





Article

A New Design Criterion to Improve the Intact Stability of Galician Small Fishing Vessels

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Abstract: The first technical factor involved in maritime accidents is related to the lack of intact stability. The current stability criterion, based on fixing a minimum value for each of the different static and dynamic righting arms, is not regarded as satisfactory. Correspondingly, a new criterion based on the transverse metacentric height, dynamic stability up to 70° heel, and critical wave height were considered for fishing vessels less than or equal to 24 m in length. This can be understood as an improvement on the Rahola criterion or an equivalent criterion of dead ship capsized mode, as assumed in the second-generation stability criteria. The proposed criterion, when used in a real case study on the Galician fishing grounds, achieved higher precision. The few vessels that did not comply with the proposed requirement can continue to operate in the area if the Meteorological and Oceanographic Coefficient (C_{MO}) is considered at the time we employ our criteria. As a result, their activity is limited to only a few fishing grounds where adequate weather conditions exist. Finally, the methodology developed can be easily extrapolated to other regions in the world.

Keywords: fishing vessels; stability criterion; accident; fishing grounds

1. Introduction

To minimize different types of vessel casualties, the International Maritime Organization (IMO) proposed a revision of the intact stability criterion [1–4], with adjustments made to suit the specific characteristics of each fishing ground and its unique features [5–8]. Moreover, the International Code on Intact Stability [1] suggested the adoption of a simplified criterion, highlighting the elimination of identifying the sea surface as a horizontal plane to improve the wave effect on a new stability criterion.

To develop the so-called “second-generation stability criteria” [8–11], different working groups have been established. In light of this fact, only limited results are available from the related research projects [12,13] and the Wolfson Unit of the University of Southampton, UK [14,15].

The intact stability criterion in current use was initially proposed by Rahola [16] and is mainly based on the righting arm. Rahola defined the minimum stability, with particular reference to the vessels navigating the Finnish waters. Based on this initial study by Rahola, an expert report and in-depth analysis of the condition of the cargo at the time of the sinking of the fishing vessel *Cruz II* was performed by O’Dogherty in 1969 [17,18]. The findings revealed that the present-day intact stability criterion based on the principle of the righting arm does not take the ship dimensions or the

heeling actions and the possibility of compensating for the lack of dynamic stability into consideration with an increase in the initial stability or vice versa [19,20].

IMO started a revision of the first stability criteria in 2001, focusing on the need to update the coefficients of the weather criteria [21]. This new criterion was revolutionary for that time; it involved the classification of failures into five failure modes at three different levels. When a ship does not pass level 2, the solution is to fix operational limitations or to be analyzed by level 3. It was useful to define the operational limitations of a ship in that situation [22] and impose some other limitations to be applied in other ship types, e.g., Navy ships [23]. New modeling methodologies [24] and Computational Fluid Dynamics (CFD) analysis [25] are being developed, improving ship design and selecting between different alternatives to improve ship stability due to the lack of a previous database or case studies like in CNG Ships. Nowadays, the second-generation stability criteria aim to consolidate the draft guidelines and complete the work at Ship Design and Construction SDC 7 in 2020 [26].

For the particular case of Spain, it has one of the most important fishing sectors in the European Union [27–29], possessing a fishing fleet of 335,000 GT in total, which comprises 22% of the total EU fleet. However, small fishing vessels represent 84% of the total fishing fleet of Spain, 99% of which are below 15 m in length. The average length of all the purse seiners, long-liners, gillnet ships, and small boats operating in the national fishing grounds are in the length range of under 24 m. The autonomous community of Galicia, in particular, owns 4664 such vessels [30].

On the other hand, the Spanish Commission for the Investigation of Maritime Accidents (CIAIM) [12,31] has reported that the main technical factor involved in marine casualties is the limitations on the stability of the vessels. Over the last few years, 50–60% of the accidents reported by fishermen occurred through the capsizing of the vessel due to flooding and stability loss. What is more, in 2005, attention was drawn to the fact that a greater number of fishing vessel accidents occurred during regular fishing and fishing net recovery operations rather than during poor weather conditions [32].

The different types of stability loss mentioned above cannot usually be ascribed to a single cause; most often, they are related to the vessel design [33–36] being incompatible with the real operational conditions [37,38]. From this perspective, the vessel design process includes the limitation of not changing the denominated gross tonnage (GT).

Therefore, vessel owners attempt to construct the largest possible ships while keeping within the maximum permissible GT. Therefore, the normal tendency during vessel design is to adjust the structure toward having a main deck that is as low as possible, with the vessel design including an extremely tight freeboard that can minimize the stability at large angles of heel. Later, the standards were altered to increase the total permissible GT, specifically for the main deck, in order to improve the working conditions and habitability of the crew. In practice, this step intended to increase the superstructure's dimensions (height) so that the resultant center of gravity would be raised upwards as well as the sail area of the vessel.

This initial design procedure had resulted in insufficient vessel stability, which made it critical to consider water ballast during vessel design and to minimize the freeboard and cargo capacity in the holds. Furthermore, this is the reason for storing the load on the main deck and reducing the fuel capacity of the structural tanks. This problem assumed larger proportions of weight when the vessels were operating in the distant grounds rather than in their local fishing grounds. In such cases, it was a common practice to transport extra fuel in jerry cans on the deck to utilize all of the available spaces that were considered void spaces in the vessel design process as fuel storage. Furthermore, it became customary to transport reserve gear on the deck, which, on occasion, doubled or tripled the weight considered during the design process. All these incorrect practices often result in the failure (or loss) of the vessel.

Consequently, in present paper, we propose a new stability criterion that considers the metacentric height (GM) vs. beam (B) relationship (GM/B), which decreases as the vessel length increases. This relationship enables suitable initial stability with reference to the acceleration issue. In particular, this new criterion considers the specific case of small Spanish fishing vessels in accordance with the Intact Stability Code proposals [1], as well as the Spanish regulations for stability and databases on

casualties [39]. This criterion, specifically, was improved by the study of the main characteristics of the Galician fishing grounds using the stability correction coefficients. At the same time, the areas the vessels navigate through to reach the fishing grounds authorized for them were also considered.

Therefore, in this research, a new criterion for Galician vessels ≤ 24 m in length, based on the limiting value of the metacentric height, dynamic stability up to 70° angles [40,41], and the value of the critical wave height (C_{WH}), was developed and adapted to the meteorological and oceanographic conditions of the Galician fishing grounds, with the intention of it being a guiding stability criterion for a particular fishing ground.

2. Materials and Methods

2.1. Criterion Definition

Different databases were used to define the appropriate technical factors necessary to adapt a stability criterion to a particular fishing ground. In this sense, the data from the Spanish Commission for the Investigation of Maritime Accidents and Incidents (CIAIM [12,31]) and those on damaged vessels recorded by the Marine Accident Investigation Branch (MAIB) [42] were used. Moreover, the published annual statistical reports of the European Maritime Safety Agency (EMSA) [43] were also considered.

