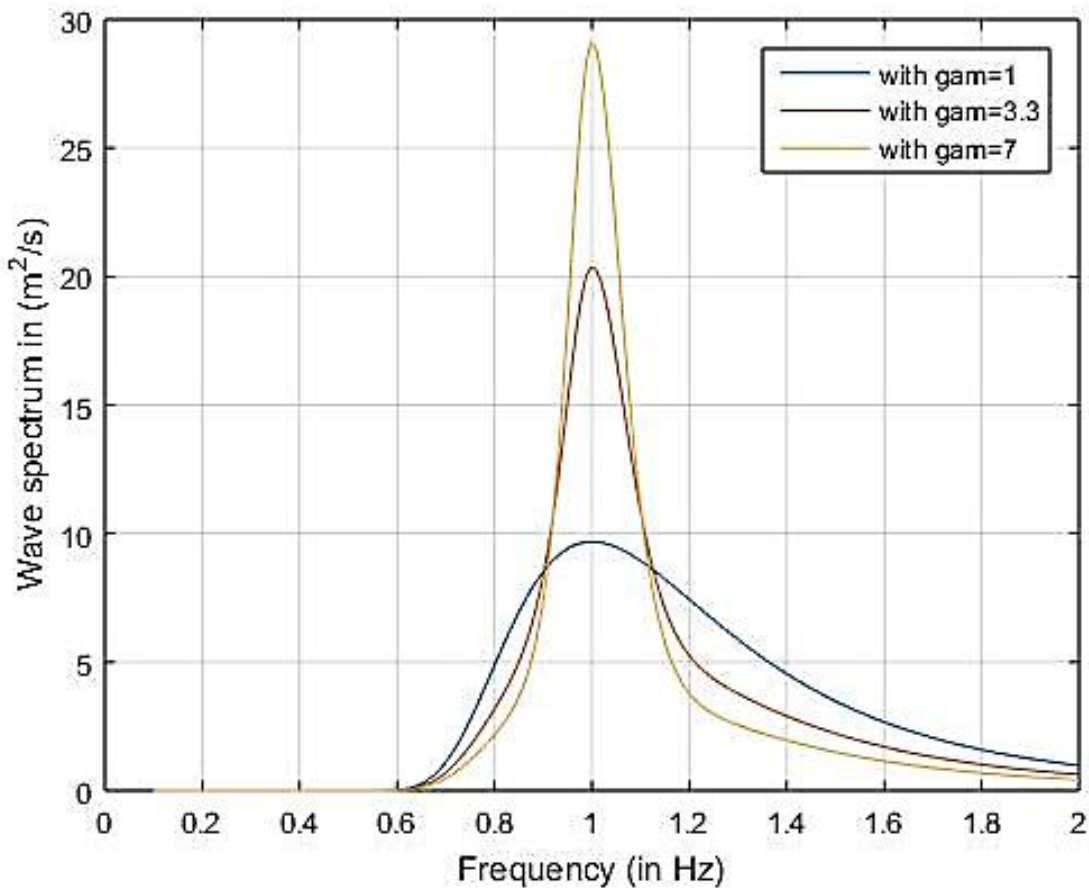


Figure 8 – JONSWAP spectrum with different  $\gamma$  values

### 5.2.3 Directional spectrum

A directional wave spectrum provides the distribution of wave elevation variance as a function of both wave frequency,  $\omega$  and wave direction,  $b$ . To represent the angular distribution of the wave, "directional" spectra  $S_\omega(\omega, b)$  is used. The formulation for directional spectrum is given by Eq. 17

$$S_\omega(\omega, \beta) = S(\omega) \cdot G(\omega, \beta) \quad (17)$$

Here  $G(\omega, \beta)$  is the spreading function which satisfies the Eqn. 18

$$\int_0^{2\pi} G(\omega, \beta) d\beta = 1 \quad (18)$$

It should be noted that in the study spreading is not considered frequency dependent and thus  $G(\omega, \beta) = G(\beta)$

Now the spreading function used for the study in both waters is "cos2s". Thus Eqn. 19 gives the direction spreading function associated.

$$G_2(\beta) = C_2(s) \cos^{2s} \frac{\beta - \bar{\beta}}{2} \quad \text{where } -\pi \leq \beta - \bar{\beta} \leq \pi \quad (19)$$

Where  $\bar{\beta}$  being the mean propagation direction and the coefficient  $C_2(s)$  is the normalising factor determined by relation

$$\int_0^{2\pi} G(\theta) d\theta = 1 \quad (20)$$

And is defined by Eqn. 21

$$C_2(s) = \frac{\Gamma(s+1)}{2\sqrt{\pi}\Gamma(s+\frac{1}{2})} \quad (21)$$

### 5.3. Sea state simulation

Wind and wave climate is much region and location dependent, affected by local properties of ocean environment. Wind and waves impact ship design, marine operations and they challenge ability of ships to maintain stable in sea states. Adverse weather conditions is to be used in assessment of ship stability.

Water depth affects wave generation. For a given set of wind and fetch conditions, wave heights will be smaller and wave periods shorter if generation takes place in transitional or shallow water rather than in deep water. There is no single theoretical development for determining the actual growth of waves generated by winds blowing over relatively shallow water. From



literature a successive approximations in which wave energy is added due to wind stress and subtracted due to bottom friction and percolation, can be found to determine actual growth of waves. Numerous research are underway to revise shallow water forecasting model.

Its already established that the wave height of coastal area for navigation is effected by the water depth. For the research the bathometric profile of various region were studied for the understanding of generation of water waves. This is tabulated in tab. 3. For further study the water depth will be assumed to be 15m for different coastal regions.

Table 3. Water depth at different coastal areas.

<b>Place</b>	<b>Water depth</b>
Belgium coast	17m
French coast	13m
Mediterranean sea	15m
German coast	16.5m

For the research, simulations are conducted in two navigation areas one in in the coastal water of east coast of American subcontinent from port of Savannah to port of Charleston and Belgian coastal waters according to vessel course shown in Fig 9 -10. Belgium is situated at the shores of southern North Sea with a shore length of approximately 65 km.

The description of open sea conditions is limited to the North Atlantic by using coastal waters of America while European waters are used as representative for closed sea conditions. This means the Belgium waters has a limited fetch while the American coast has as unlimited fetch. Correlations between wind speed and significant wave height as well as significant wave height and spectral peak period are established and compared.

For both coast the wave data is collected for a period of one year. In Belgium coastal waters the data is collected with Bol Van Heist Buoy while for east coast of United States of America information is validated using National Data Buoy Centre (NDBC) data.

The figure also shows the position of buoys which is used for the data acquisition. At US coast the wave buoy used and maintained by NDBC is used for study while at Belgium coast, the data is collected by the Bol Van Heist Buoy at the coast of Belgium. The figure 9 -10 shows the position of the buoys.

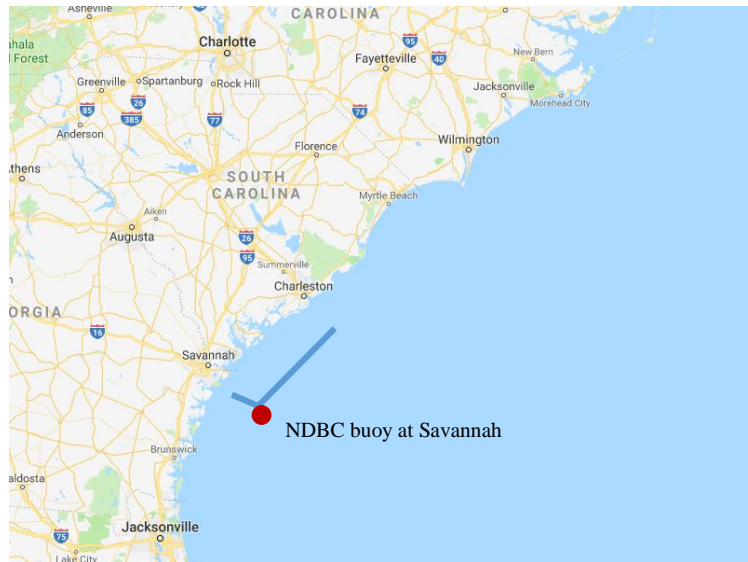


Figure 9 – American coastal water



Figure 10 – Belgium coastal waters

### 5.3.1. Wave spectrum simulation

Spectrums are the graphical representation of sea state. It is a concept used to describe mathematically the distribution of wave energy, proportional to the square of wave height with frequency. For the simulation purpose as well as consistency with current state of art seakeeping performance assessment, a JONSWAP expression which is depend only on two parameters, significant wave height and modal wave period is desirable which is already explained in previous section. The real time data obtained from buoy for a fixed period of 30 minutes were plotted as wave spectrum. The data obtained from buoy included the wave frequencies, measured spectrum and gives the significant wave height, peak period, peak wave frequency. A number of spectrum were created for various sea states with different significant wave height,

$H_s=1.2, 1.4, 1.6, 1.8$  and  $2.0$ . For the study JONSWAP spectrum was fitted with the measured spectrum. For Belgium waters, coastline orientation is approximately from South-West (SW) to North-East (NE). It was seen that at  $\gamma=1$ , the modelled spectrum was fitting very well with the measured spectrum for Belgium coast. The Fig. 11 and Fig. 12 shows the modelled and measured spectrum at significant wave height of  $1.2\text{m}$  and  $2.0\text{m}$  respectively for Belgium coast. Here we use circular frequency for the comparison.

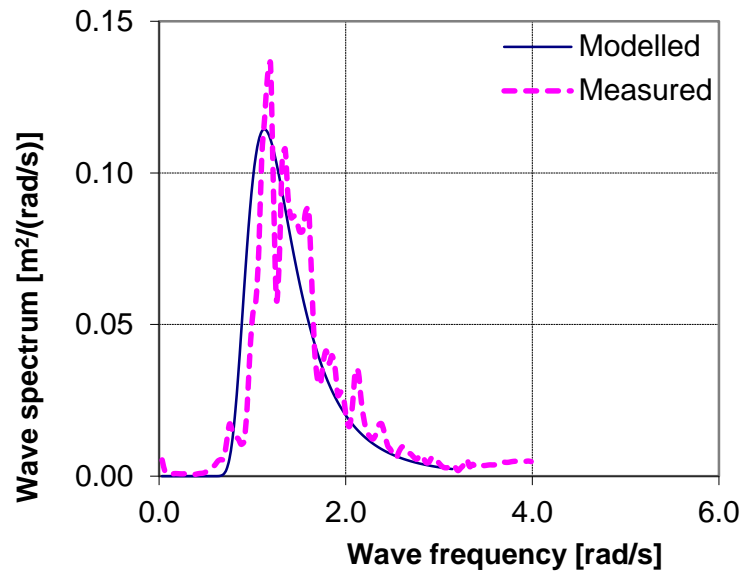


Figure 11 – Wave spectrum with  $H_s=1.2\text{m}$  at Belgium coast

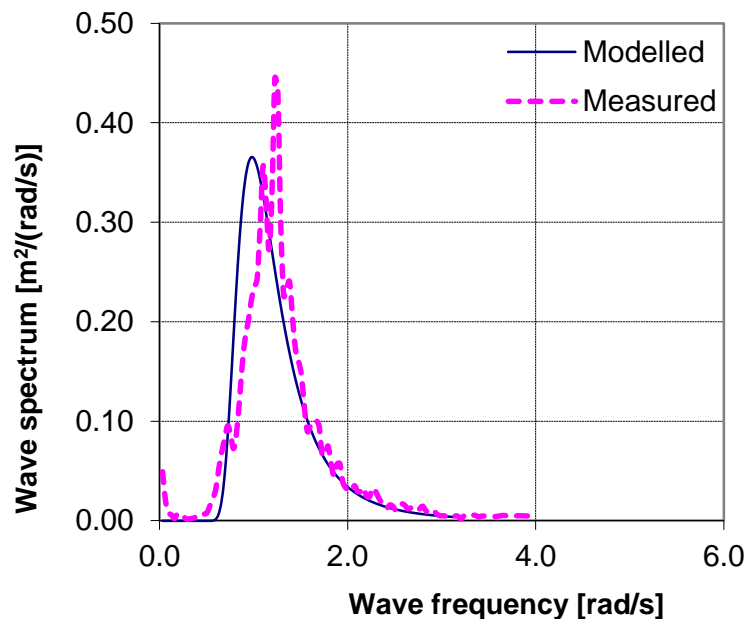


Figure 12 – Wave spectrum with  $H_s=2.0\text{m}$  at Belgium coast

Owned and maintained by National Data Buoy Centre the in situ measurements collected from the surface buoy have shown very positive agreement with modelled spectrum for  $\gamma=1.3$ . The Fig. 13 and Fig. 14 shows the modelled and measured spectrum at significant wave height of 1.2m and 2.0m respectively for the east coast of America.

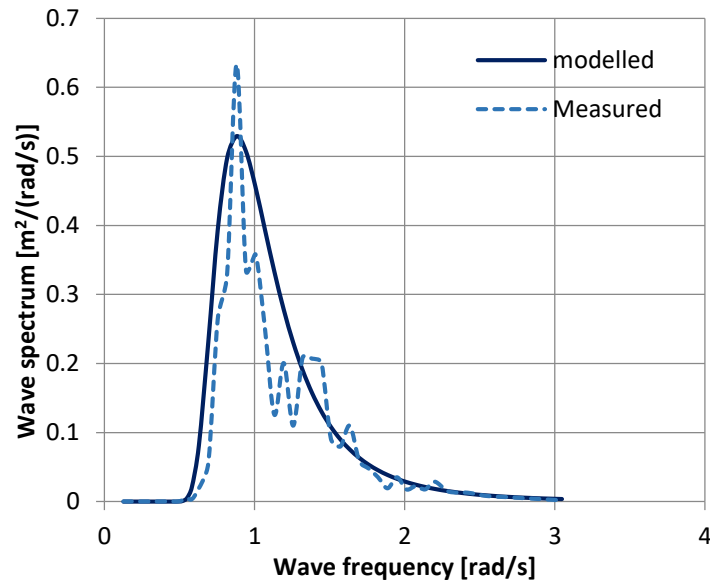


Figure 13 – Wave spectrum with  $H_s=2.0\text{m}$  at East coast USA

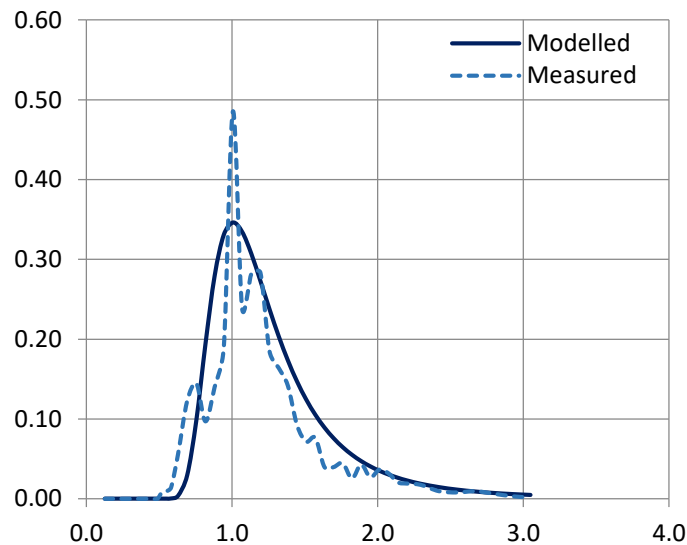


Figure 14 – Wave spectrum with  $H_s=1.8\text{m}$  at East coast USA

### 5.3.2. Wave scatter diagrams

Scatter diagrams summarises the wave climate and are typically representing the joint probability of (wave height, wave period) combinations during the time period they are encompassing. The wave scatter table gives the joint probability of significant wave height in

columns and wave zero crossing period in rows. Thus basically it is a table listing occurrence of sea-states in terms of significant wave height and wave peak period or mean upcrossing period. Applying a statistical fitting to the raw data obtained for a particular period, here with in a period of year, a scatter diagram as shown in the Fig.15 is obtained. H (wave height) bins are defined in 0.2 m intervals, ranging from 0 to 2.0 m. T (wave period) bins are defined in 1.0 s intervals ranging from 3 to 9s. In order to convey a visual impression of the wave scatter, the cells are colour coded, as follows, higher the probability darker the rows.

