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Evaluation by a Quantitative Index about Intact Stability Performance in Waves of a Set of Megayacht Units

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Abstract: Intact stability represents one of the most important topics when addressing ship safety, and it is ruled by the IMO Intact Stability code, evaluating ship stability in a calm water scenario. However, the interest in ship stability in waves has increased in recent years and this has led to the formulation of the second generation intact stability criteria (SGISc), finalized at IMO in 2020. In this research, an approach to quantitatively and comprehensively evaluate the ship stability performance in waves has been pursued. A methodology is developed with reference to the SGISc. The intact stability in waves index (ISWI) has been proposed, with the aim to become a complementary tool for designers and shipbuilders in the assessment of stability performance in waves. The ISWI represents a comprehensive stability index, able to capture the stability in waves performance of a vessel. The stability index has been verified on a set of megayacht units and its sensitivity to the wave characteristics has been tested, changing the environmental conditions. The outcomes point to a good agreement between the ISWI and the influence of environmental condition changes on the stability performance.

Keywords: intact stability; stability in waves; stability index; megayacht; operational limitation; environmental restrictions

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1. Introduction

The study of the stability of vessels has been an important aspect of naval architecture during the modern era. Research in this field, and the development of assessment procedures, has been carried out for decades and a continuous updating process is still ongoing. Currently, the Intact Stability code (IS code) represents the international mandatory regulation applicable to all types of ships; nevertheless, studies are also conducted aiming to investigate ship behavior in waves. The second generation intact stability criteria (SGISc) are the up-to-date criteria developed at IMO, taking into account the interaction between waves and the hull. An innovative aspect of such criteria, is the comprehensive view of ship safety as an integration of design and operational aspects. These criteria tackle five stability failure modes that may occur during navigation: parametric rolling (PR), pure loss of stability (PL), dead ship condition (DS), excessive acceleration (EA), and surf-riding (SR). In addition, SGISc introduces a multilayered approach, aimed at identifying different assessment tiers with an increasing level of accuracy.

The interest in ship safety, in terms of ship stability in waves, represents one of the most important aspects in ship design. From an operative perspective, studies on the implementation of on-board sensors and efficient communication systems, to evaluate in real-time the intact stability performances of a vessel, have been carried out in [1]. The outcomes of this research provide a valuable contribution to the evaluation of the intact stability of fishing vessels during their operative phases.

Besides, ship safety in waves requires the development of simple and quick tools, able to consider the ship operational characteristics, such as sailing and loading conditions. In this perspective, experimental campaigns on ship models have been carried out in [2,3], with the aim of formulating a relationship between the encountered significant wave height and the probability of a ship capsizing. Finally, in recent years, an effort to define a solid estimator of ship safety in terms of stability has been undertaken. In this perspective, several interesting works can be found in the literature: in [4] the authors created a digital system able to support the master during the navigation, providing information on the level of stability in a very clear and understandable way; the formulation of a numerical index, taking into account the IMO first generation criteria, was proposed in [5].

In this work, a comprehensive stability index, taking into account the SGISc, is presented. The proposed index will introduce a unique numerical value, that will consider the effect of the wave on the ship stability. It is aimed to provide simple and clear information to the master, contributing to the enhancement of ship safety during navigation. At the end of this work, the proposed index has been applied to a set of megayachts; the role of environmental conditions on the index has been investigated as well.

2. Intact Stability in Waves

Intact stability represents a milestone when referring to ship safety, together with hull structural strength and fire-fighting systems. For this reason, international regulations dealing with stability are constantly updated, with the aim of ensuring the highest safety standards. In this section, a review of the state of the art on the assessment of ship stability is presented.

2.1. First Generation Intact Stability Criteria

The general stability criteria based on the righting arm curve characteristics, were formulated in [6,7], applicable to ships up to 100 m . These criteria were developed relying on a statistical analysis of a large sample of ships, carried out in [8]. In the subsequent years, many studies have been undertaken and an exhaustive set of criteria have been developed, one of them is the so-called *weather criterion* [9]. All these criteria have been reviewed and collected within the IS code, which entered into force as a mandatory regulation in 2008 [10]. It is worth mentioning that, before the IS code, ship stability best practice of ship designers was the Classification Societies regulations and recommendations. A detailed historical overview of first generation criteria is available in [11,12].

All the criteria contained in the IS code, consider a scenario where the combined action of waves and wind is overlooked, and the ship is studied in calm water conditions. The only exception is represented by the *weather criterion*, which takes into account the combined action of wind and waves on the roll motion.

2.2. Second Generation Intact Stability Criteria

During the development of the IS code, experts at IMO recognized that further attention should be paid to dynamic phenomena involving the stability of a vessel in waves. Therefore, in the preamble of the code, three dynamic phenomena are identified:

- restoring arm variation due to wave profile;
- maneuvering-related phenomena;
- dead ship condition.