As an initial step, the following assumptions were established prior to developing the new criterion:

- It is advisable to establish a transverse metacentric height limit (GM_{limit}) for each vessel in relation to its length between the perpendiculars (L_{pp}) and its beam (B), but never to establish a fixed minimum value for the entire fleet.
- For such fishing vessels, the GM/B value is a good indicator of the acceleration they experience during navigation and fishing. According to the minimum initial stability criterion employed by O'Dogherty [18], which is based on the equations previously defined by de Ramón [44] from a curve fitting of real data from more than 40 fishing vessels under different weather conditions, the average GM/B value can be defined by Equations (1) and (2):

$$\text{Leaving the Port : } \frac{GM}{B} = 0.14 - 0.006 \cdot B \quad (1)$$

$$\text{Departure from the fishing ground : } \frac{GM}{B} = 0.17 - 0.01 \cdot B \quad (2)$$

- The parameters of the GM values and dynamic stability of up to 70° (e_{70°) were used, or, when not available, the progressive angle of flooding if it was smaller [18].
- Earlier studies [13–15,45,46] have highlighted that the safety level provided by the criterion should depend on the vessel size and the sea conditions where it operates. This establishes that vulnerability to stress depends to a large extent on the residual stability range and to a lesser degree on the maximum righting moment.
- Heeling effects have been considered for vessels less than or equal to 24 m in length.
- As a prior step to applying the new Meteorological and Oceanographic Coefficient (C_{MO}), the minimum GM value must be calculated as a function of the wind pressure by using Equations (3) and (4) [18]; it is to be employed as a control parameter in accordance with the recommendations of the U.S. Coast Guard in their weather criteria [47]. At the same time, the wind pressure is defined as a function of the length between perpendiculars and, in particular, for fishing vessels, Equation (4) must be employed [47]. Once the GM is greater than its minimum value, a detailed study can be made to establish a valid C_{MO} coefficient for the fishing ground where each fishing vessel exercises its activity.

$$GM_{\min} = \frac{p \cdot A_v \cdot z}{\Delta \tan \theta} \quad (3)$$

where

$$p = 0.0546 + \left(\frac{L_{pp}}{1310} \right)^2. \quad (4)$$

Δ represents the displacement of the ship for a given load condition; $\tan \theta$ represents the tangent of the angle θ ; θ is the heel angle corresponding to the immersion of half of the freeboard or 8° , if $\theta < 8^\circ$; A_v is the lateral area exposed to the wind, projected (m^2); z represents the vertical distance of the center of gravity to a point in the middle of the draft (m); and p is the wind pressure (ton/m^2). From this last equation, it is worth noting that the higher the L_{pp} , the more severe the environment in which the ship operates. Thus, the wind force per unit area will depend on L_{pp} , as determined by statistical analysis.

At the same time, it is of interest to remark that Equations (1) and (2) are employed to define the GM, which will also be used later. Equation (3) provides GM_{min} , which is the lowest allowed value of the GM. The $GM - GM_{min}$ difference is the margin to be influenced by the meteorological coefficient, reducing the GM to values always higher than GM_{min} .

Once the initial hypotheses are defined, the dimensionless coefficients must be determined: the stability criterion coefficient (SC), the initial stability coefficient (C_1), and the dynamic stability coefficient (C_2), as shown in Equation (5):

$$SC = C_1 + C_2, \quad (5)$$

where C_1 is the lower of the two values obtained from Equations (6) and (7) ($C_1 = \min(C_{1-1}, C_{1limit})$) [17]:

$$C_{1-1} = 50 \cdot \frac{GM}{B} \quad (6)$$

$$C_{1limit} = 8 - 0.12 \cdot L_{pp} + 0.0006 \cdot L_{pp}^2 \quad (7)$$

and C_2 is equal to the lower value obtained from Equations (8) and (9) ($C_2 = \min(C_{2-1}, C_{2-2})$).

$$C_{2-1} = \frac{2000 \cdot e_{70^\circ}}{L_{pp}}, \quad (8)$$

where $e_{70^\circ} = \int_0^{70^\circ} GZ \cdot d\theta$.

The expression e_{70° refers to the dynamic stability at 70° . This parameter has been selected because most of the vessels investigated in this study experience their point of progressive flooding before this degree of list and, consequently, the upper limit of the integral of e_{70° shall be 70° , or the angle of vanishing stability, or the angle of progressive flooding, whichever is less.

$$C_{2-2} = \frac{C_{WH} \cdot 100}{L_{pp}} \quad (9)$$

Notably, the constants employed in these equations (50, 100 and 2000) were selected so that the comparison of the resulting values can reasonably influence the application of the criterion. Finally, according to studies conducted by the Wolfson Unit of the University of Southampton [13,14], we can formulate the minimum or critical wave height that might cause the vessel to capsize (represented by C_{WH} in Equation (10)). The values in the equations have been obtained empirically, particularly as indicated by the Wolfson Stability Guidance proposed by Deakin [48]. It has been determined that, for the vessels within the length range used in this study ($L \leq 24$ m), the aspect ratio L/B makes it more advisable to decrease the multiplier 20 of the denominator by 10, and thus more realistically reflect this aspect ratio.

$$C_{WH} = \frac{Range \cdot \sqrt{RM_{max}}}{10 \cdot B}, \quad (10)$$

where *Range* is the residual range of positive stability in degrees; RM_{max} is the maximum residual righting moment, having taken into account any heeling moments due to offset weights, lifting, or wind, in ton-meters; and *B* is the beam, in meters. To calculate the *Range* and RM_{max} , a similar methodology of embarking water was used [39] to study the effect of wind and water on board. Moreover, the coefficients of the effect of water ingress, intense wind, and rolling motion were considered according to the current Spanish criterion [47–50]. The lower value of each was used to calculate the Critical Wave Height (C_{WH}) under the most unfavorable load condition.

Significantly, the values obtained by Equation (10) must not be applied to predict the distress of a vessel as these values are meant only to estimate the minimum height of the wave that could cause it to capsize. Finally, the main conclusion drawn was that the stability of a fishing vessel shall be considered satisfactory if the *SC* is greater than the SC_{min} , as evident in Equation (12). Prior studies by O'Dogherty [17] reported a function of L_{pp} based on the statistical data of the sinking vessels.

$$SC = C_1 + C_2 \geq SC_{min} \quad (11)$$

$$SC_{min} = [d + (e \cdot L_{pp}) + (f/L_{pp})] C_{MO}, \quad (12)$$

where $d = 2.7$; $e = -0.004$; $f = 244$; and C_{MO} is the Coefficient of the Meteorological and Oceanographic Criteria. In our case study, the C_{MO} coefficient was adjusted to be 1 since it is considered a common fishing ground for all the ships. In this sense, the C_{MO} value can be applied in the SC_{min} equation within a range of 0.9 and 1.1, with the objective of increasing or decreasing the SC_{min} by 10%, at the most. For instance, this coefficient can penalize vessels that fish outside the estuaries (1.1) and, in general, beyond the baseline, encouraging compliance. Vessels can perform their fishing activity within the estuaries and in inland water bodies (0.9), provided they have complied with the minimum *GM* indicated above. All the calculation steps of this new calculation procedure were summed up by Figure 1, paying special attention to collect the main parameters and the bibliographic origin of each one.