Hs [m]	2	0	0	7	98	69	4	0
	1.8	0	0	43	221	98	0	0
	1.6	0	0	151	364	51	1	0
	1.4	0	1	283	378	57	1	0
	1.2	0	43	713	421	48	10	0
	1	0	231	1088	277	21	0	0
	0.8	0	636	1463	229	47	3	0
	0.6	95	2195	2861	840	156	5	0
		3	4	5	6	7	8	9
		Tp [s]						

Figure 15 – Wave Scatter diagram for Belgium coast

We can see that as the wave height increases the period of the wave increases as expected. In estuary route having significant wave height greater than 1,2m the period of the wave is maximum at 6s and corresponding wave frequency is 1.05rad/sec. Thus it can be said that the model spectrum can be used for further calculations.

## 5.4. Wind Characteristics

### 5.4.1. Wind velocity

As the pressure exerted on the windage area of the ship is proportional to the wind velocity assumed and the heeling moment is directly related to the wind pressure, appropriate estimation of the wind velocity is of prime importance. Wind speed for the study is assumed to measured at a height of 10 m. The resulting wind speed series can be represented by Eqn. 22.

$$v = [v_i / i] \quad \text{where } i=1 \dots n \quad (22)$$

The basic representation of wind speed data is the wind histogram. A histogram which is used to represent the wind velocity is obtained by splitting the range of data into equally sized bins. These bins are called classes and each of these class is represented by the middle value of the bin. Another way illustrate this is the use based on the probability of wind speed. Fig. 16 below

shows the representation of probability distributions for wind speed given for the most seaward located measuring station approximately 30 km from the shoreline called “Westhinder” in Belgium. A typical wind speed is 8 m/s. Winds most frequently come from South-West (SW)

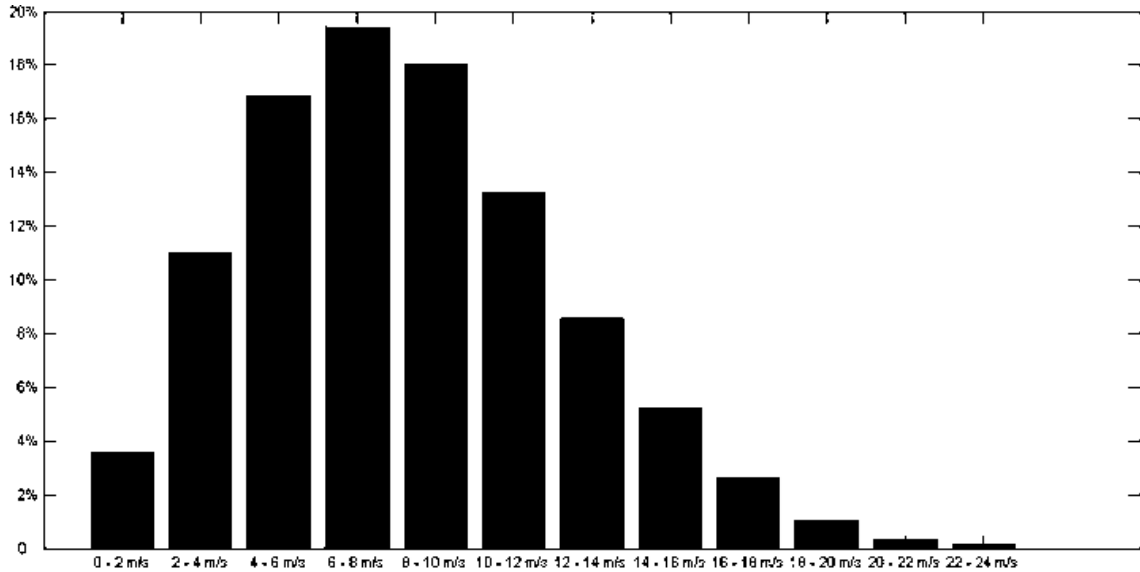


Figure 16 – Histogram of wind velocity at Westhinder.

The wind climate of a region can be better understood from the data obtained from weather station. The frictional effects due to presence of ocean can distort the wind field and thus wind speed and direction become dependent on the elevation above mean surface. Thus for the study we will assume the wind speed at 10m from the surface and corrections will be done for the same.

Now for a ship, moving air; the wind stopped by the ships lateral surface and the dynamic energy in this wind is transformed to pressure. The pressure acting on the surface is transformed into force given by Eqn. 24

$$F_w = 1/2 \rho V^2 A \quad (23)$$

$$\text{And } P_D = 1/2 \rho V^2 \quad (24)$$

Where  $F_w$  is the wind force given by Eqn. 23 in N,  $A$  surface area in  $m^2$ ,  $\rho$  is the density of air and  $A$  is the lateral surface area. The Fig. 17 wind data collected in way of West hinder weather station on Belgium coast. The plot is made between significant wave height and wind pressure induced by mean wind speed. Now it can be seen that at a wave height less than 2m has a maximum wind speed of 20m/s and from the eq. 24 we can calculate the corresponding wind pressure as  $245N/m^2$ .

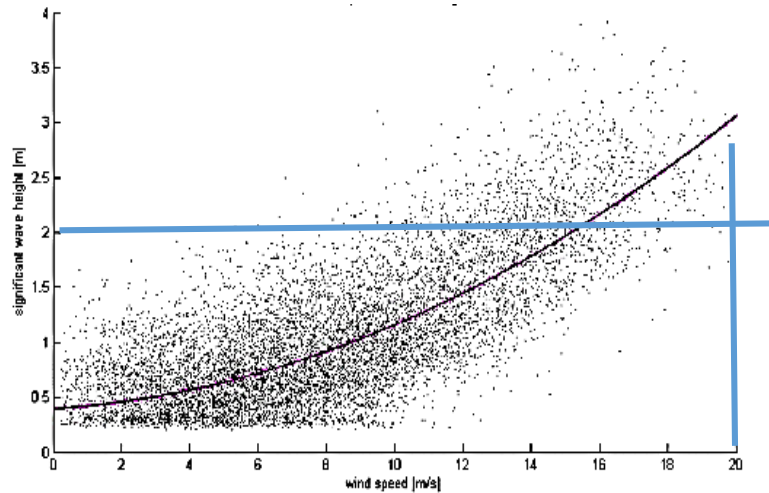


Figure 17 – Wind pressure vs HS at Westhinder station [Courtesy: Weather at Belgium coastal zone]

There are also other methods to estimate the wind pressure, these are tabulated in table 4. This together with different theoretical formulation from literature were considered for the estimation of wind pressure acting on the vessel. Among these were Derbyshire formulation, Pierson and Markowitz formulation etc.

Table 4. Relationship between Hs and wind speed

Sl no	Specifications	Requirements
1	Wind pressure considered for ships by IMO	The wind pressure of ships is considered as $0.504 \text{ kN/m}^2$ . The value of P (wind pressure) used for ships in restricted service may be reduced subject to approval of administration
3	Wind pressure considered for ships by DNV (n is nav coefficient.)	Specific wind pressure [ $\text{t/m}^2$ ] - IN(0) and IN(0.6) $P_{wd} = 0.025$ - IN(1.2) and IN(2) $P_{wd} = 0.04 \cdot n$
4	Wind pressure considered by Local Indian IV rules (KERALA IV RULES)	The value of wind pressure, P when calculating weather criteria for river sea ship can be taken as $0.168 \text{ kN/m}^2$
5	Wind pressure considered by French Regulations	The value of wind pressure, P when calculating weather criteria for river sea ship can be taken as $0.30 \text{ kN/m}^2$

In BV rule set, to calculate the lateral pressure and to determine moment due to this pressure the following formulation in table 5 is considered in Pt. D, Ch1, Sec 6 of Bureau Veritas rules for classification of inland navigation vessels, where n is navigation coefficient.

Table 5. Lateral pressure used for determining the wind moment

Range of navigation	$p_{wd}$ in kN/m <sup>2</sup>
<b>IN(0.6&lt;x&lt;2)</b>	$0.3 n^{0.5}$
<b>IN(0), IN(0.6)</b>	$0.25 n$

Concluding, different theoretical methods to estimate the wind pressure corresponding to each significant wave height has been discussed and the following can be inferred.

1. There is clear co-relation between the significant wave height and wind speed. When wind speed and wave height in simple time evolution graph shows a considerable difference, it can be attributed to swell action and variation of depth along the coastal area.
2. It can be seen that at lower wind speed the significant wave height is less while at higher speeds of wind the significant wave height shows exponential growth.
3. The wind pressure can be calculated as 0.245kN/m<sup>2</sup> at Belgian coast at significant wave height of 2.0m, calculated with Hs vs. Wind speed graph(using the equation  $p=0.613V^2$ , where V is the velocity of air at significant wave height 2m).
4. Wind pressure is to be obtained by the use of wind force as provided by relevant administration or harbour master, were the wind data is not available. The Society should reserve the rights to impose a reasonable wind force, if necessary.
5. The use of BV equation for the estimation of wind pressure given below holds well with most of the methods described above. Use of this equation for further calculation can be justified as they are in line with real time data from locations around the world where study was conducted.

#### **5.4.2. Effect of Fetch on sea state**

Fetch is defined as the region in which speed and direction of wind are reasonable constant. Computing wind generated waves from wind speed begins to deteriorate when wind direction variations exceed 15°, and further when the wind direction change is exceeds 45°. For practical wave predictions it is usually satisfactory to regard wind speed as reasonably constant if variations doesn't exceed 5knots. For the simplification for the formulation here in the study we use fetch as the distance from adjacent land mass to the point of concern. The effect of fetch width wave growth in generating area may be neglected as nearly all ocean fetches have widths about as large as their lengths. In inland waters, fetches are limited by landforms surrounding the body of water.



## 6. SEAKEEPING OF VESSEL

### 6.1 Seakeeping of vessel using potential solver

As discussed in the previous chapter it is important to analyse the seakeeping criteria of the vessel mainly in adverse weather conditions, especially the large amplitude motions (particularly roll). A good way to start is with a CFD software. For the study the potential solver Hydrostar, software developed by Bureau Veritas is used to analyse the Seakeeping nature of ships. The software is based on the Boundary Element theory. The following description will demonstrate the use of numerical method for linear wave induced motions.

#### 6.1.1 Response in regular waves.

It is possible to obtain results in irregular seas by linearly superposing results from regular wave components and thus it is sufficient from hydrodynamic point of view to analyse a structure in incident regular sinusoidal waves of small wave steepness. The hydrodynamic problem in regular waves is normally dealt with two sub problems namely wave excitation force (Froude-Krylov and diffraction problem) and a hydrodynamic loads identified as added mass, damping (both these includes the radiation problem) and restoring terms.

For steady state sinusoidal motion the Eqn. 25 gives the equilibrium of forces

$$\sum_{k=1}^6 [(M_{jk} + A_{jk})\ddot{U}_k + B_{jk}\dot{U}_k + C_{jk}U_k] = F_j e^{-i\omega t} \quad (25)$$

For  $j=1, 2, 3 \dots 6$  and where  $M_{jk}$  are components of generalised mass matrix of structure and  $F_j$  are the complex amplitudes of excitation forces.  $A_{jk}$  and  $B_{jk}$  are defined as added mass and damping coefficients. There is a total of 36 added mass coefficients, damping coefficients and stiffness matrix for single body. Under the assumption of symmetry of vessel elimination of many of these coefficients can be done.

Inertial matrix or added mass matrix can be written as in

$$[M] = \begin{bmatrix} M & 0 & 0 & 0 & M.Z_{CC} & -M.Y_{CC} \\ 0 & M & 0 & -M.Z_{CC} & 0 & M.X_{CC} \\ 0 & 0 & M & M.Y_{CC} & -M.X_{CC} & 0 \\ 0 & -M.Z_{CC} & M.Y_{CC} & I_{44} & I_{45} & I_{46} \\ M.Z_{CC} & 0 & -M.X_{CC} & I_{54} & I_{55} & I_{56} \\ -M.Y_{CC} & M.X_{CC} & 0 & I_{64} & I_{65} & I_{66} \end{bmatrix} \quad (26)$$

Where  $M$  is the mass of the body and  $X_{GC}$ ,  $XY_{GC}$  and  $Z_{GC}$  are the coordinates of centre of gravity of the body and  $I$  is the moment of inertia of the body. Hydrostatic restoring force due to oscillation of body is written as the difference between force in still water and hydrodynamic loads. The diffraction solution are potential flow around the vessel remaining immobile in incoming waves and the wave excitation loads are obtained by integrating the dynamic pressure on the fixed vessel in incoming waves.

The software Hydrostar solves the problem of diffraction and radiation (added mass and damping) around fixed and floating bodies and it's based on the following:

- First and second order potential theory of free surface flow;
- Integral equations / boundary element method;
- Efficient evaluation of associated Green functions;
- Elimination of irregular frequencies;
- Independency of the mechanic properties of the system

### ***6.1.2 Numerical method for linear wave induced motions and loads***

Panel methods are the most common technique used to analyse the linear steady state response of large volume structures in regular waves. They are based on potential theory. It should be noted that the use of potential theory cannot account viscous damping effects due to flow separation.

Rather than going to mathematical formulation of boundary element method i.e. *Converting volume integral to boundary integral by Green's formulae or the use of equations of source and sink to represent the panel and distributing the sources over the body surface satisfying the boundary conditions on mid position of each of the panel, setting up the linear system of equations for unknowns, solving the matrix and integrating for results*, we will here see how these technique can be used to analyse linear wave-induced motions and loads on large-volume structures

In order to formulate added mass and damping problem, it is useful to review, in very general terms, the linear system of equations in finite or deep water for boundary conditions

1. Bottom BC/Free slip condition:

$$\frac{\partial \phi}{\partial z} = 0 \text{ for finite depth}$$

2. Free surface boundary condition, combining (shortly) DFSBC and KFSBC we have

$$-\omega^2 + g \times \frac{\partial \phi}{\partial z} = 0$$

3. Laplace equation( incompressible and irrotational):

$$\Delta \phi = 0$$

4. Boundary condition on ship

$$-\omega^2 + g \times \frac{\partial \phi}{\partial n} = n_3 \frac{dn_3}{dt}$$

### 6.1.3 Panelling the surface.

The panelling of hull is done by plane quadrilateral elements in 3-D problem. The ‘leaks’ in body surface as the panels doesn’t fit together has no serious consequences because of 4<sup>th</sup> boundary condition (no flow through hull surface BC). Assuming a constant source density and fluid pressure on each element. This means keeping smaller elements in areas where the flow changes more rapidly and avoiding sharp corners as flow will separate at that corner. In wave zone the element size should be at least 1/8<sup>th</sup> of the wave length. Typical values of total number of panels may vary from 500 to 3000 panels. Now the iterative solutions of linear equation systems for the source densities are computed.

The source density is complex in wave problem than in 2D. The source expression is far more complicated to compute numerically in a wave problem. It can be computed by numerous method including calculation by Newman (1985) with the use of Bessel function.