This awareness triggered the development of the so-called SGISc. An IMO working group defined five stability failures, and the multilayered approach was adopted as the main structure. The main aspects of naval architecture are involved in these phenomena, such as intact stability, seakeeping, as well as maneuverability. An insight into the physics that forms the basis of each stability failure mode, can be found in the literature [13–15]. The development of SGISc was finalized in 2020, when the MSC.1/Circular 1627 [16] was issued by IMO. In the SGISc, each stability failure mode is made up of three different levels, each with an increasing level of accuracy but also increasing computational time. With reference to the above mentioned multilayered approach, the latest version of SGISc explicitly indicates that no hierarchy among levels exists. This means that a ship is considered not vulnerable to a stability failure if it is compliant with at least one level. The guidelines of SGISc define first levels (Lv1) and second levels (Lv2) as *vulnerability levels*. Several examples of Lv1 and Lv2 applications can be found in the literature, e.g., in [17,18] the SGISc vulnerability levels have been applied to an oil chemical tanker and to a fishing vessel, while in [19] the influence of systematic variations in design parameters on the PL and PR for a container ship were investigated. The direct stability assessment (DSA) represents the third level, and it is the most complex but accurate assessment approach during the design phase; it needs either a computational tool able to solve non-linear motion in the time domain or a model tank test, or a combination of them both. The DSA will be the assessment tool in the future, although currently it is a highly time-consuming approach. In the literature, work can be found paving the way for the development of affordable DSA [20–23]. As already mentioned, the guidelines on SGISc also address ship safety in terms of operational aspects, in addition to the design phase. The need for operational measures is derived from the outcomes of several studies [24–26], which pointed out that the highest level of safety cannot be achieved by relying on the design phase only. A safe ship handling in harsh weather conditions, can be provided by detailed guidance or restrictions to navigation. Therefore, operational guidance (OG) and operational limitation (OL) are defined in the MSC.1/Circular 1627 [16]. The former, provides the master with information about dangerous sailing conditions (i.e., combination of sea state, route, and speed) to be avoided; the latter, sets restrictions to the navigation in terms of geographical area and/or environmental conditions. Examples of the applications and analysis of OM have been widely published in recent years, for example: applications to different ship types have been carried out in [27–29]; the impact of the forecasrt of accurate environmental conditions has been studied in [30]; finally, the proposal and application of simplified OG has been given in [31,32].

2.2.1. First Vulnerability Criteria—Lv1

It should be noted, that the first vulnerability levels have been developed in order to roughly identify the vulnerability of a ship to a specific stability failure, using relatively quick and simple tools. However, the assumed simplifications imply the criteria are highly conservative.

As concerns the first level criterion for DS, the same structure of the *weather criterion* is adopted. The only modification affects the table describing the relation between the wave steepness S_w and the natural roll period T_ϕ. The original table is replaced by the one defined in the MSC.1/Circular 1200 [33].

$$C_{DS1_a} = \frac{b}{a} \geq 1 \qquad C_{DS1_b} = \theta_0 \geq \min\{16^o; 0.8 \cdot \theta_{SD}\} \tag{1}$$

A scenario where beam waves encounter the ship at zero speed is assumed in the EA Lv1. A loading condition compliant with Equation (2) is deemed not vulnerable.

$$C_{EA1} = \varphi \cdot k_L \cdot \left(g + \frac{4\pi^2 \cdot h_r}{T_\phi^2} \right) \leq 4.64\,\mathrm{m} \cdot \mathrm{s}^{-2} \tag{2}$$

where φ is the characteristic roll amplitude; k_L is a coupling factor taking into account simultaneous pitch, roll, and yaw motions; g is the acceleration due to gravity; h_r is the vertical position above the roll axis, where crew or passengers may be present; and T_ϕ is the natural roll period.

The structures of the PL and PR criteria in Lv1 are very simple but conservative. The analyses rely on the study of hydrostatics, evaluated for a draft passing through the wave crest and a draft corresponding to the wave trough. Wave dimensions are defined in the rule by the length λ_w (equal to the ship length), and the steepness: $S_w = 0.0334$ in PL, while

$S_w = 0.0167$ in PR. For these stability failure modes, Lv1 are not applicable to tumblehome ships; therefore Equation (3) is to be verified.

$$C_{\nabla} = \frac{\nabla_D - \nabla}{A_W \cdot (D - d)} \geq 1.0 \quad (3)$$

where D is the ship depth; d is the draft; ∇_D is the immersed volume evaluated at a draft equal to D; ∇ is the immersed volume at a draft equal to d; and A_W is the waterplane area.

The Lv1 criterion for PL deems a ship not vulnerable if Equations (3) and (4) are satisfied.

$$C_{PL1} = GM_{min} \geq 0.05\,\text{m} \quad (4)$$

where GM_{min} is the metacentric height, evaluated considering a hydrostatic at the draft d_L, passing through the wave trough. A ship is deemed not vulnerable by Lv1 of PR if Equations (3) and (5) are verified.

$$C_{PR1} = \frac{\Delta GM}{GM} \leq R_{PR} \quad (5)$$

where R_{PR} is the standard defined as a function of ship length, breadth, amidship coefficient, and bilge keel area; GM is the metacentric height in calm water; and ΔGM is the semi-difference between the metacentric heights evaluated for hydrostatics at drafts passing through the wave trough d_L and wave crest d_H.

Finally, a loading condition is not vulnerable to the Lv1 for SR if Equation (6) is satisfied.

$$Fn \leq 0.30 \qquad \text{and} \qquad L \geq 200\text{ m} \quad (6)$$

where L is the ship length and Fn is the Froude number ($Fn = V_S/\sqrt{(g \cdot L)}$).