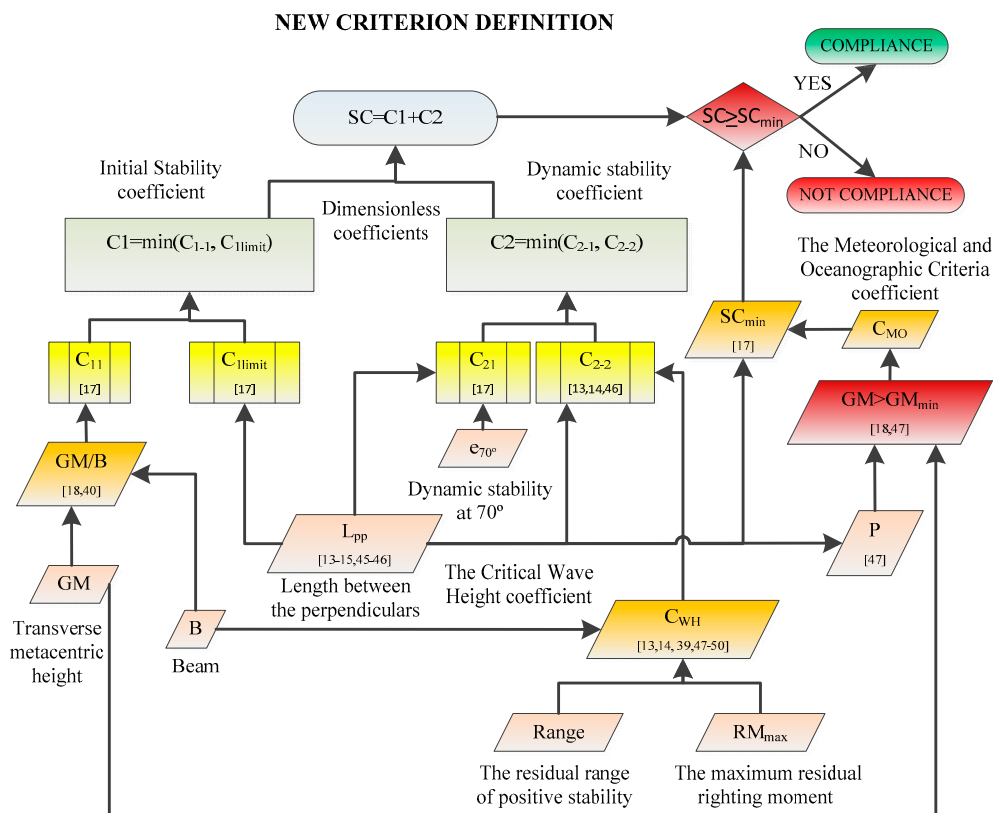


Figure 1. Proposed calculation procedure definition.

2.2. Criterion Validation

Once the criterion was defined, testing was done by utilizing the data drawn from a series of maritime accidents after careful attention was paid to the fishing vessels within the scope of this investigative research. Furthermore, the maritime conditions were related to possible adverse sea conditions. In particular, the stability data of a fleet of about 30 vessels, compiled from the publications of the Spanish Maritime Incident and Incident Investigation Commission (CIAIM), were evaluated, as several of them had capsized due to a clear lack of stability. The data relating to the remaining vessels comprising this collection were obtained from the vessels of the Galician maritime captaincies and the database of the Maritime Accident Investigation Branch (MAIB [42]).

3. Results and Discussion

The current accepted stability criteria—for example, the Rahola criterion—do not consider the vessel size and the heeling actions in the course of navigation and operations. Table 1 shows the main dimensions of each vessel and its initial and dynamic stability values at e_{70}° . The vessels with casualties are highlighted in gray and the information on these was compiled from the publications of the Spanish Permanent Commission for the Investigation of Maritime Accidents and Incidents (CIAIM). In general, accidents were caused by subsidence or overturning due to flooding and a loss of stability.

Table 1. Vessel database.

Vessel	L_{pp} (m)	B (m)	GM (m)	e_{70} (rad*m)
A	18.15	6.00	0.391	0.379
1	16.20	5.30	0.475	0.199
2	13.50	5.20	0.589	0.019
3	14.06	5.00	0.449	0.115
4	9.00	2.52	0.908	0.097
5	18.40	5.88	0.786	-0.027
6	24.00	6.50	0.375	0.616
191	16.44	5.88	1.133	0.12
244	19.70	6.00	0.775	0.122
247	16.00	5.75	1.45	0.19
250	15.50	5.00	0.845	0.124
271	19.50	6.20	0.882	0.161
303	24.00	8.00	0.727	0.428
318A	16.00	5.50	0.679	0.237
318B	22.40	7.00	0.512	0.281
403	18.60	5.90	0.593	0.058
404	15.40	5.75	1.688	0.359
408	18.00	6.20	0.419	0.304
413A	23.00	6.50	0.419	0.364
413B	21.40	6.50	0.416	0.394
414	23.88	7.50	0.531	0.218
416	22.50	6.70	0.425	0.366
421	16.86	5.84	0.86	0.127

Table 1. Vessel database.

Vessel	L_{pp} (m)	B (m)	GM (m)	e_{70} (rad*m)
DX	12.40	5.00	0.418	0.191
CCN	18.00	6.30	1.526	0.308
1C	16.35	5.70	1.243	0.392
3C	18.75	6.45	0.919	0.131
6C	16.20	5.10	1.22	0.239
8C	16.22	5.20	0.642	0.128

These values were used to verify our criterion under the most unfavorable conditions. In particular, it is worth noting that these conditions are what the ship experienced in the moment of sinking, and most of the time it was fully loaded. In the case of damaged vessels, the unfavorable conditions are the cargo condition assumed at the time of the accident.

In particular, for the selection of the safest type Vessel (vessel “A” in Table 1), the design criteria have been followed in its project phase and subsequent monitoring during the approximately fourteen years of the ship’s life, developing its fishing activity in the waters of the CCAA of Galicia.

During this time, the ship’s response was satisfactory in compromised adverse wind and sea situations, presenting a good response in terms of both static and dynamic stability. Its behavior at sea has been more than acceptable even in terms of comfort in these adverse conditions, so it can be considered a reference ship.

Finally, the main results of this calculation process are shown in Figures 2–9, where Figure 9 shows that the relationship between SC and SC_{min} will establish which vessels satisfy our criterion of intact stability or not. In these figures, the red triangles represent the vessels that experienced some kind of accident and the black points are the vessels that suffered no accidents.