### 6.1.4 Use of Green’s identity

When we use green’s second identity which can be represented as Eqn. 27

$$\int_U (\psi \Delta \phi - \phi \Delta \psi) dV = \oint_{\partial U} \left( \psi \frac{\partial \phi}{\partial \mathbf{n}} - \phi \frac{\partial \psi}{\partial \mathbf{n}} \right) dS. \quad (27)$$

Here  $\phi$  and  $\psi$  are both twice continuously differentiable. A closed surface integral is used as indicated in the Eq.23. Now Fig.18 shows the integration surface used in greens identity representation. If we apply the formula to wave load problem, the surface S consists of mean body surface  $S_B$ , a vertical circular cylindrical surface  $S_\alpha$ , a mean free surface  $S_F$  and sea bottom  $S_0$ . Representing velocity potential by a distribution of Rankine sources and dipoles is done over this closed surface. It should be noted that the dipole density on S is given by  $\Phi(s)$  and source density is given by  $\frac{\partial \phi}{\partial n}$

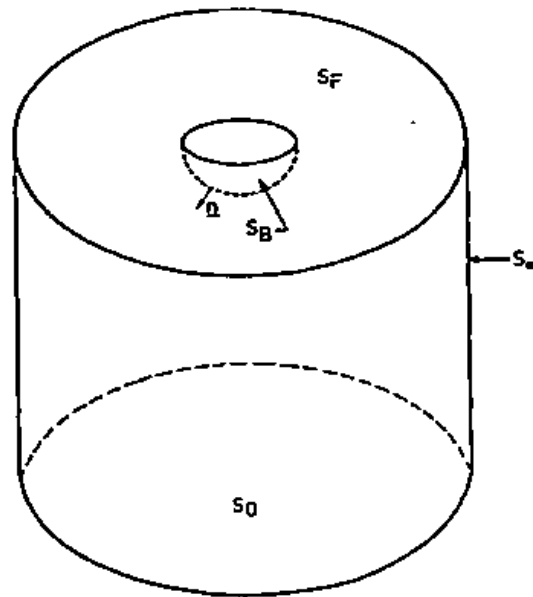


Figure 7 – Integration surfaces used in Green's identity representation. [Courtesy: Sea loads on ships and offshore structures]

Now infinite fluid sources and dipole have to be replaced by sources and dipoles satisfying boundary condition corresponding to each surface as it is a disadvantage of representing the surfaces in terms of infinite fluid sources and dipoles. This is because doing so can lead to a large equation of system for solution of unknown potential distribution. But using velocity potential in terms of infinite sources and dipoles has a great advantage as the free surface condition is so complicated that it is not possible to find analytical expression for the wave source that satisfies the nonlinear free surface condition.

## 6.2 Seakeeping analysis.

Seakeeping analysis is essentially a two part problem once estimation of environmental condition is done:

- Prediction of the response characteristics of the vessel.
- The criteria used to assess the vessel's seakeeping behaviour has to be specified which also defines the way in which the performance of different vessels is compared.

Evaluation of seakeeping performance depends on the environmental parameters that the vessels are being subjected to and the criteria which are being used to compare the designs. This makes enough complication in understanding the vessel behaviour when considering seakeeping performance than comparing calm water resistance or power requirements to

achieve a specific speed. The research presents the formulation of the criteria in order to meet the requirements of the vessels.

### 6.2.1 Prediction of response

In its simplest form, the vessel may be considered like an electronic filter. It takes an input signal (the ocean waves), filters it, and then produces an output (the vessel motions).

The boundary element analysis or potential theory gives the result in terms of

- Motion, velocity and acceleration RAO in x, y and z direction
- Pressure and relative wave elevation
- Wave loads in terms of forces and moments at a given section or a wave frequency
- Low and high frequency load in terms of forces and moments in x, y and z direction

Now the main results of interest is the vessel response, RAO. In simple form consider ship as an electronic filter- it takes an input signal, filters it and then produces as an output. The vessel's filter function or RAOs are different for the six, rigid-body, degrees of freedom (surge, sway, heave, roll, pitch and yaw). Each motion has its own characteristics and RAO. The coupling of these motions i.e. consider the vessel moving vertically up and down in heave, if the centre of floatation is not directly above the centre of buoyancy, then the vertical heave motion will initiate a pitch motion and vice versa.. In practice, for symmetrical vessels, many of these coupling effects can be neglected (being zero or very small). The Fig. 19 shows plots of linear pitch RAO for a 5m radius, 10m draft cylindrical body made by Nemoh-A BEM solver developed in ECN

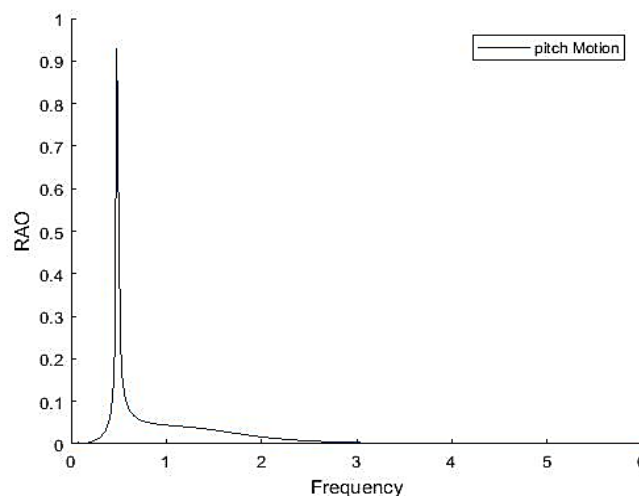


Figure 19 – RAO for cylindrical body

### 6.2.2 Specification of the criteria

It's important that to have an acceptable levels of motions, accelerations or other events which can occur without affecting the vessel's mission. They can also be relative motions, relative velocities, slamming, propeller emergence, deck wetness, motion sickness incidence, motion induced interruptions etc. Now to decide whether a vessel can operate under specific condition requires us to specify the criterion and we need statistical values or probabilities of these criteria being exceeded (or occurrences per hour) by seakeeping analysis. These data can be used to compare different vessels and to decide whether a vessel can operate under the specified conditions. This can be seen in the Fig. 20.

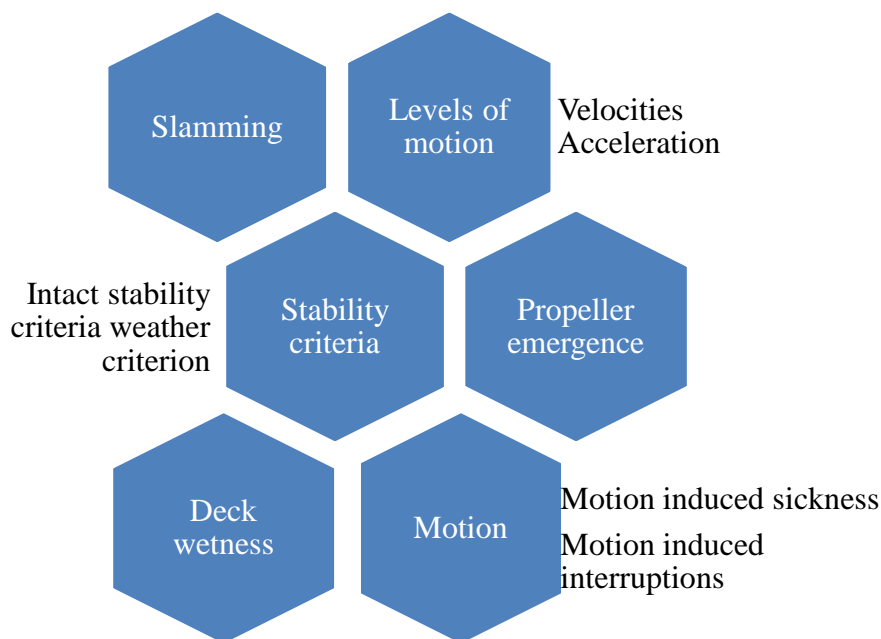


Figure 20 – Seakeeping criteria

Motions criteria may also be used to determine limiting sea conditions for operability. Combined with data for the expected sea conditions on a particular route, motions criteria may be used to predict down time, which may be used for economic evaluation of the design.

The effects of seakeeping on stability and analysis of dynamic stability is becoming more important due to increased safety requirements. This includes accounting for motions due to waves when assessing vessel stability rather than simply still water or quasi-still water hydrostatic stability. There are numerous research are now going on in this field among which pure loss of stability, broaching etc. are studied.

### 6.3 Spectral Analysis

The spectral density  $S_w(\omega)$  representing the distribution in frequency ( $\omega$ ) of the wave energy is the input of spectral analysis along with RAO of the vessel. RAO of a vessel is the characteristic of a vessel. Then the spectral density of response can be given by Eqn. 28

$$S_R(\omega) = RAO^2(\omega) \cdot S_w(\omega) \quad (28)$$

Now the spectral moments can be then defined by Eqn. 29

$$m_n = \int_0^{\infty} \omega^n S_R(\omega) d\omega \quad (29)$$

If several spectra with different directions are used, the spectral momentum are sum and can be written as in Eqn. 30.

$$m_n = \sum_i^m \int_0^{\infty} \omega^n S_R(\omega, \theta) \cdot RAO^2(\omega, \theta) d\omega \quad (30)$$

Now the mean period can be given by Eqn. 31.

$$T_m = 2\pi \frac{m_0}{m_1} \quad (31)$$

#### 6.3.1 Short term statistics

The short term analysis of response of a ship corresponds to the response of a ship during a certain period of one sea state (typically 3 hours). When considering a random variable R being the range of response and assuming the process is narrow banded the probability density of response follows Rayleigh's distribution. The distribution function of this Rayleigh function is then given by Eqn. 32

$$P(R) = 1 - \exp\left(\frac{-R^2}{8m_0}\right) \quad (32)$$

#### 6.3.2 Long term statistics

A long term distribution is obtained by cumulating the results from all the short term analysis. The method involves counting of all maxima's in response for all the sea states which are considered. Now this can be mathematically represented by Eqn. 33.

$$n_{ex(X)} = \sum_{SS=1}^{SS=N_{SS}} n_{SS} (1 - P(X)) \quad (33)$$

Here  $N_{ss}$  is the total number of sea states,  $N_{ex}(X)$  is the expected number of exceedence of response level  $X$  over a reference period,  $P(X)$  is the Rayleigh's distribution of sea states  $SS$  and  $n_{ss}$  is the response cycles for a sea state  $SS$ . Now the long term probability can be expressed as in Eqn. 34.

$$P(R) = \prod_{ss}^{N_{ss}} \left(1 - e^{-\frac{R^2}{8m_0}}\right)^{n_{ss}} \quad (34)$$

#### 6.4 Problems with analytical part

Computational fluid dynamic software tools for analysis of seakeeping of vessels have not yet reached the stage where they can reliably predict absolute motions data with accuracy we demand. But these softwares are useful for comparative analysis, particularly in initial design where seakeeping performance would perhaps otherwise be virtually ignored due to constraints of time and budget. Now the use of empirical methods for the calculation of roll angle can be interesting which will overcome the technical difficulties raised from the use of numerical methods.

Also it should be noted that developing better understanding of seakeeping criteria of river sea vessels has to be conducted and an analysis is to carried out to identify the critical values to the successful operation of their vessels. These criteria should be able to address the loading in offshore conditions, cargo handling and other mission characteristics of the vessel when going to sea.

#### 6.5 Empirical formulation of roll angle in waves from literature

Considering the wave exciting moment without wave diffraction uncoupling of roll motion from other motion modes can be done and considering nonlinear roll damping effect the amplitude of resonant roll in regular beam waves,  $\Phi$  (degrees), can be obtained as in Eqn. 35.

$$\phi = \sqrt{\frac{\pi r \theta}{2N(\phi)}} \quad (35)$$

Where  $\theta$  (=180s): maximum wave slope,  $r$ : effective wave slope coefficient and  $N$ : Bertin's roll damping coefficient

In the stability standard of USSR (USSR, 1961), the maximum roll amplitude of 50 roll cycles is estimated as in Eqn. 36.

(36)



$$\varphi_R = kX_1X_2 \varphi_A$$

Here  $k$  is a function of bilge keel area,  $X_1$  is a function of  $B/d$ ,  $X_2$  is a function of the block coefficient and  $\varphi_A$  is roll amplitude of the standard ship. This formula was developed by systematic calculations for a series of ships utilizing the transfer function and wave spectrum (Kobylinski & Kastner, 2003).

Another approximation in extreme value of roll amplitude in rad is predicted by the Eq.37

$$A_R = H_W \left( \sqrt{\frac{GM}{\delta} + 2.15} \right) \frac{1}{\sqrt[3]{\Delta}} \quad (37)$$

Where  $H_w$  is the navigation coefficient

## 6.5 Sea keeping criteria.

The main parameters involved for long term seakeeping considerations in terms of hydrodynamic responses of a vessel are

- Average acceleration in all DOF esp. in Heave, Roll and pitch
- Average motions in all DOF esp. in Heave, Roll and pitch
- Deck wetness
- Slamming
- Wave bending moment

To address the safety of the vessel in adverse weather conditions, large amplitude motions in roll motion has to be accounted for. The weather environment a ship operates is a general field. So it is important to incorporate random sea and wind in a ship motion problem and there is nonlinear relation between the excitation and the response. In this context wave conditions that produce rare events have to be defined.

## 7. SOFTWARE TOOLS

### 7.1. ARGOS

ARGOS software is a naval architecture system for ship hydrostatics, stability and longitudinal strength calculations developed by Bureau Veritas. It is modular software made of a standard package and some additional modules related to particular applications. In this study, ARGOS is used to compute the stability of existing vessel.

Some modules of the software which are related to the needs of the study are briefly explained below.

#### Basic Ship Data

This module allows the user to enter the identification and the main dimensions of the ship. Also, the location of the hull frames is defined.

#### Lines Plan

This module performs the ship hull geometry description by vertical sections drawn in the transverse plan. Each section is described by points defined by Y and Z coordinates. The geometry can be completed by appendages to be added or deducted to the main hull.

#### Part Definition

This module is to enter the definition of the parts (sets of sections) which are used to describe the capacities. The parts are elementary volumes defined by the transverse sections which can be directly entered by keyboard.

#### Hydrostatic Particulars

In this module, the results of the hydrostatic calculations of the vessel can be displayed. Moreover, hydrostatic curves can be plotted.

#### Capacity Plan

In this module, capacities of the tanks and the compartments can be displayed considering the permeability of the part. The user has the opportunity to select the order of the tasks. If the selected operation needs a previous definition of data or an intermediate calculation which has not been executed yet, a message appears to inform the user regarding the necessity of some previous operations to perform the selected one.

## Intact stability module

In intact stability module, the GZ curve calculation can be done in various loading condition and with different criteria definition. Here the software utilises varying FSM in tanks and thus accounts for the same for the calculations.

## 7.2. HYDROSTAR

One of our goals of the numerical model is to evaluate the body motions caused by action of gravity waves up to significant wave height 2.0m. In the study, the seakeeping of vessels were done using stability software Hydrostar. Hydrostar is a hydrodynamic software developed by Bureau Veritas to evaluate wave loads and induced motions of marine structures of any type in deep and finite water depth by boundary element method. It has been developed 20 years before and it is continuously updated by Bureau Veritas and improved to rise to technological challenges. Hydrostar is composed of an automated mesh generator and starspec, a spectral post-processing module. The following are the advantages of using the software for the calculation

- Rapid results
- Inputs for green water & slamming estimation
- Linear and non-linear wave loads

The theory behind the software has been already discussed in previous chapter, which is based on three dimensional potential flow theory.

### 7.2.1. Methodology of software

The aim of the research is to construct long term responses of 60 inland vessels and thus develop intact weather criterion applicable to river-sea vessels. The softwares requires lines plan, weight distribution, hydrostatic particulars etc. from imported stability files and with the help of Visual Basic macro these are exported as inputs for the software. To further automise the process, scripting was done to minimise the user interference. In Fig. 21 below demonstrates the seakeeping assessment procedure, which uses short and long term approaches.