2.2.2. Second Vulnerability Criteria—Lv2

The second vulnerability criteria are based on a long-term analysis evaluating the risk of a stability failure occurring. Therefore, they share a similar structure as reported in Equation (7).

$$C_{\text{LT}} = \sum_{i=1}^{N} C_{\text{ST}_i} \cdot W_{S_i} \leq R \quad (7)$$

where C_{LT} is the long-term criterion; C_{ST} is the short-term criterion for each considered sea state; N is the total number of considered sea states; Ws represents the probability to encounter a specific sea state; and R is the threshold to be satisfied, namely the standard. Each stability failure differs by the calculation procedure to obtain the short-term criterion C_{ST}. A technical description of the complete procedure to evaluate each C_{ST} is not provided in this paper, but it can be found in [16]; moreover, in the literature, many application cases and detailed descriptions of their structures can be found [34–37]. The short-term criterion of DS is evaluated by a dynamic-based simplified model, depending on the wind and wave energy spectra combined with the roll motion response amplitude operator (RAO). The EA short-term criterion analyzes the lateral acceleration RAO and the wave energy spectrum. Both PR and PL are defined with two different short-term criteria. In PR, on one hand the criterion evaluates the magnitude of stability variation in a set of 16 waves, on the other hand the second criterion takes into account the amplitude of the roll motion, by the application of a simple time-domain dynamic model. In PL, both criteria evaluate the decrease in ship stability performance by the study of the righting arm in waves. Finally, the short-term criterion for the SR is iteratively computed by the evaluation of the propeller thrust, hull resistance, and wave surge force.

3. Assessment of the Intact Stability Performance

The literature review presented in the Introduction, points out that several studies have been carried out aiming to identify a representative factor of the stability performance. However, in each study a wide and exhaustive analysis on the main intact stability parameter is missing. In [38], a comprehensive index based on the first generation intact stability criteria is proposed. With this regard, in the following paragraph a comprehensive index measuring the stability in waves performance is presented. It relies on the SGISc introduced by IMO to tackle dynamic stability phenomena.

The Intact Stability in Waves Index

The intact stability in waves index (ISWI) is defined in Equation (8) as the averaged linear combination of the stability in waves partial indexes PI.

$$\text{ISWI} = \frac{\sum_{i=1}^{N} k_i \cdot PI_i}{\sum_{i=1}^{N} k_i} \quad (8)$$

where N is the total amount of the assessed criteria (Table 1); PI_i is the partial intact stability index evaluated for each criterion; and k_i is the weighting factor associated with each partial index.

The partial intact stability index PI, is determined by two different formulations according to the criterion type. The partial index formulation applicable to those criteria characterized by an upper threshold (i.e., the criterion is met if it is lower than the standard threshold; $Crt < Std$), is defined in Equation (9). Vice versa, Equation (10) defines the partial index formulation applicable to those criteria characterized by a lower threshold (i.e., $Crt > Std$). In summary, the latter is applicable to criteria C_{DS1_a} and C_{PL1}, the former is applicable to all other criteria.

$$PI = 1 - \frac{Std - Crt}{Std - Crt_{min}} \quad (9)$$

$$PI = 1 - \frac{Crt - Std}{Std} \quad (10)$$

where Std is the standard threshold; Crt is the evaluated criterion; and Crt_{min} is the minimum value achievable by the considered criterion.

Table 1. Summary of second generation intact stability criteria.

Criterion		Standard	Criterion		Standard
C_{DS1_a}	$\geq$	1.00	C_{DS2}	$\leq$	0.06
C_{DS1_b}	$\leq$	$\min\{16^o; 0.8 \cdot \theta_{SD}\}$	C_{EA2}	$\leq$	3.9×10^{-4}
C_{EA1}	$\leq$	$4.64\ \text{m} \cdot \text{s}^{-2}$	C_{PL2}	$\leq$	0.06
C_{PL1}	$\geq$	0.05 m	C_{PR2_a}	$\leq$	0.06
C_{PR1}	$\leq$	R_{PR}	C_{PR2_b}	$\leq$	0.025
			C_{SR2}	$\leq$	0.005

4. Application Case

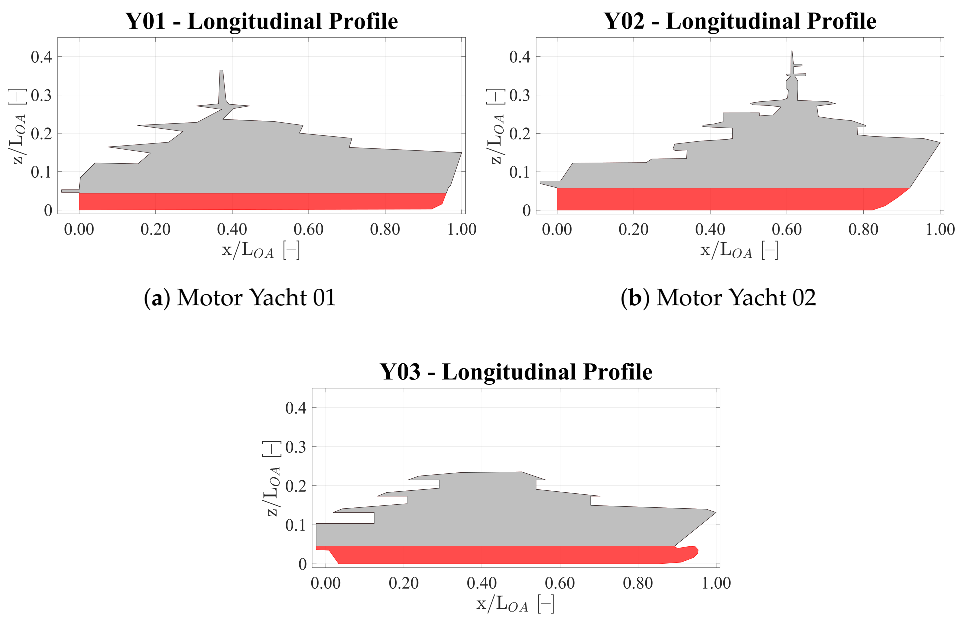
In this work, the ISWI has been applied to three megayacht units for a set of loading conditions. Application of the criteria under development to a set of pleasure crafts, have also been presented at the 1st Ship Design and Construction (SDC) meeting [39] (annex 9). In recent years, in the literature, a limited amount of studies on SGISc specifically applied to pleasure motor yacht units [40] or large sailing vessels [41] can be found. Moreover, a sensitivity study of the environmental conditions on the ISWI outcomes has been carried out for the investigated loading conditions. According to the MSC.1/Circular 1627, restrictions to navigation related to the geographical area have been considered as well. Finally, a summary of SGISc considered in the following analysis is given in Table 1. Due to the extremely simple structure of Lv1 for SR, this criterion has not been taken into account in the following analysis.