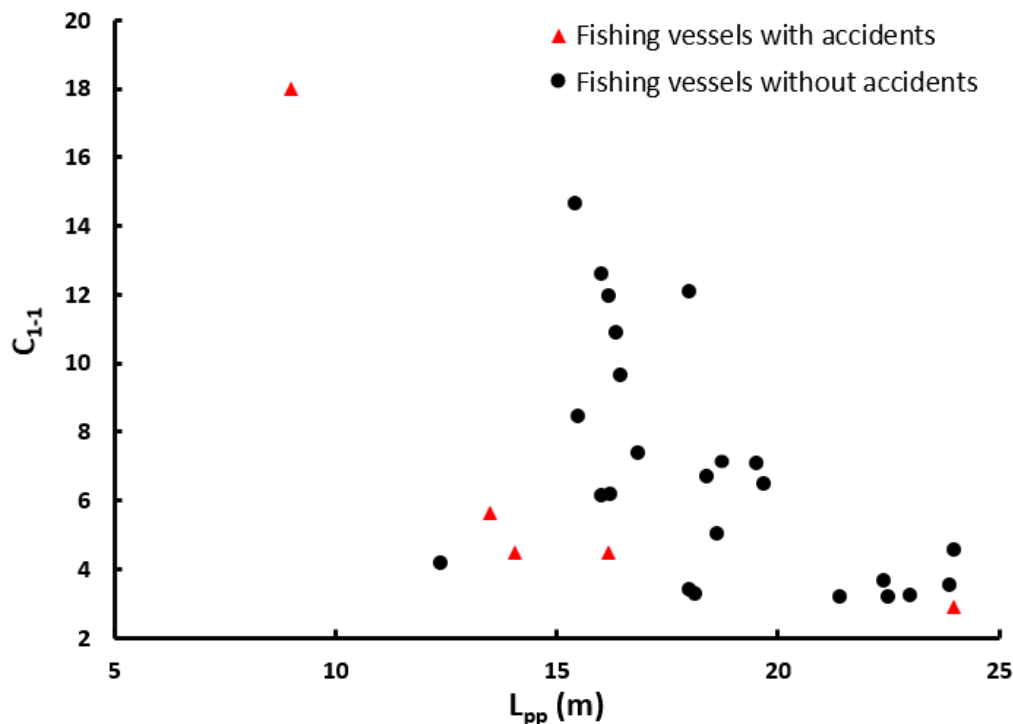


Figure 2. Fishing vessels with and without accidents in accordance with C_{1-1} coefficient as a function of vessel length (L_{pp}).

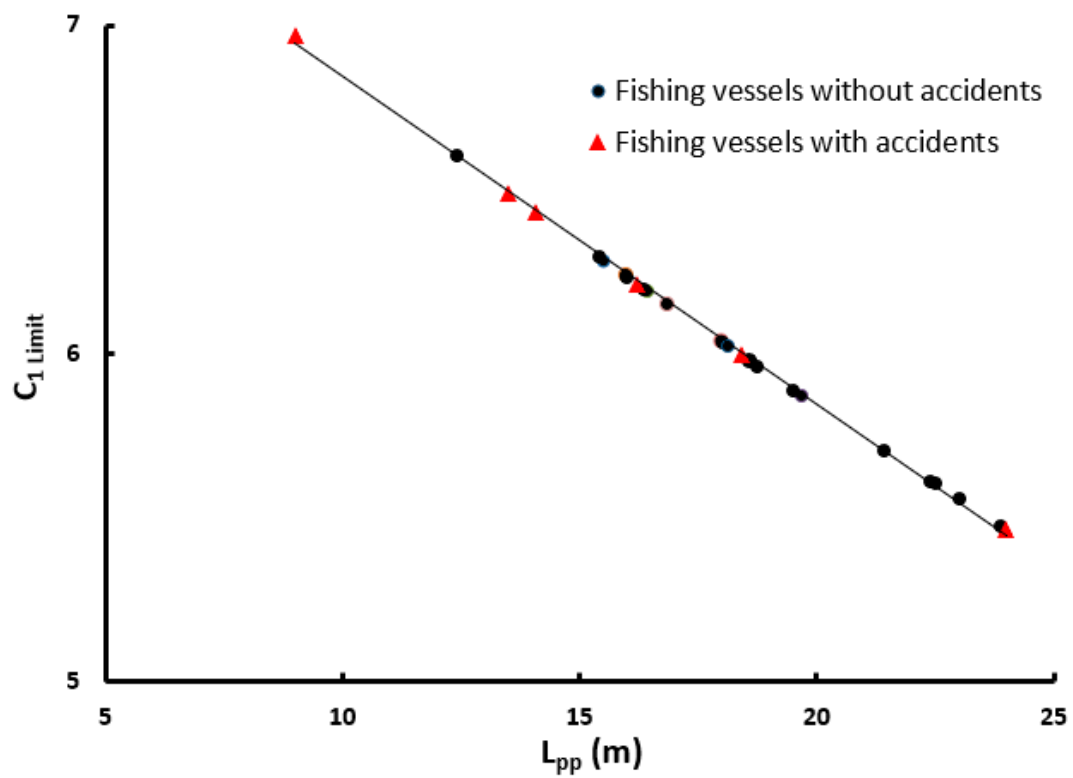


Figure 3. The limiting values of C_1 coefficient of the analyzed vessels with and without accidents as a function of vessel length (L_{pp}).

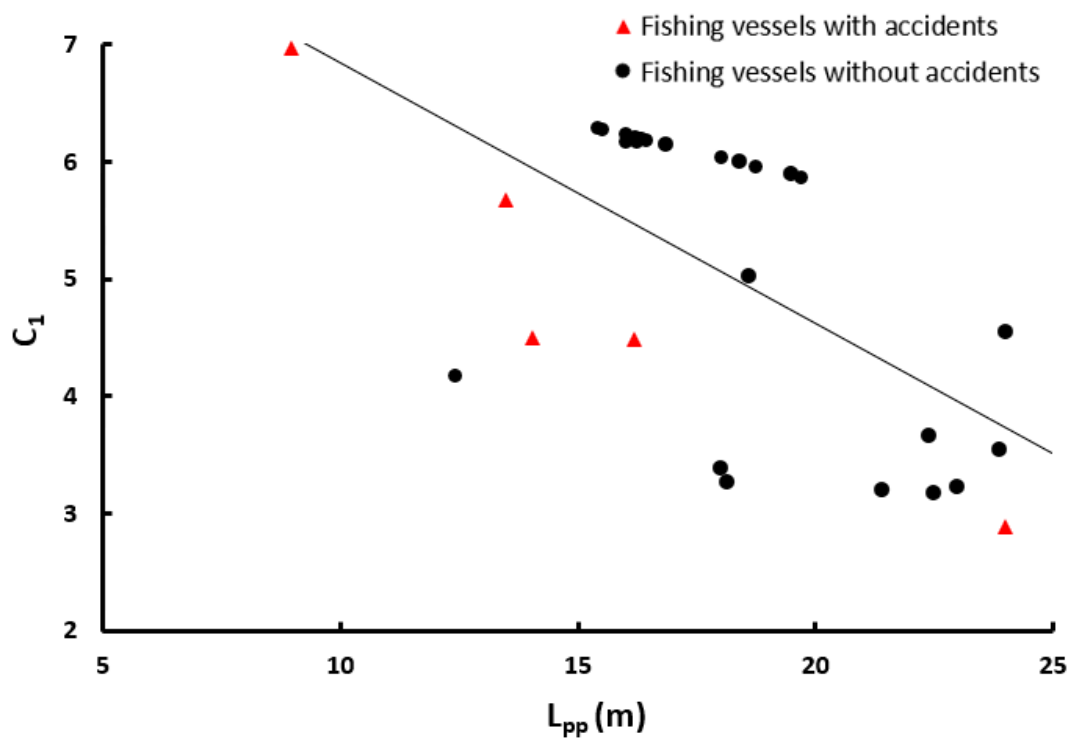


Figure 4. The initial stability coefficient C_1 of the analyzed vessels as a function of the vessel length (L_{pp}).