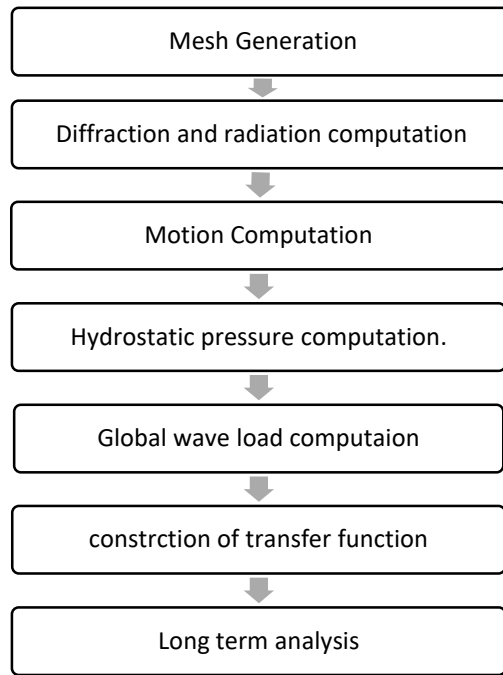


Figure 21 – Block diagram for seakeeping analysis

### 7.2.2. Mesh generation

Input file for Hydrostar for mesh generation is two text files with extension \*.mri along with \*.hul file. The origin of reference system used by Hydrostar is at the free surface level and following coordinate system is followed.

- OX is positive forward direction
- OY is positive portside direction
- Oz is positive upwards direction.

The wave heading is defined by angle between the propagation direction and positive direction of axis OX. This can be further illustrated with the help of Fig. 22

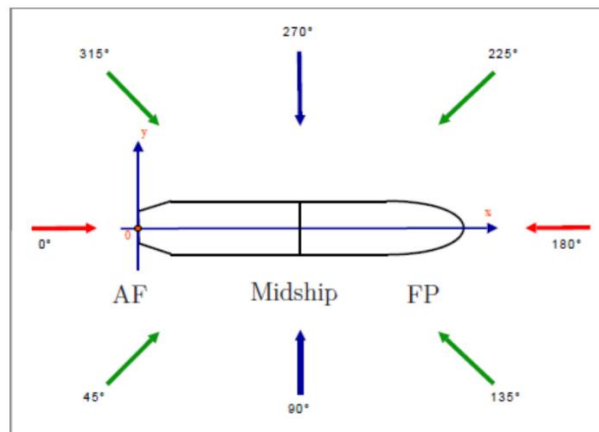


Figure 22 – Heading convection [Courtesy: Hydrostar Manual]

Automatic mesh generator is used to import ship geometry which gives coordinates of nodes as output file. The panels are made with nodes of coordinates in the input files as in fig. 23. The input file for a floating body contain only under water surface. This means that there should be no panels cut by the free surface. The upper part of the body is only for visualisation purpose.

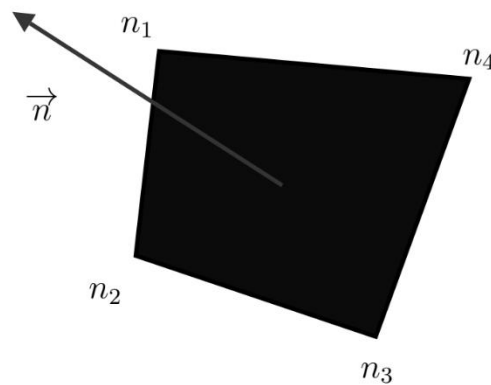


Figure 23 – Flat quadrilaterals [Courtesy: Hydrostar Manual]

The basic steps of the procedure are the following

- Identification of the ship type
- Cutting the mesh at the required draught and accounting for trim and heel angles
- Fine subdivision of each section according to the adaptive cosine rule
- Longitudinal subdivision of the midship part
- Special treatment of the fore and aft parts
- Writing of the output file \*.hst

The hull geometry shall be represented by flat quadrilaterals or flat triangular with the normal vector oriented towards the fluid. The most important part to be checked for will be the displacement and LCG of the vessel and this should corresponds the actual loading condition to give the draft and trim of the vessel. This should be followed by checking mesh. The check for mesh is done for zero-area panels, superposition, inconsistencies, and neighbour absence and symmetry problems. The Fig 24 shows the underwater surface of a sample vessel meshed with normal of the panels normal to fluid surrounding it.

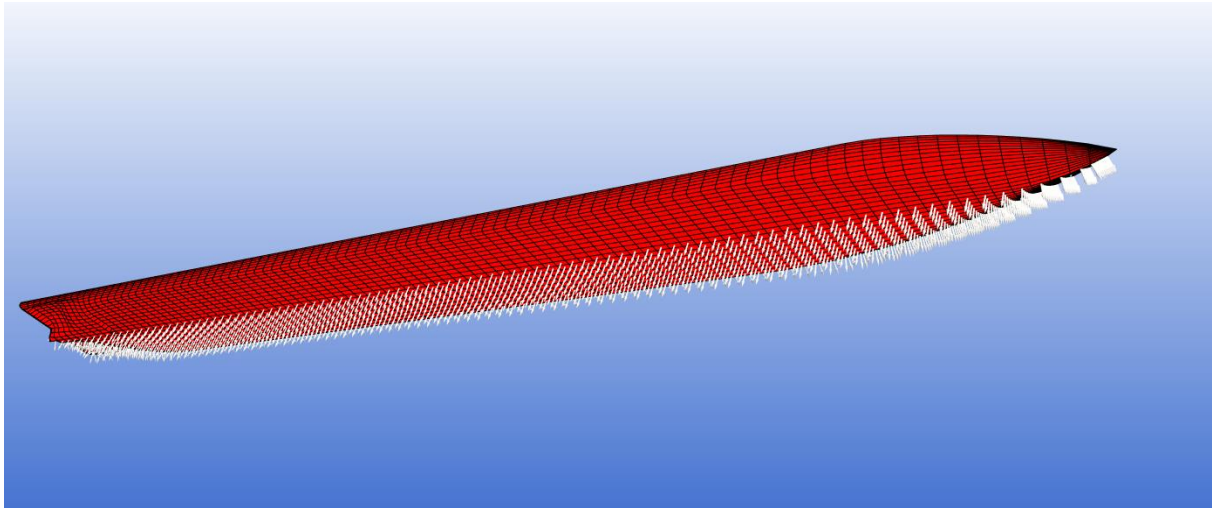


Figure 24 – Meshed vessel with normal vectors

### ***7.2.3. Diffraction and radiation computation***

From already established theory, the hydrodynamic loads induced by free floating body is calculated by the software. The radiation solutions are the potential flow around the vessel when the vessel moves in the otherwise quiescent fluid. For the computation of radiation and diffraction definition of wave frequencies, heading and depth (intermediate) is to be defined. A step of 0.1(rad/s) and  $10^0$  are given for calculation for wave frequency and heading respectively. For the calculation of encounter frequency, a forward speed of 10knots was given for the vessel. The result of diffraction radiation computation are the added mass, radiation damping and first order loads.

### ***7.2.4. Motion and global wave efforts computation***

The solution for Newton's second law applied to describe the motions of floating bodies shall require the position of the centre of gravity, the inertia matrix, additional stiffness matrix and the additional damping matrix. These values are to be obtained from actual loading condition of the vessel. The radius of gyration is assumed to be 35% of breadth of vessel. From these values Hydrostar calculates the inertial matrix as per theory described in previous section.

The hydrostatic stiffness matrix is also computed by Hydrostar along with damping matrix. Damping due to radiation is calculated by Hydrostar in radiation computation. However the non-linear damping coefficients are not calculated by the software. These are the fluid viscosity, lift damping and part by appendages on roll damping which are generally 40-70% of total

radiation damping. Most of the vessels in the database as discussed in sections before are having appendages and are not modelled because of the complexity of structure. For the purpose of study linear damping in percentage of critical damping is mostly used. This is because it is the easiest way for calculation and the one that need less computational effort. A value of 4% of critical damping is taken for calculations.

For the calculation the centre of gravity is considered as reference point and the radius of gyration is regarded as 35% of the beam. As the vessel is operating in restricted water in coastal area the water density is taken as  $1.025\text{t/m}^3$ .

#### ***7.2.5. Construction of transfer functions***

All vessels have different motion characteristics making them respond and move differently in the same sea state. The results from motion computations are the constructed transfer functions that transfers a sea state into a function that shows how the ship responds to that particular sea state. Every ship has its own unique RAO. RAO represents a linear approximation of the frequency response of the ship motion in regular waves. Here the response of the ship is evaluated in frequency domain and end result sought is to check ship performance with prescribed limit in statistical terms of occurrence of once in a life time or in  $10^{-8}$  cycles. Having these responses one can combine them with the sea spectrum to get the power spectrum of the motion components of the ship and thus ultimately long term response of the vessel in all motion components of the ship; surge, sway, heave, roll, pitch and yaw.

### **7.3. VISUAL BASIC FOR APPLICATION**

Visual Basic for application is an event-driven programming language. It allows building user defined functions and automating process. It is used in many cases where it manipulates interface features such as menus and toolbars and working with custom user form dialogue boxes. However, VBA code normally runs within a host application and is not a standalone program. In our case we use Microsoft Excel as the host application.

VBA program can solve the repetitive work and can perform tasks and accomplish a great deal of work and is powerful language that can use to extend Microsoft Excel. The great power of the program is that nearly every program operation that is performed by the input hardware's can be automated by using VBA. Further it can be done once with VBA, it can be done easily many more times.

The VBA in the thesis is used to extract data from software ARGOS in terms of GZ curve and to calculate the weather criterion of each vessels automatically. This means that the areas under the graphs and safety clearances for each vessels are calculated by the software individually and is plotted in excel sheets for further calculation.



## 8. SIMPLIFIED FORMULAS FOR LONGTERM RESPONSE PREDICTION

In order to obtain distributions of responses of ships in its lifecycle, the need of probability distribution of service dependent parameters is important. As stated above wave statistics is an excellent representation of probability of sea states. These are actual real life observations done with a period of time. Still with the given details one cannot do a direct calculation of appropriate design value of response because of the complexity of dynamic interaction between vessel and waves. Usually the components for the safe operation of vessels are designed such that, the probability of design response exceeding these values to  $10^{-8}$  per life time of the vessel.

The main step of the research here is the development of simplified formula allowing prediction of long term wave induced responses to be used for development of upgraded class rules. These upgraded class rules are applicable to river sea vessels for the intact stability weather criterion. This was done in two steps. One by using direct simulations conducted on typical inland vessels and second by cross checking the applicability of these new formulas to existing vessels. Here, in this section, the hydrodynamic simulation for establishing criterion in terms of simplified formulation will be done. Simulation of navigation condition followed by seakeeping analysis using potential theory software will be done to achieve this objective.

### 8.1. Long term response

Seakeeping analysis generally involves assessing the extreme response of the vessels. Numerous methods to evaluate seakeeping of vessels can be found from literature. The extreme values depend on the number of members involved in the derived spectral family.

From the Fig. 25 the relevant roll frequency curve for a sample vessel can be seen. This is RAO of roll motion in frequency domain and at different headings ranging from 0 to 180° at steps of 10° is given in figure below. It should be noted that the maximum roll angle will be obtained in beam seas. The resonance of the vessel in roll motion in beam seas is at 1.25Hz.

All results available in previous step was in form of response amplitude operators in frequency domain. But for interpretation, this doesn't give any meaning as response amplitude operator of a vessel is the vessels characteristics. So to obtain a meaningful interpretation of the motion characteristics the results have to be combined with wave climate and motion criteria. With help of JONSAWP spectrum a short term analysis is performed. The estimation of risk function on basis of random event is carried out. The formulation of JONSWAP introduced were linked

to  $H_s$  and  $T_p$  of that sea states. So long term distribution is obtained by cumulating the results from short term analysis in order to obtain an extreme value at probability of exceedance of  $10^{-8}$  for local motions.

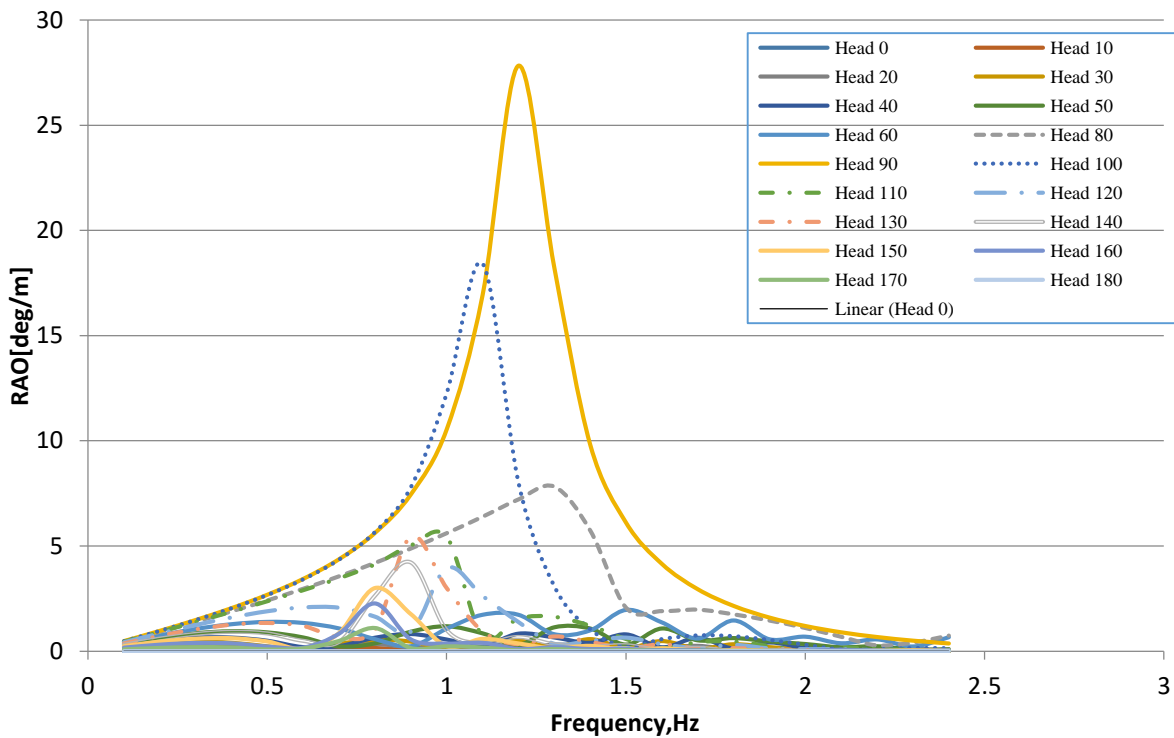


Figure 25 – RAO of sample vessel

The aim here should be to develop techniques of predicting the roll angle of the vessel along with defining the wave elevation a ship will experience at the given navigational notation. If this is achieved it will enable the ship designer to eliminate unsatisfactory and unsafe ships at early stage in design process.