Investigated Units

The investigated units are a selection of representative megayachts, with a length range spanning from 40 m to 75 m, in order to cover a large sample of motor units built in recent years. In addition, these sizes provide an interesting cause of reflection about the interaction with the typical environmental conditions that characterize the Mediterranean Sea. In Table 2, the main particulars of the investigated vessels are given. Besides, the longitudinal projection of the exposed areas are reported in Figure 1. Three loading conditions are considered for each investigated unit: arrival, mid-voyage, and departure.

Table 2. Main particulars of the investigated units.

Main Dimensions					
Unit			Y01	Y02	Y03
Overall length	L_{OA}	$[m]$	44.70	47.00	74.40
Maximum breadth	B	$[m]$	8.60	9.00	13.2
Depth	D	$[m]$	4.30	4.80	7.00
Service speed	V_S	$[kn]$	20.0	13.0	17.5
Displacement	Δ	$[t]$	348	485	1630
Transverse metacentric height	GM	$[m]$	1.43	0.82	1.91
KG / D		$[-]$	0.784	0.773	0.733
KG / d		$[-]$	1.762	1.433	1.666



(**a**) Motor Yacht 01 (**b**) Motor Yacht 02

(**c**) Motor Yacht 03

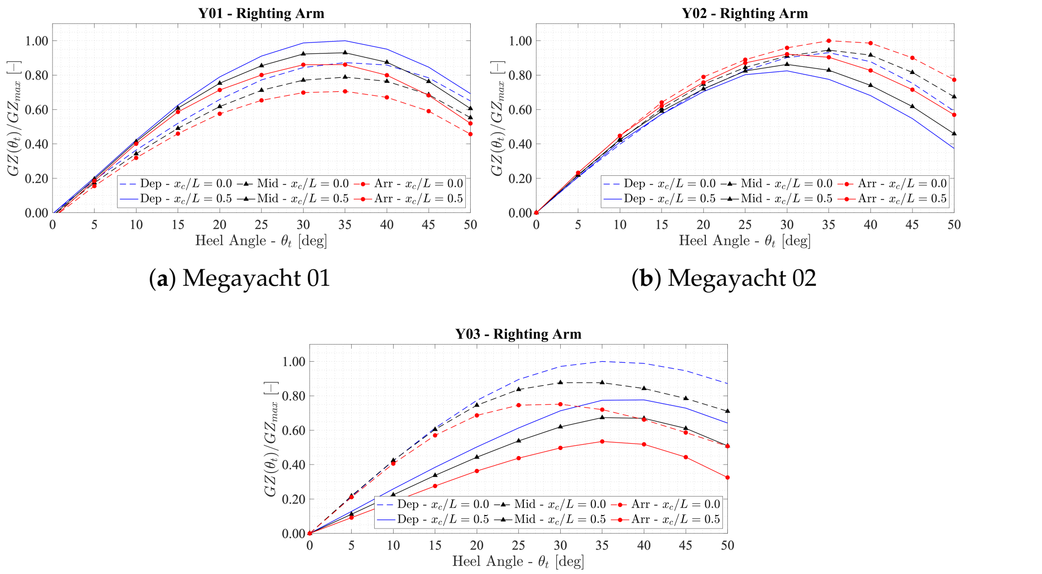
Figure 1. Graphical representation of the lateral exposed areas for the investigated units.

5. Results

5.1. Stability in Waves Calculation

As first step in the stability in waves assessment, the SGSIc have been applied for each investigated loading condition. In order to evaluate the criteria, the effect of the wave profile along the hull on the righting arm, GZ, has to be considered. Since ten different wave steepness and ten wave crest positions are required in the SGISc calculations, only a selection of representative GZ curves are shown in Figure 2, for each loading condition.

The GZ curves in waves considering both the wave crest and the wave trough amidship, are represented for a wave steepness, S_w, equal to 0.0334.



(**a**) Megayacht 01 (**b**) Megayacht 02

(**c**) Megayacht 03

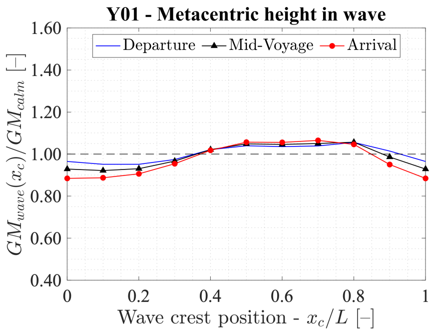
Figure 2. Diagram of the righting arm in waves for each unit. The wave crest amidship conditions are represented by continuous lines while the wave trough amidship conditions are represented by dashed lines. The wave steepness, S_w, is equal to 0.0334 and the wavelength equal to the ship.