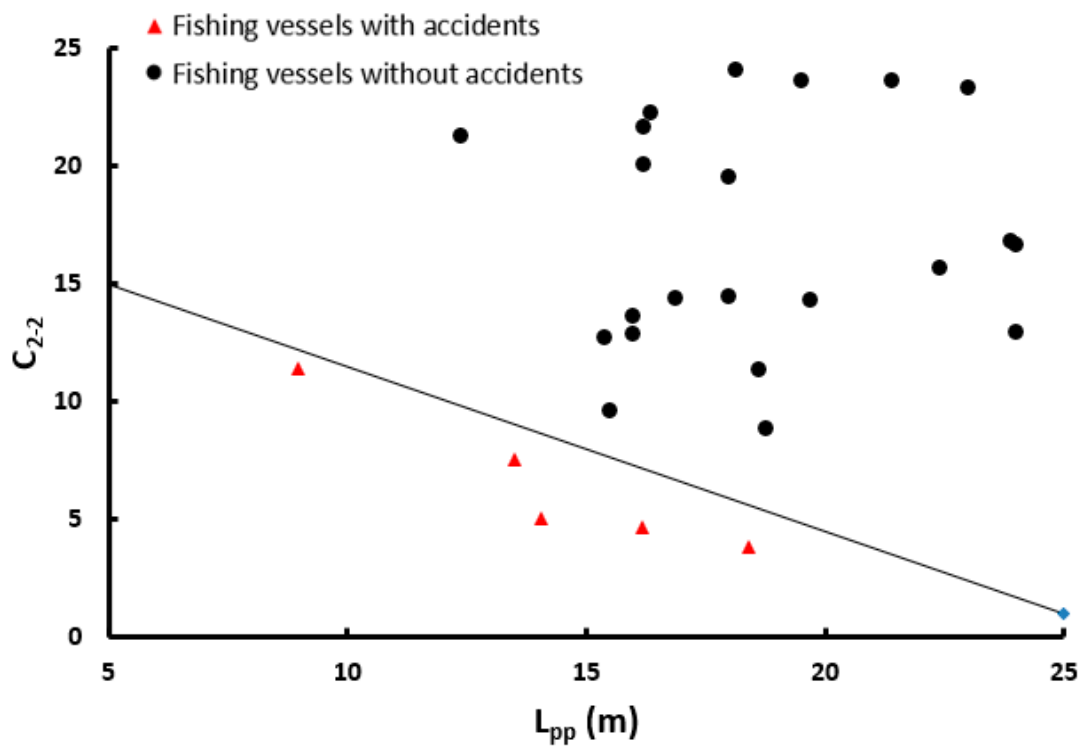


Figure 5. The effect of ship length (L_{pp}) over C_{2-2} coefficients for the analyzed vessels with and without accidents.

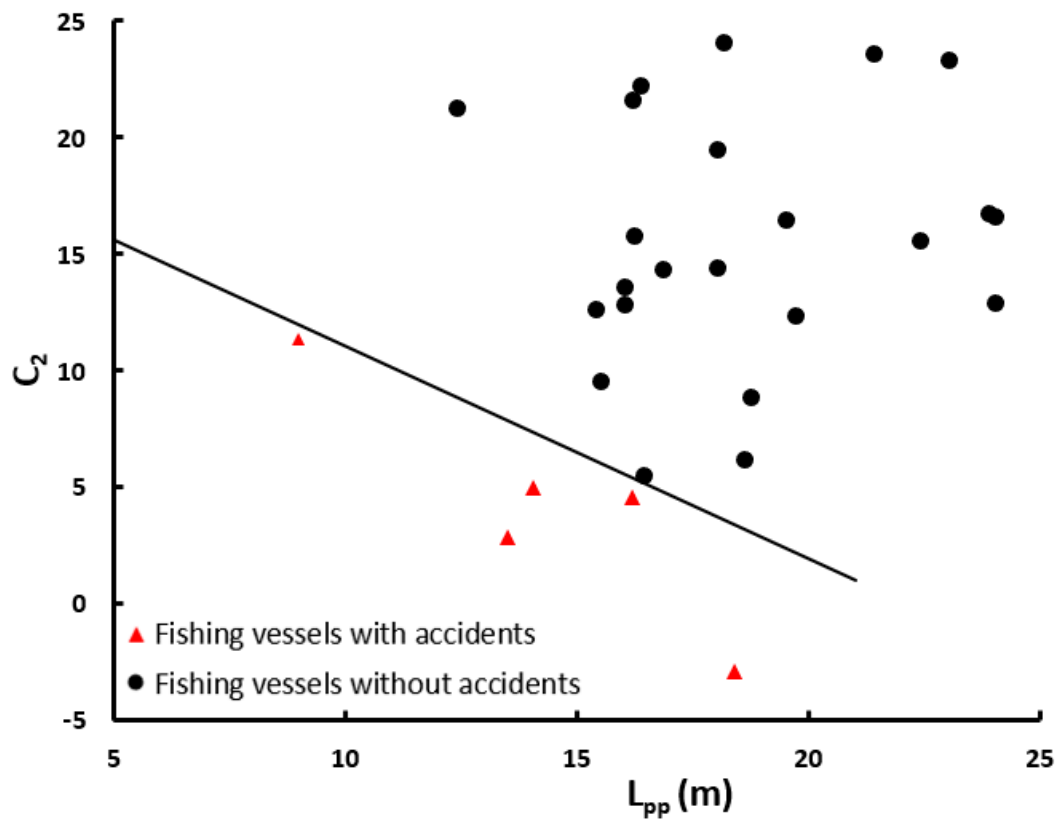


Figure 6. The effect of ship length (L_{pp}) over the C_2 coefficients for the analyzed vessels with and without accidents.