Now we shall see the comparison of responses between the two areas considered. The Fig. 26 and Fig. 27 illustrates the comparison between the vessel response in terms of heave acceleration and roll amplitude. We can see the similarities in both the graphs. This can be attributed to the fact that both navigation areas studied has more or less same scatter diagram envelop and thus vessels response obtained for two navigation zone are very close as emphasized. The vessels which is having length between 40m and 35m has higher accelerations and angle of rolls as seen in the Fig. 27

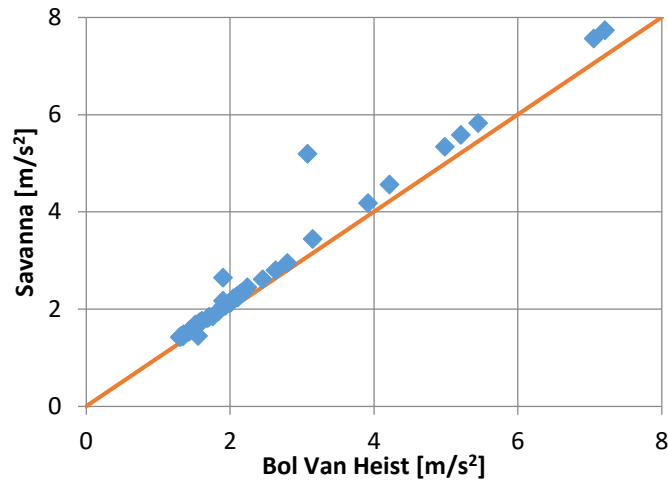


Figure 26 – Comparison of heave acceleration

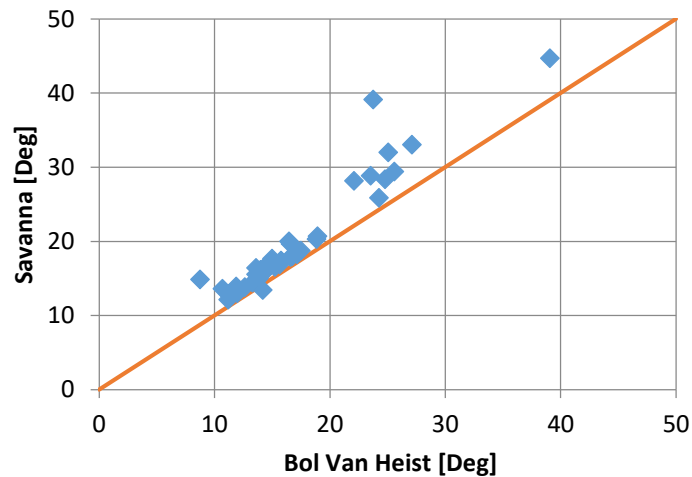


Figure 27 – Comparison of roll amplitude

## 8.2. Development of simplified formulas

In order to predict the stability of a vessel, the roll angle and relative wave elevation plays an important role as discussed. The accurate prediction thus depends on the calculation of hydrodynamic coefficient matrices viz, added mass, diffraction and radiation damping matrices. Calculating these values with the help of advanced tools like boundary layer methods and finite element theory can be expensive and time consuming. Thus a simple formulation for predicting these values with consideration of shallow water effects and influence of various frequencies is required for the quick analysis of body responses. It should be also noted inland navigational vessels are usually subjected to significant wave height up to 1.2m and thus these vessels doesn't require to consider the weather criterion and thus usually the residual stability of these vessels are not evaluated properly. For this a proper guidance has to be set to understand roll

angle estimation when the vessel is subjected to corresponding navigation notation along with wave elevation.

### 8.2.1. Roll amplitude

From literature we have formulations to calculate the extreme value of roll amplitude for sea going vessels as seen in chapter 1. Simple way to apply these formulations for River Sea vessels will be to modify these formulations with the help of sea keeping analysis of existing inland vessels. The amplitude of the vessel has a direct influence on the navigation notation of the vessel and to build a simplified formula, the added mass coefficient induced in roll angle has to be also formulated.

In most mathematical models only environmental effects are considered, mainly waves. Now the sample vessels are subjected to numerical simulations with sea state described by JONSWAP spectrum with significant wave height of its navigation notation. When calculating the lifetime probability, a great number of possible situations has to be analysed by calculating all short term probability. The number of situations considered might be considerably reduced because in reality the majority of situations considered has a low probability of capsizing. In simple terms the angle of roll of vessels obtained after long term analysis will be much lower than what is obtained as response amplitude operator. Now the extreme value of roll amplitude, in radian is predicted by Eq. 38

$$A_R = H_W \left( \sqrt{\frac{GM}{\delta}} + 0.9 \right) \frac{T_1^{6.3}}{B \sqrt[3]{\Delta}} \quad (38)$$

Here GM is the distance in m, from the vessel's centre of gravity to transverse metacentre for the loading considered,  $T_1$  is the draught associated with each cargo and ballast distribution, B is the breadth of the vessel and  $\Delta$  is the vessels displacement. The wave parameter  $H_w$  for roll motion is given by the Eqn. 39

$$H_W = \frac{n}{1.7} \quad (39)$$

A plot is then done between the results of long term response from Hydrostar in terms of extreme values of roll amplitude and thus the accuracy of developed prediction formula in case of roll amplitude can be observed from Belgian coast and American coast. It can be seen that the values of roll amplitude predicted by the formulation holds good for both the navigation ranges from Fig. 28 - 29.

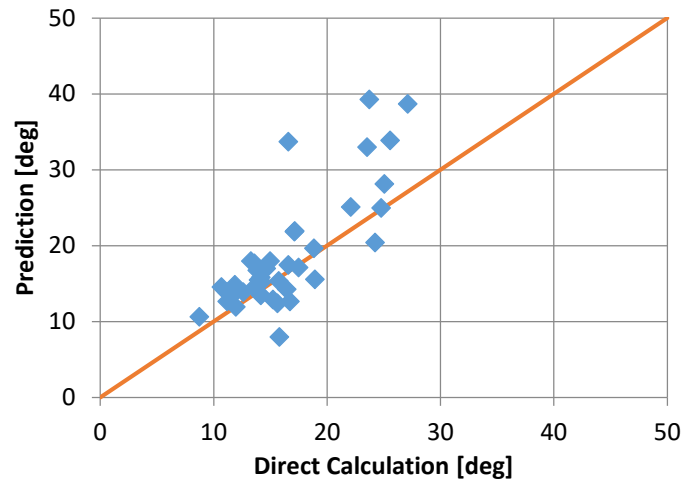


Figure 28 – Roll amplitude- prediction vs. direct calculation at Belgium Coast

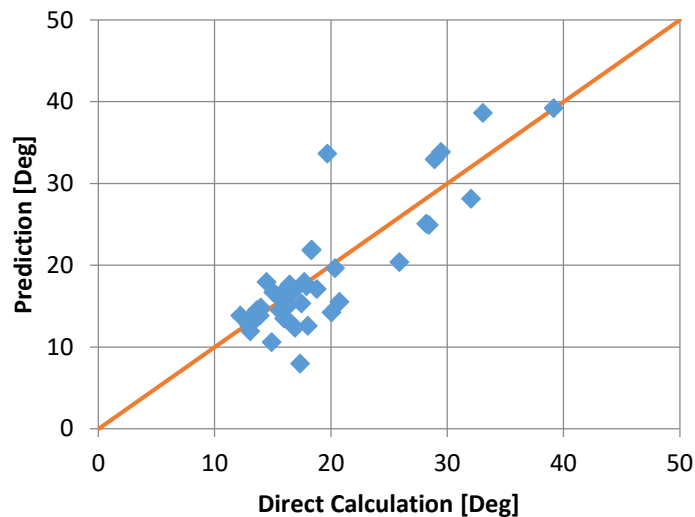


Figure 29 – Roll amplitude- prediction vs. direct calculation at US Coast

### 8.2.2. *Relative wave elevation*

For assessing the seakeeping qualities of ships the important factors includes deck wetness, slamming and propeller emergence. Statutory rules in most of the coastal areas include this as the probability of their occurrence as seen in the first section. The occurrence of the above mentioned events is directly governed by so called “Relative wave elevation”, which is the measure of vertical motion of a ship with respect to undulating free surface motion.

Bottom slamming is considered for many years as a damage to ship. This phenomenon occurs when bow of the ship emerges out of the water and subsequently submerge into water. This action produces large amount of forces on the ships bottom for a short time duration. These impulsive force can cause severe damage to the bottom and can introduce whipping on the

structure. So in order to check the probability of slamming per a minimum draught at most forward point of keel should be set. Now the extreme value of relative wave elevation at reference value  $h_2$  calculated for  $x=L$ ,  $h_{2,FE}$  is given by the Eqn. 40.

$$h_{2,FE} = H_W \frac{12}{\sqrt[3]{L}} \quad (40)$$

Here  $L$  is the length of the ship and the wave parameter  $H_w$  for relative wave elevation is given by Eqn. 41.

$$H_W = \frac{n}{1.7} \quad (417)$$

Now a plot is done between the predicted values and is compared with the values obtained by the seakeeping analysis. This can be seen from the Fig. 30

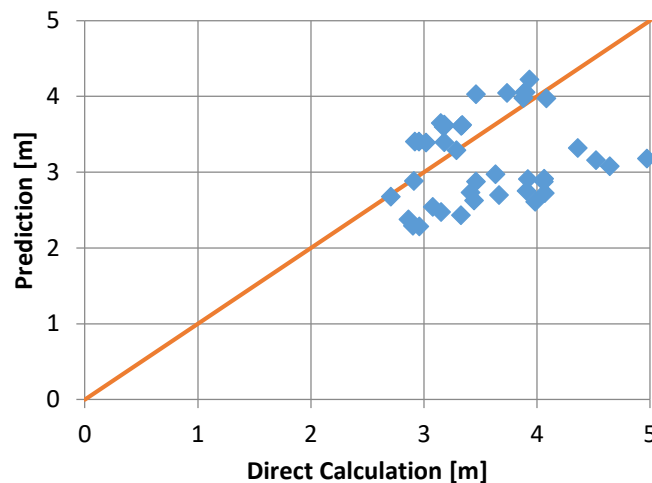


Figure 30 – Slamming Criteria- prediction vs. direct calculation

Hull integrity of the vessel is necessary as water ingress to hull can significantly reduce the stability of the vessels and can cause damage to payload. These can be expressed by limiting lowest non-weather tight openings, the freeboard and angle of roll. This essentially solves the green water shipping in to hull.

For different frequency responses these can be different. It can be seen that for long waves i.e. at low frequency the wave elevation with respect to ship will be less as ship moves in unison with vertical motion of the free surface directly below the hull points. Thus at low frequency the relative wave elevation will be zero for this frequency of wave. But for instance when a large ship is moving in small waves, there is no motion of the ship, but the relative motion of ship would be negative of the wave motion. Given the wave spectrum and response amplitude operator of the ships at various frequencies one can compute the response spectra.

When a ship is advancing in waves, the mean freeboard may be changed by several effects including sinkage, trim and wave profile due to forward speed. This can be coupled by the shift of oscillatory motions of the ship and waves. The extreme value of relative wave elevation in inclined condition  $h_2$  at different positions along the vessel are predicted by the formulas Eqn. 42 – 43 and are compared with the results obtained from the potential solver. The agreement for freeboard is generally satisfactory for the ships in database. Part of the discrepancy which can be seen is caused by the unusual shapes of the vessels. They have a low L/B ratio compared to other vessels in database. These plots can be seen from Fig 31 – 37.

$$0 \leq x \leq 0.75L \quad h_{2,FC} = H_W \left[ \left( 0.63 - \frac{2.5L}{1000} \right) + (BT_1)^{0.14} \right] \quad (42)$$

$$0.75L < x < L \quad h_2 = h_{2,FC} + \frac{h_{2,FE} - h_{2,FC}}{0.25} \left( \frac{x}{L} - 0.75 \right) \quad (43)$$

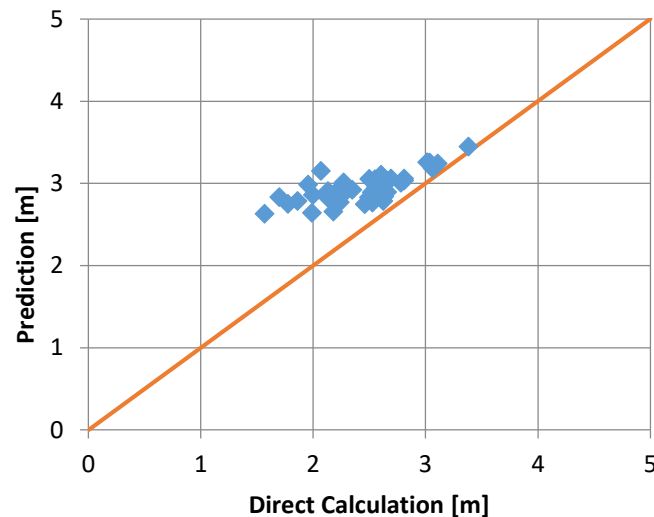


Figure 31 – Relative wave elevation- prediction vs. direct calculation at Aft-Star board side

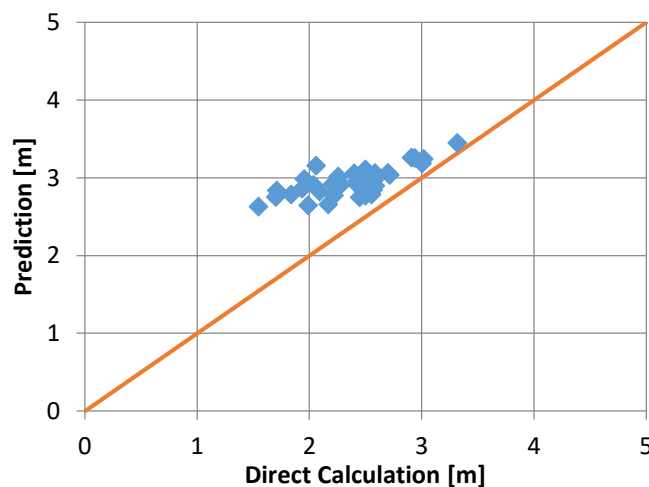


Figure 32 – Relative wave elevation- prediction vs. direct calculation at Aft-Port side

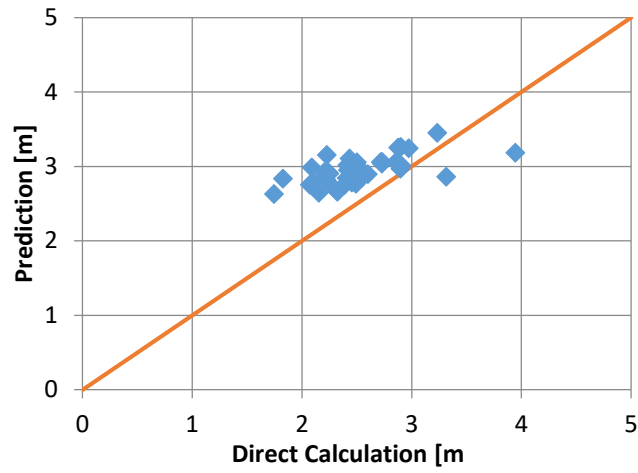


Figure 33 – Relative wave elevation-prediction vs. direct at Midship-Starboard side

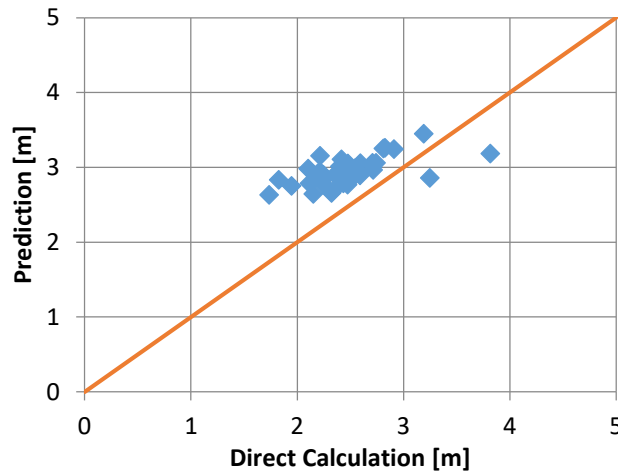


Figure 34 – Relative wave elevation-prediction vs. direct at Midship-Port side

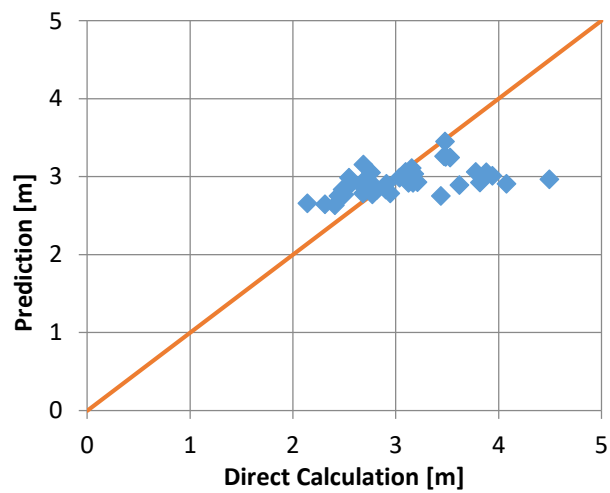


Figure 35 – Relative wave elevation-prediction vs. direct at fore shoulder-STBD side