In addition, the changes in transverse metacentric height, GM, in waves is another important parameter to be considered in the SGISc evaluation. Due to the large amount of wave cases to tackle within the assessment, only a representative selection of data is presented in this work. In Figure 3, the GM in wave, as a function of the wave crest position, is shown. The represented cases have a wave steepness equal to 0.0334. It should be noted that Y02 and Y03 present improved values of GZ and GM for the wave through amidship, and a reduced stability for the wave crest amidship. On the contrary, Y01 displays the opposite behavior, i.e., the stability is improved when the wave crest is amidship and vice versa. This effect may be due to the hull form of Y01, which is a planning hull and has a hard chine and spray rails. On the contrary, Y02 and Y03 are semi-displacement units, with typical round-bilge hulls.

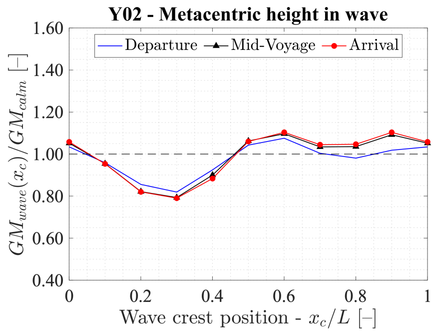
Finally, the SGISc have been evaluated. In Tables 3–5, the outcomes of the calculations are listed for each unit and loading condition. The cell is highlighted in green if the criterion is met, otherwise it is highlighted in red. The outcomes show that all loading conditions do not meet the surf-riding Lv2 criterion. As expected, Lv1 seems more conservative than Lv2 except for Y01, which appears to not be compliant with Lv2 more times than Lv1. Furthermore, the results of Y01 point out some inconsistencies between levels for the dead ship condition failure mode, i.e., Lv1 is met while Lv2 is not. Considering the PR and PL of Y01, it appears that, for the arrival loading condition, the Lv2 criteria are not met, on the contrary Lv1 are all compliant.

Table 3. Comprehensive assessment of SGISc vulnerability levels for Y01. Criteria compliant with the standard are highlighted in green. Criteria not compliant with the standard are highlighted in red.

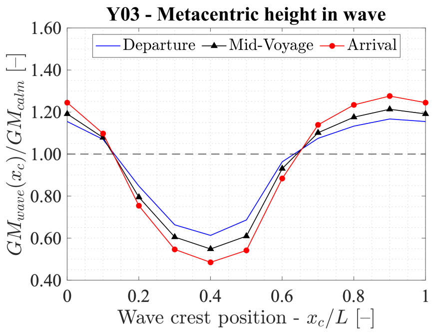
Level 1	Loading Conditions			Level 2	Loading Conditions		
Criterion	Arrival	Mid-Voyage	Departure	Criterion	Arrival	Mid-Voyage	Departure
C_{DS1_a}	0.966	1.393	7.986	C_{DS2}	0.790	0.745	0.655
C_{DS1_b}	8.560	7.830	7.140	C_{EA2}	2.27×10^{-2}	2.43×10^{-2}	2.20×10^{-2}
C_{EA1}	6.226	5.957	7.813	C_{PL2}	0.305	0.004	0.000
C_{PL1}	0.409	0.543	0.183	C_{PR2_a}	0.115	0.000	0.000
C_{PR1}	0.206	0.183	0.192	C_{PR2_b}	3.77×10^{-4}	3.67×10^{-6}	7.24×10^{-6}
				C_{SR2}	0.104	0.104	0.104



(**a**) Megayacht 01



(**b**) Megayacht 02



(**c**) Megayacht 03

Figure 3. Diagram of the variation in transverse metacentric height in waves for each unit. The wave steepness, s_w, is equal to 0.0334 and the wavelength is equal to the ship length.

Table 4. Comprehensive assessment of SGISc vulnerability levels for Y02. Criteria compliant with the standard are highlighted in green. Criteria not compliant with the standard are highlighted in red.

Level 1	**Loading Conditions**			**Level 2**	**Loading Conditions**		
Criterion	**Arrival**	**Mid-Voyage**	**Departure**	**Criterion**	**Arrival**	**Mid-Voyage**	**Departure**
C_{DS1_a}	0.769	0.675	0.704	C_{DS2}	0.392	0.405	0.400
C_{DS1_b}	8.45	8.73	8.78	C_{EA2}	5.86×10^{-4}	3.79×10^{-4}	2.11×10^{-4}
C_{EA1}	6.226	5.957	5.686	C_{PL2}	0.009	0.013	0.029
C_{PL1}	−0.041	−0.044	0.082	C_{PR2_a}	0.000	0.000	0.000
C_{PR1}	0.479	0.490	0.475	C_{PR2_b}	0.000	0.000	0.000
				C_{SR2}	0.0079	0.0076	0.0078

Table 5. Comprehensive assessment of SGISc vulnerability levels for Y03. Criteria compliant with the standard are highlighted in green. Criteria not compliant with the standard are highlighted in red.