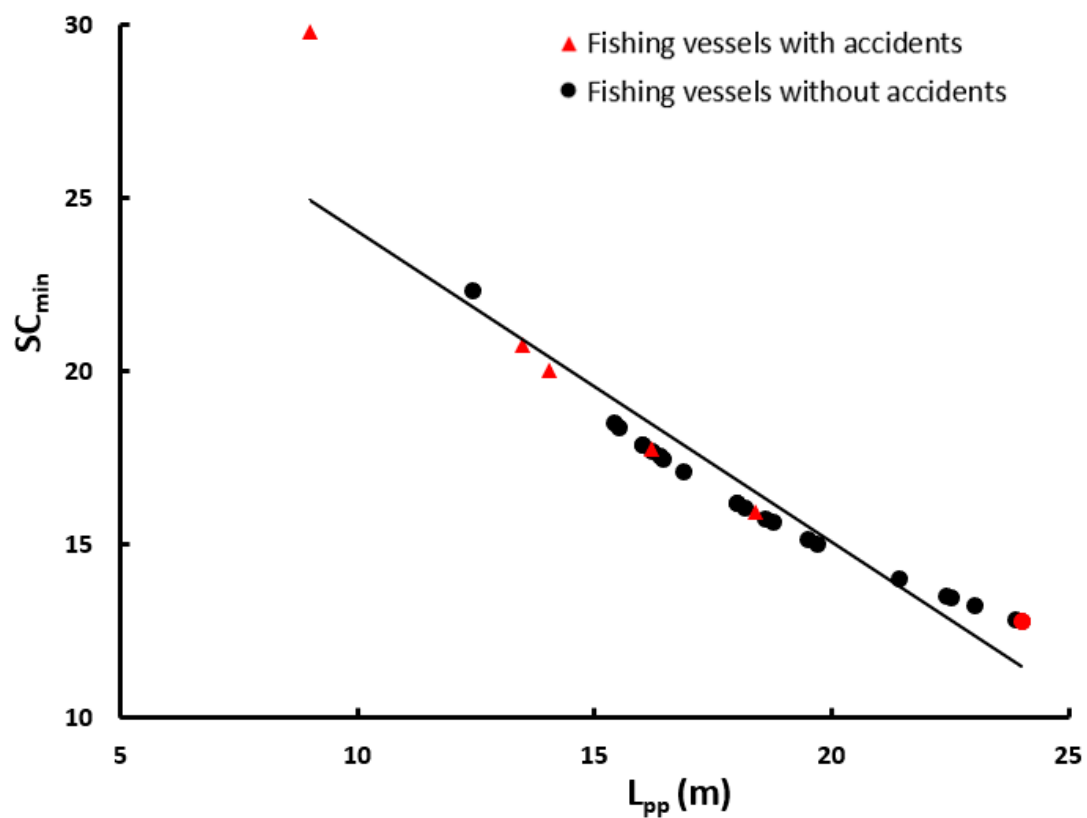


Figure 7. The minimum SC value as a function of the Meteorological and Oceanographic Criteria (SC_{min}) of the analyzed vessels as a function of vessel length (L_{pp}).

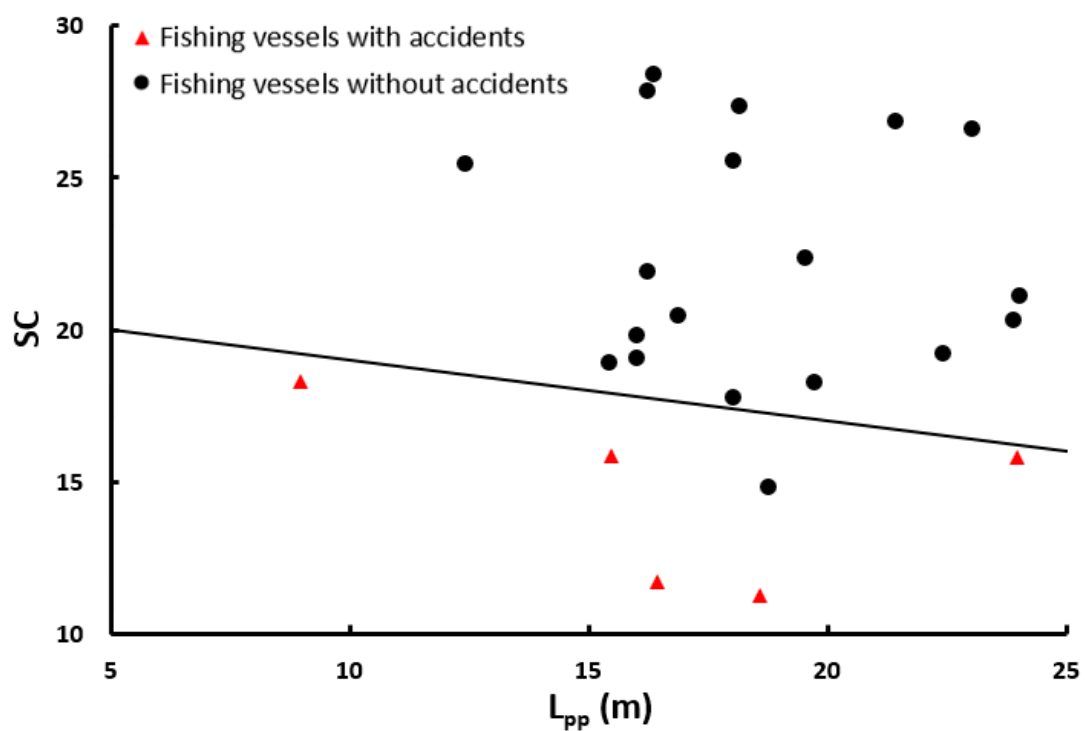


Figure 8. The effect of vessel length (L_{pp}) over the sum of the initial stability coefficient (C_1) and the dynamic stability coefficient ($C_1 + C_2 = SC$).