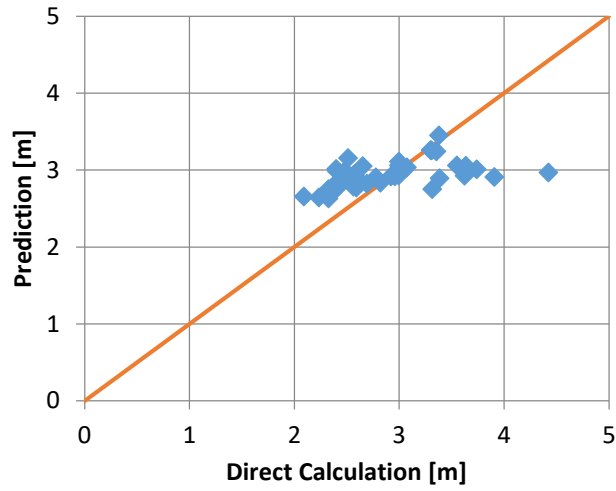


Figure 36 – Relative wave elevation-prediction vs. direct at fore shoulder-Port side

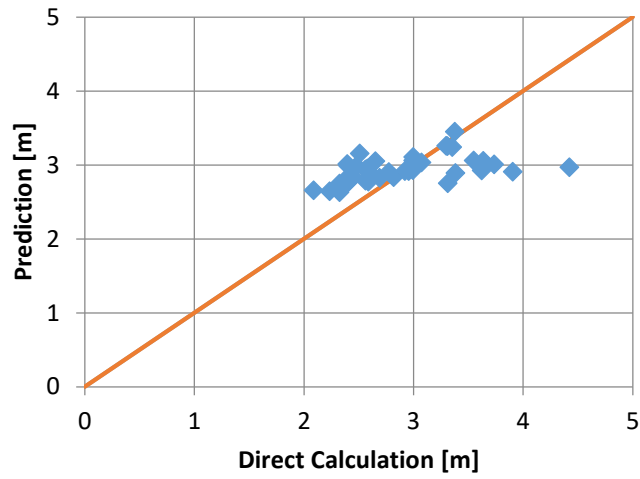


Figure 37 – Relative wave elevation-prediction vs. direct at fore peak

## 9. EVALUATION OF VESSEL STABILITY OF EXISTING VESSELS

### 9.1. Adequate intact stability design criteria

We have already established different parameters to evaluate the stability of the vessels. Also for seagoing vessels we have international code on intact stability set out in IMO resolution MSC.267 (85). Now assessing the vessel stability 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.

- GZ curve area: The area under the righting lever curve (GZ curve) as shown in Fig. 38, shall not be less than 0,055 m.rad up to  $\theta = 30^\circ$  angle of heel and not less than 0,09 m.rad up to  $\theta = 40^\circ$  or the angle of down-flooding  $\theta_f$ . Additionally, the area under the righting lever curve (GZ curve) between the angles of heel of  $30^\circ$  and  $40^\circ$  or between  $30^\circ$  and  $\theta_f$ , if  $\theta_f$  is less than  $40^\circ$ , shall not be less than 0.03 m.rad. In case that the angle of down-flooding  $\theta_f$  is less than  $30^\circ$ , the area under the righting lever curve (GZ curve) shall not be less than 0,09 m.rad up to  $\theta_f$ .
- Minimum Righting lever: The righting lever GZ shall be at least 0.2m at an angle of heel equal to or greater than  $\min(30^\circ, \theta_f)$
- Angle of maximum righting lever: The maximum righting lever shall occur at an angle of heel not less than  $\min(25^\circ, \theta_f)$ .
- Angle of down-flooding: The angle of down flooding,  $\theta_f$  shall not be less than  $17^\circ$
- Initial metacentric height: The initial metacentric height  $GM_0$  is not to be less than 0.15m.

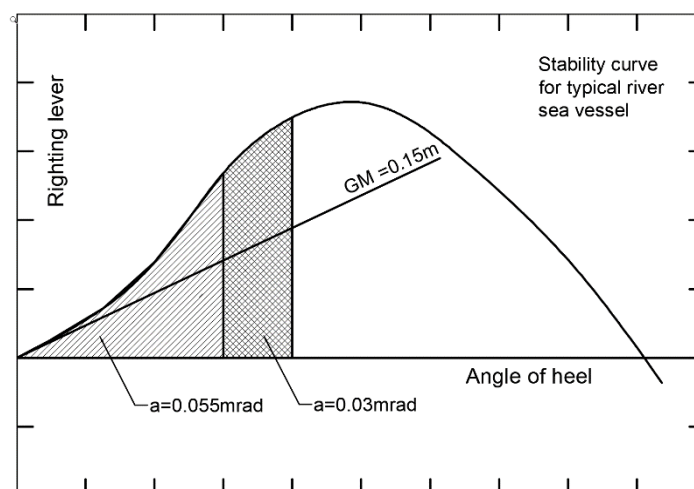


Figure 38 – GZ curve

For the analysis the vessels are grouped into three categories based on their navigation notation, i.e.. IN (0.6), IN (1.2) and IN (1.2<x<2). A range of navigation IN(x) is assigned to a vessel having a structure scantlings and other design deemed suitable including vessel stability to navigate on stretches of water on which maximum significant wave height is x, in meters which can develop in estuaries and restricted maritime stretches of water. Also there are two cases to consider for the evaluation of stability (i) fully loaded departure and (ii) lightship.

### 9.1.1. Design criteria at navigation notation IN(0.6)

The vessels are usually least stable when they are fully loaded. When the vessel departs from the port, fuel oil and fresh water tanks are full and thus the vessel will be at its design draft. 39% of the vessel in navigation notation passes the intact stability criteria and a detail analysis on each criteria is given in the table. 6 for the vessels assigned to IN (0.6) in fully loaded departure. Higher percentage of vessels failing is given highlighted with dark shades depending upon their values.

Table 6. Percentage of vessels failing the criteria in fully loaded condition at IN (0.6)

SI #	Estuary Plus Rule	All Vessels	Barge	Container	Misc	Passenger vessels	Tanker
1.	Areas [0 30]	21%	33%	67%	0%	15%	50%
2.	Areas [0 40]	4%	0%	0%	0%	5%	0%
3.	Areas [30 40]	7%	0%	0%	33%	5%	25%
4.	Min. righting lever	4%	17%	33%	0%	0%	0%
5.	Angle of max. righting lever	30%	0%	0%	0%	41%	0%
6.	Angle of down-flooding	23%	67%	33%	0%	17%	25%
7.	Initial metacentric height	0%	0%	0%	0%	0%	0%

For container ships the area criteria from 0° to 30° is crucial because the stability in fully loaded scenario has low GZ values. This can be attributed to the fact that the sample ships has 2 or 3 tiers of containers stacked on the deck increasing the KG of the vessel. The tankers in database has a low down flooding angle and thus doesn't satisfy the area criterion.

It should be noted that the angle of maximum righting lever criteria for passenger vessel fails in case of 40% of the vessels. The rules used for passenger vessel i.e., NR 217 Nov 2014 in Pt D Ch. 1 Sec 2 stipulates that the maximum righting lever arm shall occur at a list angle  $\varphi_{\max} \geq (\varphi_{\text{nom}} + 3)$  m where  $\varphi_{\text{nom}}$  is the maximum list angle which shall not be in excess of the value of  $12^\circ$  and this can be the reason behind vessels failing maximum righting lever criteria. The figure 39 illustrates the scatter plots of down-flooding angles for different types of vessel. It can be seen that the tankers, barge and container vessels has a low down-flooding as compared to passenger vessels. Inlands cargo vessels usually doesn't operate in harsh climate and thus the requirement on down-flooding angle was moderate.

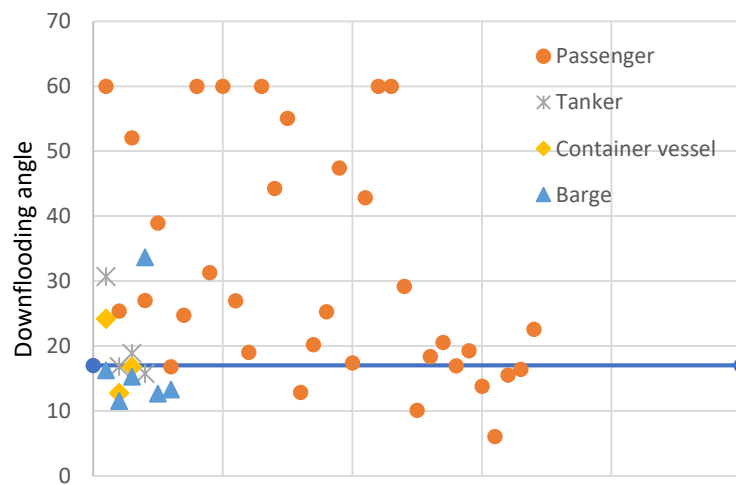


Figure 39 – Range of down flooding angles

So for existing vessels to pass the new criteria will be challenging as the down-flooding angle and corresponding unprotected openings is most vulnerable criteria. In the fig. 40 the relationship between unprotected openings and minimum safety clearance criteria imposed for cargo vessels is shown. Here passenger vessels as they have usually openings well above safety clearance (as per previous rule criteria) is not considered. The vessels which doesn't pass the criteria have non-watertight openings at deck height. These are usually doors to accommodation or deck house or unprotected opening to hull in case of barges. While a simple modification can be done for the latter case by introducing hatch coamings, the former one cannot be dealt that easily.

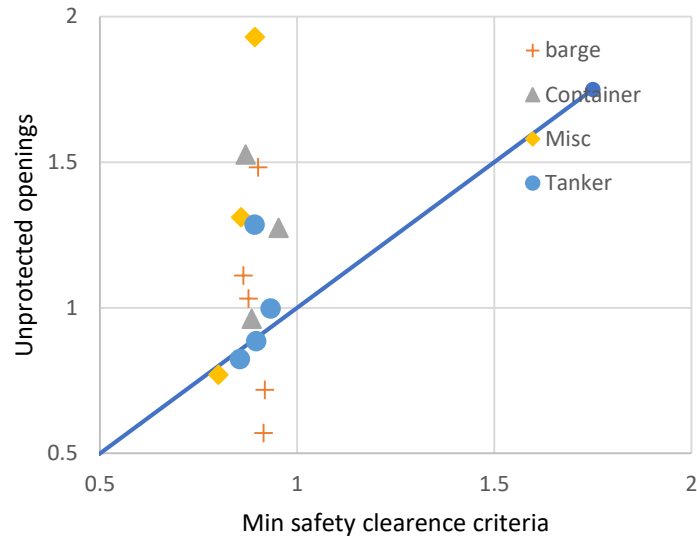


Figure 40 – Range of down flooding angles

In light ship condition of vessels, the design criteria in terms of GZ areas are easy to satisfy while it can be seen that the angle of maximum righting lever is not. The table 7 shows a detail analysis on each criteria for the vessels assigned to IN (0.6) in light ship condition. Higher percentage of vessels failing is highlighted with dark shades depending upon their values. 47% of vessels fails the design criterion where 33% of vessels fails angle of maximum righting lever.

Table 7. Percentage of vessels failing the criteria in Light ship condition at IN (0.6)

SI #	Rule	All Vessels	Barge	Container	Misc	Passenger vessels	Tanker
1.	Areas [0 30]	5%	0%	33%	0%	5%	0%
2.	Areas [0 40]	4%	0%	0%	0%	5%	0%
3.	Areas [30 40]	5%	0%	0%	33%	5%	0%
4.	Min. righting lever	0%	0%	0%	0%	0%	0%
5.	Angle of max. righting lever	33%	0%	0%	0%	44%	25%
6.	Angle of down-flooding	9%	17%	33%	0%	7%	0%
7.	Initial metacentric height	0%	0%	0%	0%	0%	0%

### 9.1.2. Design criteria at navigation notation IN(1.2)

The vessels operating at significant wave height 1.2m is not considered to have estuary plus navigation notation. But for the purpose of the study the vessels operating at IN (1.2) is considered and severity of the design criteria when applied to vessels with 1.2 navigation notation is analysed in this section. The table 8 shows a detail analysis on each criteria for the vessels assigned. 47% of the vessels passes the design criteria while most of the vessels failed down-flooding angle and thus the area criteria. The vessels failing the area criteria had low down-flooding angle and thus the area criteria used to evaluate the stability under the righting lever curve is 0.09m.rad up to down-flooding angle. The physical value of this area was too low as the down-flooding area was less. This can be seen especially in case of container vessel- all container vessels having down-flooding angle less than 17° has failed the area criteria.

Table 8. Percentage of vessels failing the criteria in fully loaded condition at IN (1.2)

	All vessels	Barges	Container Vessel	Passenger vessel	tanker	Misc
Areas [0 30]	27%	33%	30%	6%	20%	75%
Areas [0 40]	0%	0%	0%	0%	0%	25%
Areas [30 40]	2%	8%	0%	0%	0%	0%
GZ Max	6%	0%	0%	0%	40%	0%
angle of GZmax	18%	25%	0%	28%	0%	25%
GM initial	0%	0%	0%	0%	0%	25%
Downflooding angle	27%	33%	30%	11%	20%	0%

The same will be analysed for light ship scenario. The table 9 shows a detail analysis on each criteria for the vessels assigned to IN (0.6) in light ship condition. The only criteria which fails in this case is the angle of maximum righting lever. As the vessel is light the GM increases and thus the area under the curve.

Table 9. Percentage of vessels failing the criteria in Light ship condition at IN (0.6)

SI #		All vessels	Barges	Container Vessel	Passenger vessel	tanker	Misc
1.	Areas [0 30]	0%	0%	0%	0%	0%	0%
2.	Areas [0 40]	0%	0%	0%	6%	0%	0%
3.	Areas [30 40]	2%	0%	0%	0%	0%	0%
4.	GZ Max	0%	0%	0%	0%	0%	0%
5.	angle of GZmax	28%	45%	10%	25%	40%	20%
6.	GM initial	0%	0%	0%	0%	0%	0%
7.	Downflooding ang.	0%	0%	0%	0%	0%	0%

Now check on value of angle of maximum GZ criteria shows that most of the vessels has failed with small differences. This can be illustrated from the fig 41.