Level 1	**Loading Conditions**			**Level 2**	**Loading Conditions**		
Criterion	**Arrival**	**Mid-Voyage**	**Departure**	**Criterion**	**Arrival**	**Mid-Voyage**	**Departure**
C_{DS1_a}	0.445	0.441	0.436	C_{DS2}	0.213	0.183	0.161
C_{DS1_b}	5.74	4.89	4.33	C_{EA2}	2.01×10^{-4}	4.70×10^{-4}	7.91×10^{-4}
C_{EA1}	7.042	7.379	7.470	C_{PL2}	0.07	0.033	0.013
C_{PL1}	−0.440	−0.116	0.176	C_{PR2_a}	0.000	0.000	0.000
C_{PR1}	0.506	0.408	0.299	C_{PR2_b}	0.012	0.007	0.008
				C_{SR2}	0.0329	0.0320	0.0455

5.2. Calculation of the Intact Stability in Waves Index

The results of the ISWI application to the investigated megayacht units, are presented in this section. In Tables 6–8 the partial stability index PI_i is reported for each loading condition. The partial index should be lower than 1.0 in those cases where the criterion is met; otherwise, the partial index is larger than 1.0 the further the considered criterion is away from the standard threshold. The partial index is equal to 1.0 when the criterion has exactly the same value of the standard. According to this definition, a criterion is met whenever the partial index is equal to or lower than 1.0 .

Table 6. Partial index, taking into account stability in waves performance of Y01. Values of *si* equal to or lower than 1.0 means the loading condition is compliant with the criterion.

Partial Index PI for Y01											
Loading Condition	C_{DS1_a}	C_{DS1_b}	C_{EA1}	C_{PL1}	C_{PR1}	C_{DS2}	C_{EA2}	C_{PL2}	C_{PR_a}	C_{PR2_b}	C_{SR2}
Arrival	1.034	0.535	1.260	−6.180	0.110	13.167	58.205	5.083	1.917	0.015	20.800
Mid-Voyage	0.607	0.489	1.206	−8.860	0.098	12.417	62.308	0.067	0.000	0.001	20.800
Departure	−5.986	0.446	1.582	−1.660	0.103	10.917	56.410	0.000	0.000	0.000	20.800

Table 7. Partial index, taking into account stability in waves performance of Y02. Values of *si* equal to or lower than 1.0 means the loading condition is compliant with the criterion.

Partial Index PI for Y02											
Loading Condition	C_{DS1_a}	C_{DS1_b}	C_{EA1}	C_{PL1}	C_{PR1}	C_{DS2}	C_{EA2}	C_{PL2}	C_{PR_a}	C_{PR2_b}	C_{SR2}
Arrival	1.231	0.528	1.260	2.820	0.900	6.533	1.503	0.150	0.000	0.000	1.580
Mid-Voyage	1.325	0.546	1.206	2.880	0.917	6.750	0.972	0.217	0.000	0.000	1.520
Departure	1.296	0.549	1.151	0.360	0.855	6.667	0.541	0.483	0.000	0.000	1.560

Table 8. Partial index, taking into account stability in waves performance of Y03. Values of *si* equal to or lower than 1.0 means the loading condition is compliant with the criterion.

Partial Index PI for Y03											
Loading Condition	C_{DS1_a}	C_{DS1_b}	C_{EA1}	C_{PL1}	C_{PR1}	C_{DS2}	C_{EA2}	C_{PL2}	C_{PR_a}	C_{PR2_b}	C_{SR2}
Arrival	1.555	0.359	1.426	10.800	1.378	3.550	0.515	1.167	0.000	0.480	6.580
Mid-Voyage	1.559	0.306	1.494	4.320	1.111	3.050	1.205	0.550	0.000	0.280	6.400
Departure	1.564	0.271	1.512	−1.520	0.814	2.683	2.028	0.217	0.000	0.320	9.100

Once the partial index of each criterion for a loading condition has been calculated, it is possible to proceed with the estimation of the ISWI value by a linear combination. Considering the physical-based approach of Lv2 more robust and detailed than that of Lv1, it was decided to differentiate the weighting factor, keeping it constant within the same vulnerability level. All criteria of Lv2 have been associated with $k_i = 1.0$, while all criteria of Lv1 have been associated with $k_i = 0.5$. The weighting factor of Lv2 has been selected to be twice the factor of Lv1 because of their, in principle, more robust and accurate structure. The precise results of Lv2 have been weighted more in the ISWI. In this way, a ship passing only Lv2 is considered safer than a ship compliant only with Lv1. Results of the ISWI for each loading condition are reported in Table 9.

The outcomes show that, according to ISWI, the vessel having the worst stability in waves performance is Y01. In fact, the ISWI of Y01 is much larger than 1.0 for each loading condition, and compared to the indexes of other vessels, the ISWI of Y01 is one order of magnitude larger. The significant vulnerability of Y01 can be ascribed to the limited dimension of the hull (i.e., Y01 is the smallest investigated unit) and to the vertical position of the CoG. In fact, Y01 presents the largest values of the KG/D and KG/d ratios, indicating a relatively high position of the CoG compared to the other units (Table 2). On the contrary, Y02 has the best ISWI (i.e., the lowest value) for all loading conditions, even if all cases are still larger than 1.0, i.e., the threshold of safety. As expected, the departure loading conditions show the lowest value of ISWI. Therefore, for the assessed cases, the departure condition can be deemed always to be the safest loading condition.

Table 9. Summary of the evaluation of the ISWI for all investigated loading conditions.