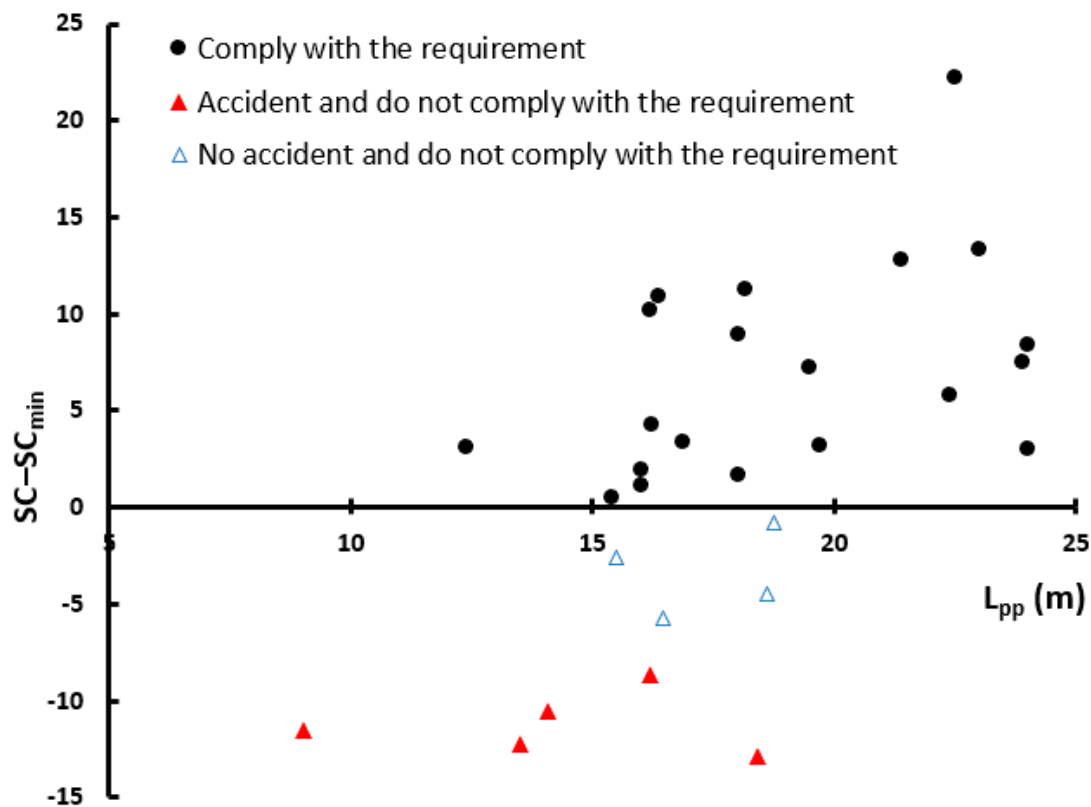


Figure 9. The evolution of $SC - SC_{min}$ difference of the analyzed vessels as a function of vessel length (L_{pp}).

Figure 2 shows the C_{1-1} values as a function of the length between the perpendiculars (L_{pp}) of a vessel. From this figure, it is clear that for the length of the vessels in the range of this study ($L \leq 24$ m) that comply with our criterion, the vessels must have a high GM/B ratio, as such types of fishing vessels are normally designed with a very tight freeboard.

Simultaneously, Figure 3 illustrates the minimum C_1 value for each vessel length (C_{1limit}). From this figure, we can see that, as the length between the perpendicular axes increases, the C_{1limit} decreases and the associated transverse metacentric height (GM) gets closer to the periods of rolling motion with a high period that can be considered normal; these are not the usual sudden movements caused by the high GM s or the already identified drawbacks of the periods of extremely slow rolling motion corresponding to the excessively low GM s.

The values of the initial stability coefficient C_1 , which are influenced by the GM and beam (B), are shown in Figure 4. The figure illustrates that C_1 decreases when the length between the perpendiculars increases and that it gains greater importance as the vessel dimensions decrease. In this sense, it is noteworthy that longer vessels are normally designed with a shelter cover and a larger freeboard.

On analyzing the dynamic stability coefficient (C_2) conforming to the formulation of our criterion, it is observed that it is composed of two other coefficients, C_{2-1} and C_{2-2} . From the relation C_{2-1} , it was not possible to draw relevant conclusions. Despite this, Figure 5 shows that almost all the vessels that have been damaged during their normal working life fall below the limit established by the C_{2-2} criterion (risk line). The critical wave height coefficient (C_{WH}) is added to this original criterion to define casualties during the vessel designing process.

Importantly, the longer these vessels, the lower their C_{2-2} values, which was much clearer when evaluating the C_2 coefficients in Figure 6. This reduction in the C_2 values suggests that the dimensionless coefficient of dynamic stability could exert a greater influence on vessels of shorter length.

In order to complete the graphical representation of the new criterion, the SC_{min} dimensionless coefficient, under which a vessel would not satisfy the criterion of intact stability, is represented in

Figure 7 as a curve defined by Equation (12), as we can see in the point distribution of the chart. The reason why a straight line is given in Figures 3–8 rather than a curve fitting of points is that we wanted to look for the differences in behavior of each ship with respect to the ordinate variable, which in Figure 7 is the SC_{min} coefficient and in Figure 8 is the SC coefficient. These values present a downward curve in relation to the increase in length, i.e., it is possible to establish a SC_{min} value in a linear descending relationship that is inversely proportional to the distance between the perpendicular axes of a vessel.

Finally, Figure 8 depicts the dimensionless coefficient of intact stability (SC) of our criterion. In this figure, the damaged vessels are shown in red; in accordance with the observed tendency, the present SC values are lower than the rest and show commendable accuracy for this criterion. An in-depth analysis of Figure 8 reveals that, with an SC value above 18, no vessel has been observed to experience intact stability problems, regardless of its length, within the range of this study. Similarly, the rest of the fleet in our database lies between the indicated value of 18 and 28. What is more, we can define the safer vessels, which have values approaching 28.

Once the final results were determined and, after considering that these vessels satisfied the IMO stability and Rahola criteria during their initial design process, it was determined that these criteria were inadequate in six of the 29 ships due to the fact that they sank. In other words, for 20% of ships the stability criterion employed was not adequate.

This percentage can be considered to be higher than that obtained after the application of our new criterion (Figure 9 and Figure 11). Figure 9 represents the difference between the SC and SC_{min} to recognize graphically those ships that fail to satisfy our criterion since they are placed in the negative region of the chart. In this sense, all the vessels in our database that had been damaged due to stability issues failed to meet the criterion when placed in the negative region. This observation can be attributed to the fact that in this new criterion our particular C_{WH} was improved, and the meteorological and oceanographic coefficients were established for the specific characteristics of the Galician fishing grounds.

Moreover, although the four vessels shown in white in Figure 9 were not damaged, they did not meet the minimum parameters to comply with the requirement, despite being very close to it. This region near the $SC = SC_{min}$ condition can be defined as an uncertainty area. The vessels within this area demonstrated several common characteristics, such as a low GM/B ratio and, therefore, an extremely tight freeboard and a positive residual stability range. Therefore, the insufficient stability range was certainly low in relation to the rest of the vessels that failed to meet the requirement and could be considered safe in terms of intact stability. Consequently, the four vessels that did not comply with the requirement can do so if their Meteorological and Oceanographic Coefficients (C_{MO}) are corrected or their activity is limited to only a few fishing grounds.

From Figure 10, it is evident that, as the vessel length decreases, a higher C_1 value is required to fulfill the criterion or higher C_2 values are needed to compensate for the initial stability loss. Therefore, it is possible to compensate for a small lack of initial stability by using greater dynamic stability at greater angles or vice versa. If now we analyze Figure 1 we can see that the initial stability coefficient (C_1) depends on the minimum value of the main vessel shapes (L_{pp} , B) and weights distribution (GM , GZ). At the same time, the dynamic stability coefficient (C_2) is defined by a comparison of the dynamic stability up to 70° and the effect of the critical wave height or, what is the same, the vessel design and the weather effect over the dynamic stability. So, in conclusion, vessel shapes, weights, and weather must be adjusted in the design process to reach better stability at different conditions.