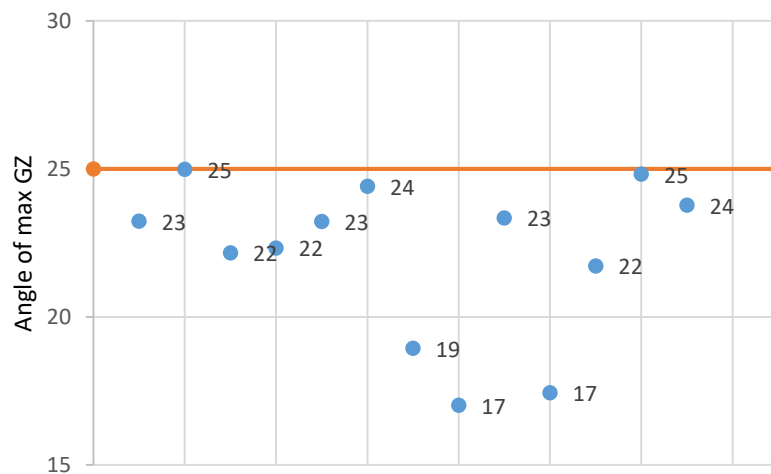


Figure 41 – Angle of GZ max values

### 9.1.3. Design criteria at navigation notation $IN(x>1.2)$

The Design criteria of vessels with navigation notation greater than 1.2 is grouped together and analysed. This can be seen from table 10. Here two container vessels operating at navigation

notation IN (1.7), one container vessel, a barge and tanker operating at IN (2) are considered. Also in database there were ro-ro ships operating in unrestricted waters

Table 10. Vessel design criteria check at full load condition Light ship condition at IN (0.6)

Ship name		Vessel 01	Vessel 02	Vessel 03	Vessel 04	Vessel 05	Vessel 06	Vessel 07
Type	Units	Container Vessel	Container Vessel	Barge	Container Vessel	tanker	RO-RO CARGO SHIP	RO-RO CARGO SHIP
Nav not	m	1.70	1.70	2.00	2.00	2.00	Unrestricted	Unrestricted
LBP	m	134.0	134.3	20.0	135.0	65.5	58.0	79.0
Breadth	m	14.5	14.5	7.5	14.5	16.0	13.0	11.4
Depth	m	5.3	5.7	3.2	5.7	3.9	3.0	4.7
Draft	m	3.1	3.5	1.1	1.1	3.6	1.7	3.3
Displacement	t	5393	6199	132	1800	3034	1053	2776
KG	m	4.15	5.56	3.29	3.47	4.62	4.29	2.15
Unprot. weath-tight open.	m	3.31	3.71	2.69	6.04	5.22	1.32	1.21
Areas [0 30]	m <sup>2</sup>	0.37	0.20	0.20	1.24	0.10	0.09	0.09
Areas [0 40]	m <sup>2</sup>	0.00	0.00	0.29	1.77	0.00	0.00	0.00
Areas [30 40]	m <sup>2</sup>	0.00	0.00	0.09	0.53	0.00	0.00	0.00
GZ Max	m	1.54	0.77	0.63	3.17	0.53	0.93	0.71
angle of GZmax	deg	27	30	25	26	20	11	14
GM initial	m	3.21	1.39	2.06	13.54	2.88	4.83	2.86

## 9.2. Weather Criterion

The ability of a vessel to withstand the combined effects of beam wind and rolling shall be demonstrated here. This can be demonstrated by the following criterion.

- The vessel is subjected to a steady wind pressure acting perpendicular to the vessel's centre line which results in a steady wind heeling lever ( $l_{wl}$ ) as shown in Fig. 42;



- From the resultant angle of equilibrium ( $\theta_0$ ), the vessel is assumed to roll owing to wave action to an angle of roll ( $\theta_1$ ) to windward. The angle of heel under action of steady wind ( $\theta_0$ ) should not exceed  $16^\circ$  or 80% of the angle of deck edge immersion, whichever is less;
- The vessel is then subjected to a gust wind pressure which results in a gust wind heeling lever ( $l_{w2}$ ); and
- Under these circumstances, area "b" shall be equal to or greater than area "a" as indicated in Fig 42.

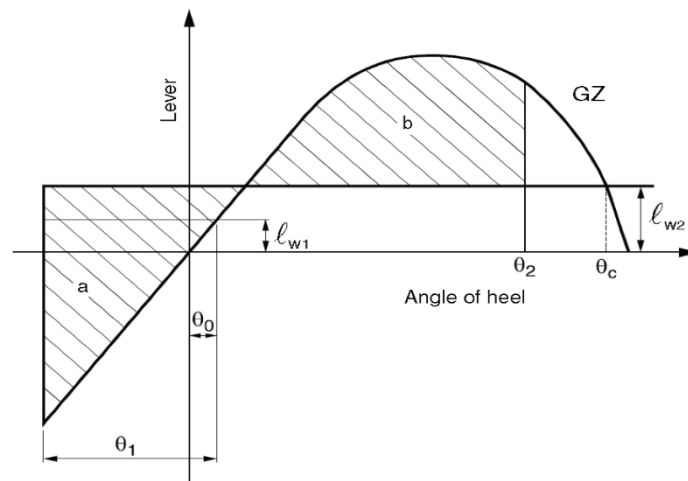


Figure 42 – Severe wind an rolling criteria

### 9.2.1. Weather criterion of vessels at IN(0.6)

At fully loaded condition and lightship condition the weather criteria for the vessels are checked with navigation notation IN (0.6) for the applicability of the IMO criterion. It can be seen that 9% of vessels have failed the criterion in fully loaded condition while 5% of the vessels has failed lightship condition - but this can be attributed to the fact that all these vessels has roll angle estimated using Eq. 34 which is applicable only to vessels with breadth less than 35m. So risk analysis has to be performed for individual vessels for operation which is beyond the scope of study.

### 9.2.2. Weather criterion of vessels at IN(1.2)

With navigation notation IN (1.2) in fully loaded departure, 39% of the vessels failed the new criterion. The Fig. 43 shows the severity of the condition when applied to the vessels.

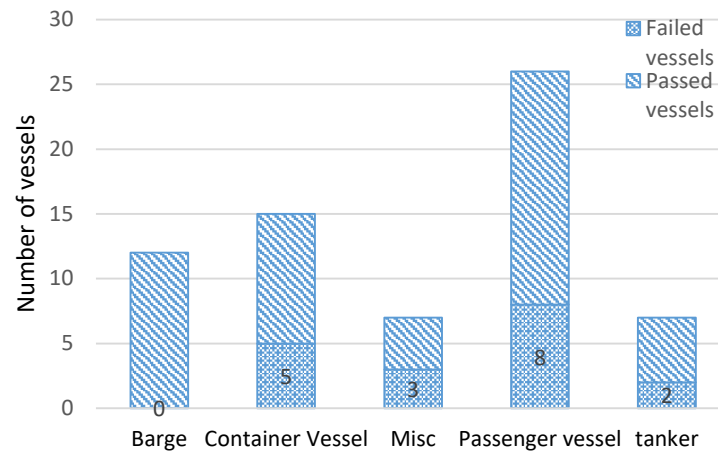


Figure 43 – Number of vessels failing criteria

It can be seen that barges in the data base has significant GZ values and heeling wind lever or lost GZ area percentage is considerably low. This can be illustrated from the Fig. 44. Here the value of lost area due to wind arm in percentage of the total GZ area is plotted. The wind lateral area and area arm for the vessels are considerably low along with low KG value and this can be the reason for this trend in the database.

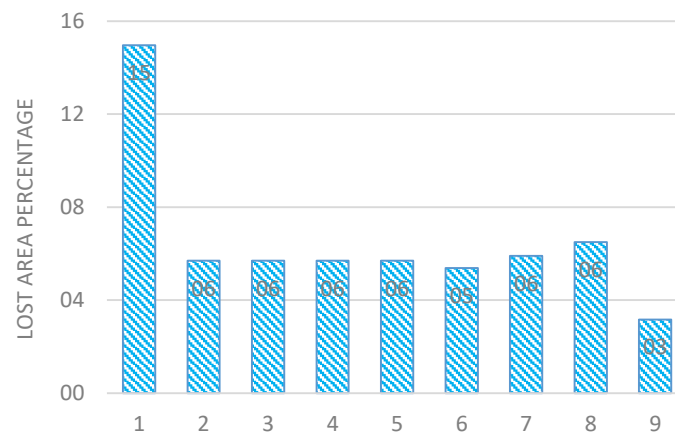


Figure 44 – Lost area percentage

In light ship scenario 9% of the vessels fails the weather criterion out of which 2 where passenger vessels, 1 cargo ship and a dredger.

### 9.2.3. Weather criterion of vessels at $IN(x>1.2)$

The table 11 below shows the weather criterion checked for vessels with navigation notation more than 1.2. The last three rows of the table shows the check for weather criterion and the vessels which failed the criterion has been highlighted using dark colours. There are three container vessels of which two are assigned 1.7 navigation notation while the other one at 2.0 and others are tanker and a barge. It can be seen that except the barge all vessels are well within

range, the barge which failed the criterion has a length 20m within which application of Eqn. 34, the roll angle estimation can be misleading.

Table 11. Vessel design criteria check at full load condition Light ship condition at IN (0.6)

Ship name	Units	Vessel 01	Vessel 02	Vessel 03	Vessel 04	Vessel 05	
Type		Container Vessel	Tanker	Barge	Container Vessel	Container Vessel	
Nav not	m	2.00	2.00	2.00	1.70	1.70	
LBP	m	135.00	65.50	20.00	133.98	134.26	
Breadth	m	14.50	16.00	7.50	14.50	14.50	
Depth	m	5.70	3.85	3.20	5.30	5.70	
Draft	m	1.11	3.64	1.11	3.07	3.45	
Displacement	t	1800	3033	131.	5392	6198	
KG	deg	3.47	4.62	3.29	4.15	5.56	
GM initial	m	13.54	2.88	2.06	3.21	1.39	
Wind Lateral A	m <sup>2</sup>	1360.56	173.16	92.24	1248.58	1040.93	
Area Lever (z)	m	12.18	7.28	7.36	14.69	13.57	
Rolling P	s	4.85	8.12	5.42	6.87	10.15	
Lever [Lw1]		0.37	0.02	0.21	0.13	0.08	
Lever[Lw2]		0.73	0.03	0.41	0.25	0.17	
Steady wind angle	deg	3.26	1.14	14.78	4.48	5.98	
Heeling wind moment area	[%]	92.62	16.39	149.68	117.40	206.46	
Righting wind moment area	[%]	21.23	11.01	91.06	29.37	35.52	
Weather Criterion	Angle of roll	deg	8.65	13.75	28.25	9.42	8.49
	Area A	m <sup>2</sup>	15.40	3.39	24.37	5.43	2.94
	Area B	m <sup>2</sup>	132.29	5.18	1.30	14.90	7.96

Now looking at the GZ curves for the above vessels, fig. 45 shown below shows the severe wind and rolling criterion of vessel operating at 1.7 navigation notation at fully loaded and light ship condition. At fully loaded condition the influence of righting lever can be shown as lost percentage of righting area and can be estimated as 35% and thus when accounting for the

weather criterion consideration of mean wind speed along with gust wind speed to better approximate the weather criterion is to be done.

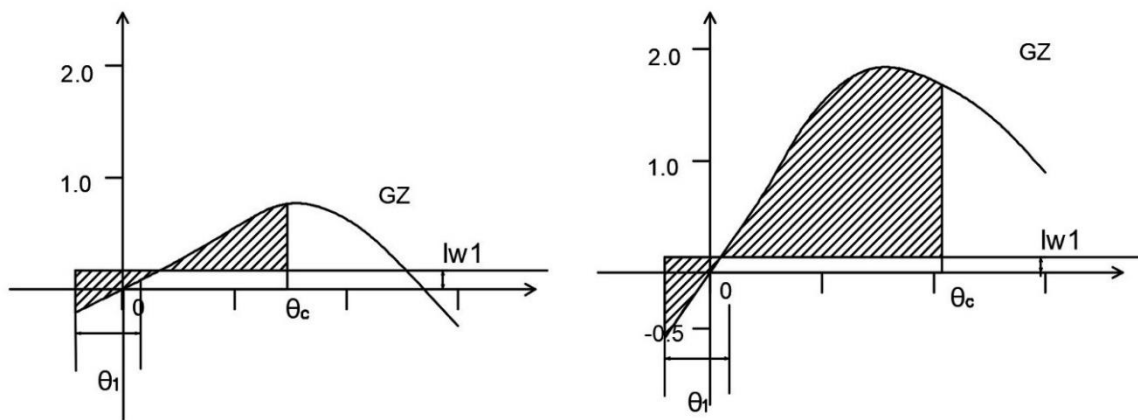


Figure 45 – Severe wind and rolling criterion for sample container vessel at IN (1.7).

### 9.3.Safety clearances

Hull integrity and safety on design of the vessel can be defined by minimum safety clearances in terms of minimum draught at the most forward point of the keel, safety clearance of lowest non-weather tight openings, minimum freeboard clearance and limitation on angle of roll.

The probability of slamming can be considered by the minimum draught required at the most forward part of the keel. It can be calculated by Relative motion of the forward part of the bow in upright condition by the formulation given in Eq. 44 and allowing a factor of safety the draught is to be such that

$$T_{min} = 1.3 h_2 \quad (44)$$

Where  $h_2$ , the reference value of relative motion in upright condition at the most forward part of the keel as explained in previous section. Applying these formulations to the inland vessels at their navigation notations is very important to see the implication of river sea vessels to susceptibility to slamming. For the purpose of the research it is assumed that the vessel has almost straight and steep stem and the most forward point of the keel is situated at 96% of the total length of the ship. Then calculation were carried out to find the relative wave motion of the vessel. The fig. 46 shows the graph for the vessels at navigation notation IN (0.6) and IN (1.2). 24% of the vessel operating at 0,6m significant wave height fails the criterion while 45% of the vessels operating at significant wave height 1.2 fails the criteria. This can be attributed to the fact that the inland vessels has usually low draft and thus failing the criteria.

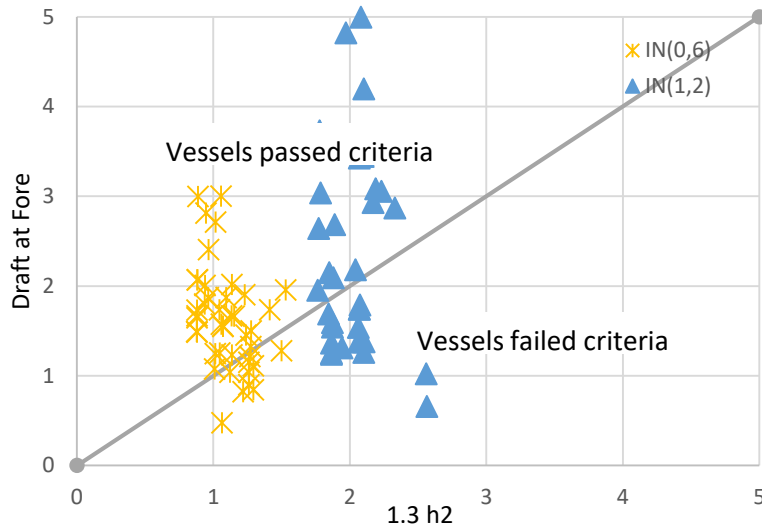


Figure 46 – Minimum draught at most forward point of keel

The safety clearance of lowest non-watertight opening is considered to be greater than  $1.5 h_2$ . This limitation is vital in the sense of water ingress into hull. The fig.47 shows the graph between unprotected weather tight opening and minimum permissible safety clearance for the vessels operating at IN (0.6) and IN (1.2). Most of the vessels operating at IN (0.6) passes while the vessels with low down-flooding angle fails the criteria. It should be noted that most of the vessels which failed criteria has non water tight opening at deck level like accommodation doors or hatches without coamings.

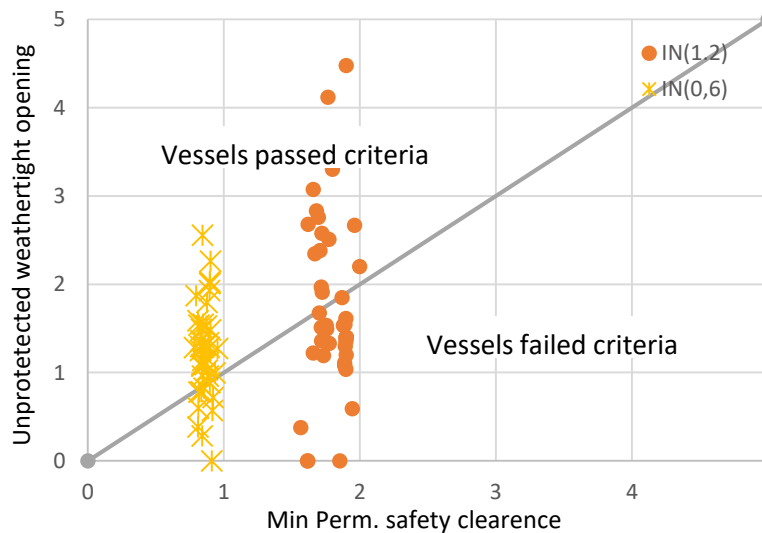


Figure 47 – Minimum Permissible safety clearance

The freeboard of the vessel is very important as it represents the residual stability of the vessel. The freeboard of the vessel is calculated by the Eqn. 45.

$$Freeboard > 1.5 h_2 - 0.95 \tag{45}$$

Now from the fig. 48 the minimum permissible freeboard vs actual freeboard of vessels for that vessel for navigation notation IN (1.2) and IN (0.6) where x is the assigned navigation condition.