ISWI—Intact Stability in Waves Index			
Unit	**Arrival**	**Mid-Voyage**	**Departure**
Y01	11.4748	10.8662	10.0435
Y02	1.5453	1.5171	1.3361
Y03	2.3589	1.8682	1.8434

5.3. The Impact of the Environmental Conditions on the ISWI

As a further analysis, the influence of selected environmental conditions on the ISWI has been studied. According to the MSC.1/Circular 1627, the SGISc are defined with reference to the North Atlantic Ocean. This is represented by the wave scatter table defined in [42]. However, the SGISc allow a change in the environmental conditions, by the application of the operational limitations (OL). In particular, a limitation on the geographical area can be applied by a change in the wave scatter table. A detailed description of the OL can be found in [43].

Due to the typical operational area of a motor yacht unit, it has been deemed interesting to analyze the geographical area of the central Mediterranean Sea. This kind of OL will affect all Lv2 and Lv1 criteria of PR and PL. The formulations of other Lv1 criteria are not dependent on a change in environmental conditions. The change in geographical area affects the wave steepness, S_w, used in the evaluation of Lv1 PR and PL, which becomes equal to 0.0452 and 0.0905, respectively. In Tables 10–12, criteria obtained by the application of the OL are given.

Table 10. Comprehensive assessment of SGISc vulnerability levels for Y01 considering the central Mediterranean Sea. Criteria compliant with the standard are highlighted in green. Criteria not compliant with the standard are highlighted in red.

Level 1	**Loading Conditions**			**Level 2**	**Loading Conditions**		
Criterion	**Arrival**	**Mid-Voyage**	**Departure**	**Criterion**	**Arrival**	**Mid-Voyage**	**Departure**
C_{DS1_a}	0.966	1.393	7.986	C_{DS2}	0.652	0.635	0.581
C_{DS1_b}	8.56	7.83	7.14	C_{EA2}	2.69×10^{-2}	2.89×10^{-2}	2.72×10^{-2}
C_{EA1}	6.226	5.957	7.813	C_{PL2}	0.282	0.116	0.076
C_{PL1}	−2.152	−2.021	−1.867	C_{PR2_a}	0.899	0.027	0.000
C_{PR1}	0.973	0.875	0.717	C_{PR2_b}	1.50×10^{-3}	5.51×10^{-4}	2.12×10^{-4}
				C_{SR2}	0.0991	0.0993	0.0991

Table 11. Comprehensive assessment of SGISc vulnerability levels for Y02 considering the central Mediterranean Sea. Criteria compliant with the standard are highlighted in green. Criteria not compliant with the standard are highlighted in red.

Level 1	**Loading Conditions**			**Level 2**	**Loading Conditions**		
Criterion	**Arrival**	**Mid-Voyage**	**Departure**	**Criterion**	**Arrival**	**Mid-Voyage**	**Departure**
C_{DS1_a}	0.769	0.675	0.704	C_{DS2}	0.218	0.208	0.205
C_{DS1_b}	8.45	8.73	8.78	C_{EA2}	5.00×10^{-4}	2.63×10^{-4}	1.12×10^{-4}
C_{EA1}	6.226	5.957	5.686	C_{PL2}	0.028	0.038	0.076
C_{PL1}	−1.762	−1.786	−1.767	C_{PR2_a}	0.000	0.000	0.000
C_{PR1}	1.058	1.088	1.001	C_{PR2_b}	0.000	0.000	0.000
				C_{SR2}	0.0179	0.0177	0.0208

Finally, the calculation of the ISWI has been performed. In Table 13, the final values of the ISWI, considering a change in the environmental conditions, are reported.

Table 12. Comprehensive assessment of SGISc vulnerability levels for Y03 considering the central Mediterranean Sea. Criteria compliant with the standard are highlighted in green. Criteria not compliant with the standard are highlighted in red.

Level 1	Loading Conditions			Level 2	Loading Conditions		
Criterion	Arrival	Mid-Voyage	Departure	Criterion	Arrival	Mid-Voyage	Departure
C_{DS1_a}	0.445	0.441	0.436	C_{DS2}	0.087	0.087	0.083
C_{DS1_b}	5.74	4.89	4.33	C_{EA2}	2.27×10^{-2}	2.43×10^{-2}	2.20×10^{-2}
C_{EA1}	7.042	7.379	7.470	C_{PL2}	0.041	0.031	0.024
C_{PL1}	−2.491	−2.2170	1.963	C_{PR2_a}	0.000	0.000	0.000
C_{PR1}	1.149	0.971	0.820	C_{PR2_b}	7.70×10^{-3}	5.00×10^{-3}	5.40×10^{-3}
				C_{SR2}	0.0204	0.0200	0.0245

As initial comment on the analyzed vessels, it appears that setting a restriction on the geographical area to the SGISc turns to be more severe than the original assessment, i.e., considering the North Atlantic Ocean. This is especially evident for Lv1 criteria, which are the most influenced by the change in wave scatter table. In general, the values of the criteria seem to be worse than the previous analysis, i.e., the criterion is much larger than the standard upper threshold (criterion met when $Crt < Std$) and vice versa. In contrast, for Lv2 criteria, a defined trend in their values is not easily identified. It seems there is a slight improvement in Lv2 criteria, although this is not confirmed in all criteria. The general worsening of SGISc when applying the geographical restriction, may be related to the limited dimensions of the investigated vessels (LOA < 75 m), which are comparable to the mean wavelength of the central Mediterranean Sea wave scatter table, i.e., about $\lambda = 65$ m.

The general worsening of the stability in waves performance is well reproduced by the ISWI. In fact, the ISWI values register a mean increase of about 208%, with a maximum increase of 496% for Y03 in the mid-Voyage condition. The significant worsening of Lv1 criteria compared to Lv2 criteria, may justify the huge increase in ISWI for Y03.