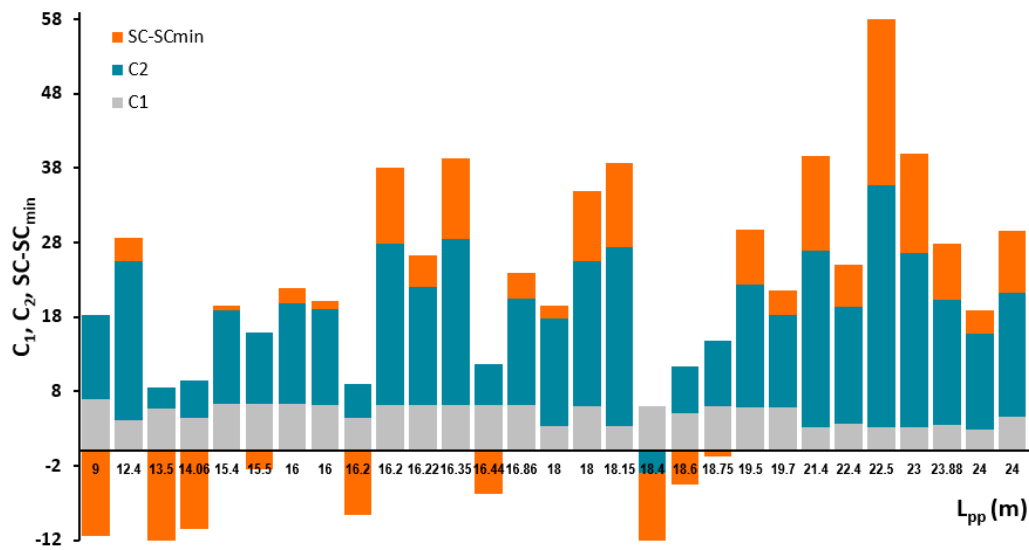


Figure 10. Evolution of C_1 , C_2 , and $(SC - SC_{min})$ coefficients as a function of vessel length (L_{pp}) as a new criterion.

To conclude, a criterion was obtained that could adequately consider the transverse metacentric height (GM), dynamic stability up to 70° (e_{70°), critical wave height (C_{WH}), and the meteorological criterion adjusted to the Galician fishing grounds. In this sense, it is interesting to highlight that there are some limitations of this research work; for example, on one hand, a limited number of vessels were employed due to the difficulty of getting information from different accidents and, on the other hand, a more detailed study is needed of the loading conditions of vessels that do not meet our criteria but do not experience any accident.

Finally, Figure 11 depicts the SC as a function of SC_{min} and the vessel length. From this perspective, the earlier SC/SC_{min} ratio can now be defined by a three-dimensional curve fitting, using a correlation coefficient of 0.95 for the Galician fishing grounds, as seen in Equation (13):

$$SC = a + b \cdot L_{pp} + c \cdot SC_{min}, \quad (13)$$

where $a = 33.74279$, $b = 0.03510$, and $c = -0.97699$.

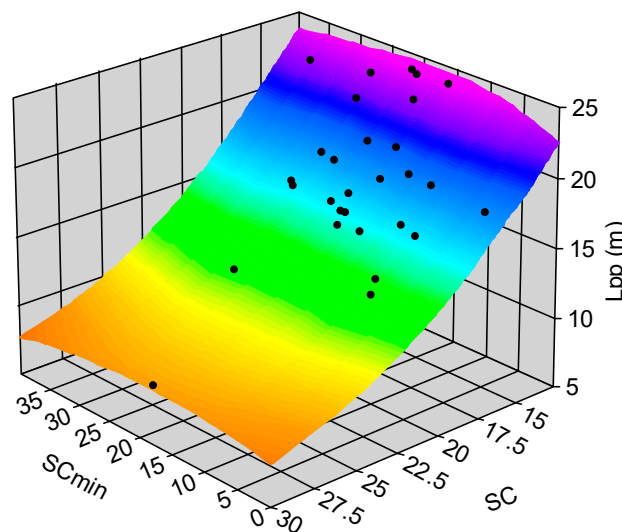


Figure 11. Three-dimensional representation of the proposed decision criteria $SC > SC_{min}$ as a function of each vessel length (L_{pp}).

The authors have proposed the possibility of using the inverse process based on our new equation. In this sense, SC_{min} can be defined for a specific vessel, as well as the minimum meteorological coefficient. Moreover, it can be used to define the fishing grounds in which an existing vessel can safely operate.

Finally, it has been proposed that the coefficients should be clearly indicated in the stability book of the Galician vessels for the application under regulations of loading conditions. Furthermore, such loading conditions need to be updated whenever a change is required in the fishing zones or grounds. Furthermore, future research to improve this methodology based on more real sample data will enable the validation of this procedure, as well as the development of a more precise procedure.

4. Conclusions

The main conclusions drawn from this research work are as follows:

- A specific intact stability criterion for Galician fishing grounds has been developed for fishing vessels ≤ 24 m in length. In calculating their metacentric height values, the dynamic stability up to 70° , critical wave height, and meteorological and oceanographic conditions of the fishing grounds where the fishing operations shall be carried out and the seas that they cross to reach those grounds have all been considered.
- Our new calculation procedure confirms the original idea of compensating for the small lack of initial stability with greater dynamic stability at greater angles or vice versa.
- A new model that relates the stability criterion coefficient to the length between the perpendiculars was adapted for Galician fishing grounds and then applied to define a particular minimum meteorological coefficient for an existing vessel or to define the fishing grounds within which such a vessel can operate.

Finally, some limitations of this research work must be commented on. Only a few vessels were found not to meet the authors' criteria and also had experienced no casualties and, therefore, fell within an area of uncertainty. A more detailed study of the loading conditions for such vessels is needed. Despite this, the number of such vessels is lower when the Meteorological and Oceanographic Coefficients that limit their activity and navigation are applied, as was done for the Galician sea inlets. As another validation, future research must be done to compare the results obtained by our criterion with the results defined by the IMO Sub-Committee on Ship Design and Construction (the interim guidelines were finalized in February 2020). In particular, our criterion can be compared to the dead ship condition, which is a mode of capsizing assumed in the second-generation stability criteria. Thus, such a comparison may be a future research area.

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Nomenclature

A_v	Projected lateral area exposed to the wind
B	Beam (m)
C_1	Initial stability coefficient
C_{1-1}	New model coefficient
C_{1limit}	New model coefficient
C_2	Dynamic stability coefficient
C_{2-1}	New model coefficient
C_{2-2}	New model coefficient
C_{MO}	The meteorological and oceanographic coefficient
C_{WH}	Critical wave height (m)
e_{70°	Dynamic stability at 70 degrees (rad*m)
GM	Transverse metacentric height (m)
L_{pp}	Length between the perpendiculars (m)
p	Wind pressure (ton/m ²)
RM_{max}	Maximum residual righting moment (ton meters)
SC	New stability criterion coefficient
θ	Heel angle (°)
z	Vertical distance of the center of area to the middle of the draft

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