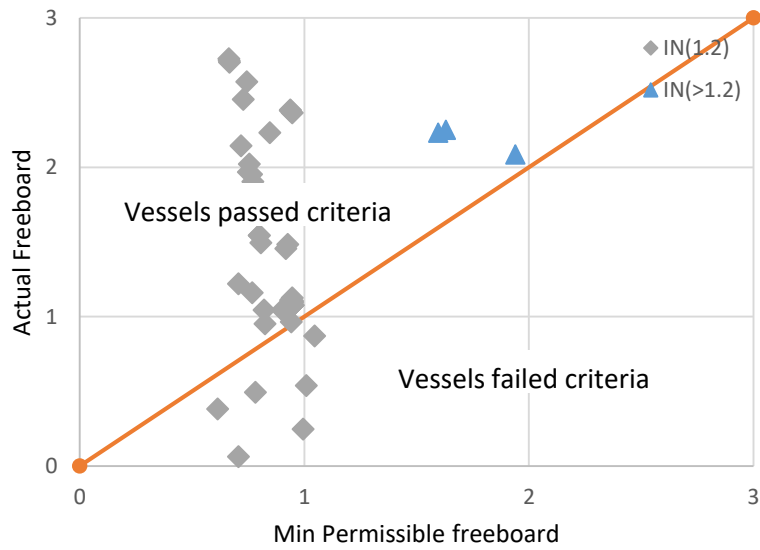


Figure 48 – Minimum freeboard

The angle of roll to windward due to wave action can be calculated by the Eqn. 46.

$$\theta_1 = \theta_R + \theta_o \tag{46}$$

Where

$$\theta_R = \frac{180}{\pi} A_R \tag{47}$$

Here  $\theta_o$  is the heel under steady wind and  $A_R$  is the roll amplitude determined according to Eqn. 48. Now the angle of roll is to be limited as follows

$$\theta_R \leq 2\theta_f/3 \tag{48}$$

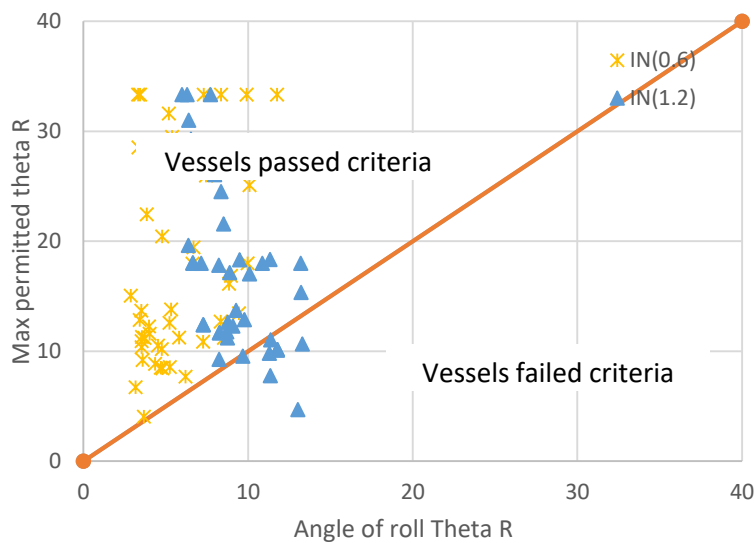


Figure 49 – Angle of roll

It should be also noted that in all cases the angle of roll  $\theta_R$  shall not exceed  $15^\circ$ . Applying this criteria for the set of vessels can be seen in the figure 49. As the formula for roll amplitude has not been verified for vessel less than 35m in length the result obtained for roll amplitude of these vessels is not used for the study and as mentioned before is to be further studied.

#### 9.4 Suitability of other developed equations

Apart from the above developed equation, to enable the ship designer to eliminate the necessity of using detailed loading condition at early design stages, an approximate formulation for finding the vessels GM, metacentric height is taken from the literature and is given by Eqn. 49

$$GM = \frac{0.95 B^2}{12 T_1 C_B} + 0.5T - KG \quad (49)$$

The above formulation was checked with the sample vessels at their two loading condition, fully loaded departure and light ship condition. The result is found satisfactory and can be inferred from the fig. 50 and fig. 51

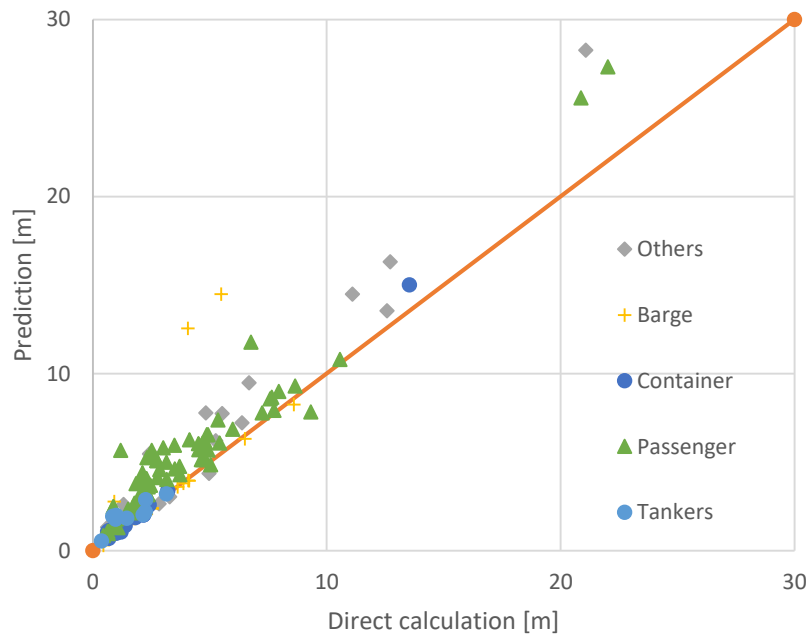


Figure 50 – Comparison of GM at fully loaded departure

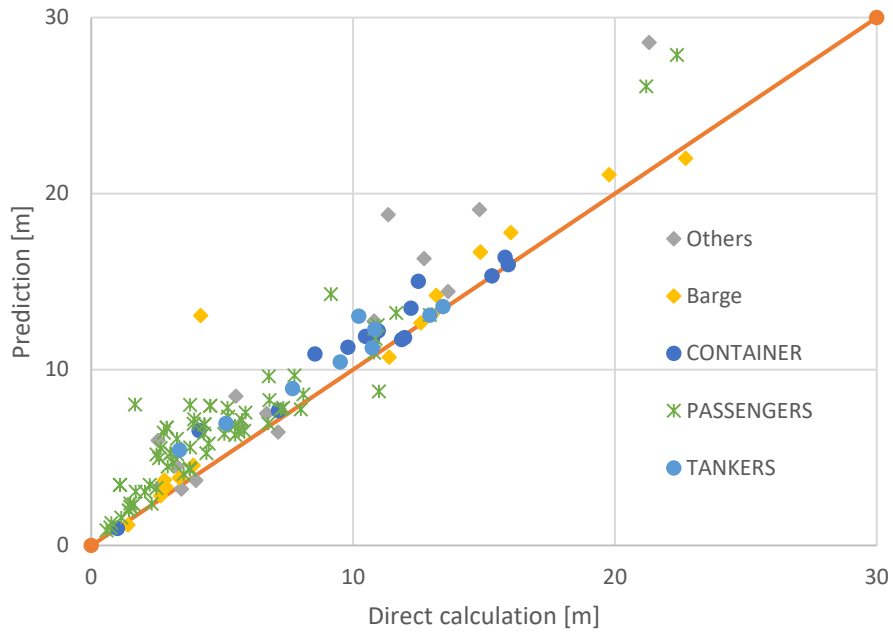


Figure 51 – Comparison of GM at Light ship condition

The values of distance in m, from the keel to the vessels centre of gravity KG when unknown may be assumed as per the following table 12 for the calculation of roll amplitude different type of vessels.

Table 12. Distance from keel to vessels centre of gravity KG

	Full Load	Light ship
<b>Others</b>	0.64 D	0.54 D
<b>Tugboat</b>	0.73 D	0.73 D
<b>Barge</b>	1.2 D	0.59 D
<b>Container</b>	0.71 D	0.54 D
<b>Passenger</b>	1.1 D	1.1 D
<b>Tanker</b>	0.64 D	0.57 D

The accuracy of developed prediction formula is shown as prediction in m and plotted against the actual KG on the loading condition at fully loaded departure and light ship condition in fig. 52 and fig. 53 respectively.



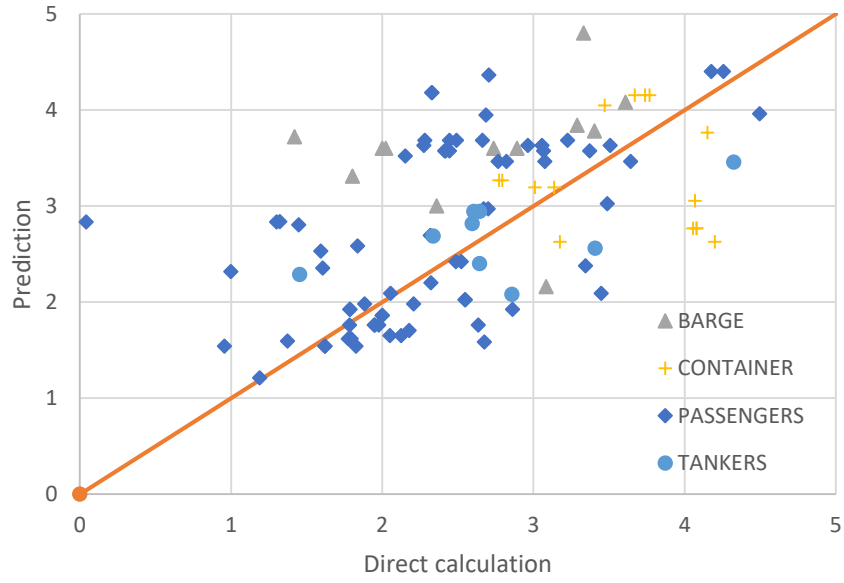


Figure 52 – Comparison of GM at fully loaded departure

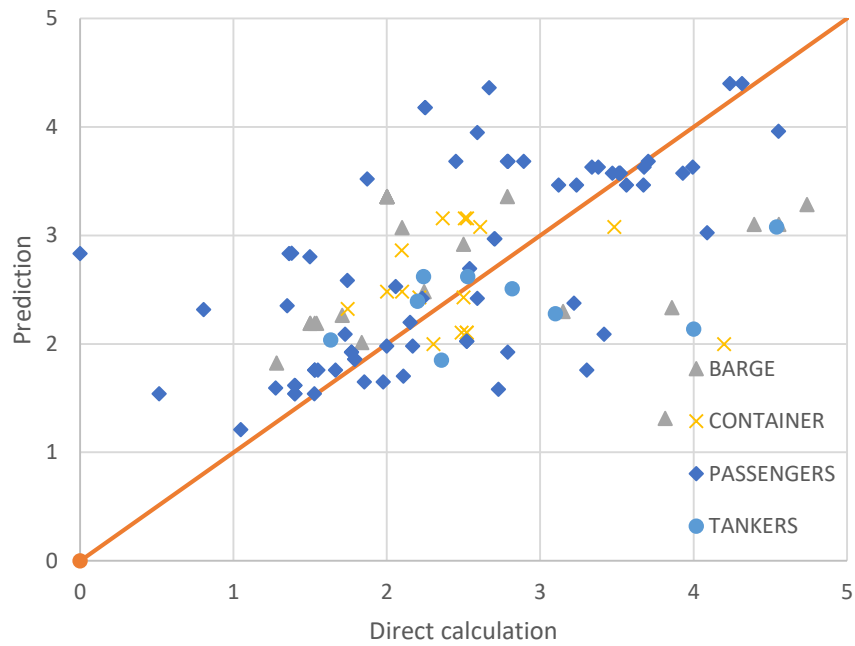


Figure 53 – Comparison of GM at fully loaded departure

## 10. CONCLUSION

Restricted navigation at sea is next step for water transport system. There is a significant increase in finding new ways to reduce the costing of the transportation system which includes the use river sea vessels. Although for a long time river-sea transport used to be a forgotten market segment we have recently been witnessing renewed, ample investment in this area, with various shipping companies ordering new river-sea ships to be built.

There is no uniform weather criterion on intact stability of the sea going inland vessel. There is an array of national, regional and international rules that contain different criteria with some exceptions made. Usually we use IMO regulation for sea going vessel for stability standards. So it is necessary to develop rules and regulation to check the suitability of the vessel by compliance with appropriate rules. This can be from recognised classification society or applicable regulatory requirements. For the development of these rules we have to do proper study of vessels operating in coastal areas and this is an iterative process which includes experiments and simulations of rare events like extreme roll and capsizing in order to assure accuracy in a statistical sense. The parameter combinations of experiments must be carefully selected in order to avoid an intolerable amount of work.

In this scenario the paper presents a short review of existing rules and regulations implemented by classification societies, statutory regulations and harbor administrations. Concentration was given to existing regulations on weather criterion which is applicable for river-sea vessels. Further through this work development of intact weather criterion applicable to river-sea vessels were done. The criterion was developed with sea-keeping analysis of 60 inland navigation vessels by the potential solver Hydrostar and verified by the stability analysis of 160 vessels to see the applicability of developed criterion.

Sea-keeping behavior is considered in two navigation areas for the study and were compared to give satisfactory results due to similarity in scatter diagram envelop. This being said the developed formulations will not be able to provide satisfactory results for vessels with unusual design or having  $L < 35\text{m}$  or vessels without bilge keel and the sea-keeping behavior of these vessels has to be specially considered for eligibility of assignment of class notation.

The weather criterion which we discussed in the thesis were based on physical modelling and was adjusted in a form of wind speed, based on casualties of capsized ships. So the stability standard has only an empirical meaning. So in order to account for parametric rolling or pure loss of stability these method were never intended to be used. Now IMO is developing an

additional set of intact stability criteria, so called “Second generation intact stability criteria” which will be finalised around 2019- so it might be become sensible to verify the rule against these criteria. The new proposed criterion has to consider the static stability and dynamic stability of the vessel.

Relatively young branch of science CFD is improving along with computational power needed for its operation. In coming years it may be possible to the implementation of seakeeping analysis and it will become efficient and use of these tools for seaworthiness will be tremendous thus rather than using empirical formulation given by rules and regulations the use of these softwares will be utilised.

Caution has to be taken while advising safety standards for ships with respect to stability and strength which can lead to loss of life or capsizing from rare event. The ship’s safety margin, by the compliance with stability criteria, is generally unknown and it still remains a concerning matter. The level of stability required for the sea going inland vessel is still yet to be determined and moreover the safety margin is strongly influenced by the ship’s dimensions. Design for safer ships, regulations, recommendations, knowledge based seamanship are the tools to improve the safety status of a ship. The ship crew and master should be given sufficient knowledge on possible outcomes of a severe situation and should be able to operate the ships even in extreme weather conditions.

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