Table 13. Summary of the evaluation of the ISWI for all investigated loading conditions in the central Mediterranean Sea.

ISWI—Intact Stability in Waves Index			
Unit	Arrival	Mid-Voyage	Departure
Y01	16.8940	15.2407	13.9300
Y02	3.5394	3.4977	3.5529
Y03	11.0437	11.1348	10.2035

6. Conclusions

A continuous improvement in the field of intact stability field is revealed by the continuous effort of the IMO sub-committees. In fact, SGISc can be considered one of the most important innovations in the last 15 years, thanks to its multilayered approach and the integration between design and operational criteria. In addition, the literature review shows that there is a relevant interest in the study of a quantitative index able to measure the comprehensive stability performance of a vessel. Different parameters have been identified as possible stability indexes; however, it seems that a comprehensive view is missing, except in a few cases. In this work, the merging of these two important topics has been attempted. After an introduction to the SGISc, an all-embracing index, taking into account the stability in waves performance, has been proposed. The main outcomes and relevant conclusions of this work are presented hereafter:

– As a first analysis, the effects on the righting moment and on the metacentric height of the wave passages have been studied. It appears that Y01 has a different behavior to the other units, in terms of the investigated stability parameters. This trend is ascribed to the typical planning hull shape and to the presence of spray rails. In turn, all other units are semi-displacement hull, with a classic round bilge hull.

– The outcomes provided by the SGISc application, show that Y01 seems to be the worst unit in terms of stability in waves performance. This can be attributed to it having the smallest size and to its vertical position of the CoG. In fact, Y01 presents the highest value of the dimensionless ratios KG/D and KG/d, compared to the other units. These results are well reflected in the ISWI application.
– The outcomes show that the change in geographical area negatively affects the Lv1 criteria, resulting in larger related criteria for all vessels. On the contrary, Lv2 criteria assume an undefined trend, which in some cases results in an improved performance.
– The application of the ISWI results in consistent outcomes, reflecting well the changes in stability in waves criteria due to the chosen operational restriction related to the geographical area, i.e., the central Mediterranean Sea. The results of the ISWI reflect well the behavior of the SGISc, resulting in a consistent assessment of the intact stability in waves performance.
– It is deemed that the definition of an exhaustive index for each loading condition, will positively affect the assessment of operative aspects by the master during navigation. In fact, the availability of a stability index related also to the environmental conditions, may be a valuable support to the decision making process in the routing operations.

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Abbreviations and Symbols

The following abbreviations and symbols are used in this manuscript:

ΔGM	Metacentric height variation in waves, [m];
Δ	Ship displacement, [t];
∇_D	Immersed volume at a draft equal to D, [m^3];
∇	Immersed volume at a draft d, [m^3];
θ_0	Heel angle due to the steady wind action in the weather criterion, [deg];
θ_{SD}	Angle of side-deck immersion, [deg];
φ	Characteristic roll amplitude, [-];
A_W	Waterplane area at a draft equal to d, [m^2];
a	Weather criterion left-side area below the righting arm, [m·rad];
b	Weather criterion right-side area below the righting arm, [m·rad];
B	Ship breadth, [m];
C_∇	Lv1 criterion on the hull shape, [-];
C_{DS1_a}	Lv1 criterion of dead ship condition on the underlined GZ area, [-];
C_{DS1_b}	Lv1 criterion of dead ship condition on the heeling angle θ_0, [deg];
C_{DS2}	Lv2 criterion of dead ship condition, [-];
C_{EA1}	Lv1 criterion of excessive acceleration, [-];
C_{EA2}	Lv2 criterion of excessive acceleration, [-];
C_{LT}	Generic long-term criterion, [-];
C_{PL1}	Lv1 criterion of pure loss of stability, [-];
C_{PL2}	Lv2 criterion of pure loss of stability, [-];
C_{PR1}	Lv1 criterion of parametric roll, [-];
C_{PR2_a}	Lv2 criterion of parametric rolling on the righting arm variations in waves, [-];
C_{PR2_b}	Lv2 criterion of parametric rolling on the dynamic roll response, [-];
C_{SR2}	Lv2 criterion of surf-riding, [-];

C_{ST}	Generic short-term criterion, [-];
Crt_{min}	Minimum value achievable by the considered criterion;
Crt	Value of the considered criterion;
d_H	Draft passing through the wave crest, [m];
d_L	Draft passing through the wave trough, [m];
D	Ship depth, [m];
d	Ship draft, [m];
Fn	Froude number, [-];
g	Gravity acceleration, [m·s^{-2}];
GM_{min}	Minimum metacentric height in waves, [m];
GM	Metacentric height in calm water, [m];
GZ	Righting arm in calm water, [m];
h_r	Vertical position above the roll axis where crew and passengers may be present, [m];
k_L	Coupling factor taking into account the simultaneous action of pitch, roll, and yaw, [-];
k	Weighting factor in the ISWI, [-];
L_{OA}	Overall ship length, [m];
L	Ship length according to IS code, [m];
PI	Partial index constituting the ISWI, [-];
R_{PR}	Standard threshold for the Lv1 PR, [-];
R	Generic standard threshold for Lv2, [-];
S_w	Wave steepness, [-];
Std	Standard threshold of the considered criterion;
T_ϕ	Ship natural roll period, [s];
V_S	Ship service speed, [m·s^{-1}];
W_S	Sea state weighting factor, [-] ;
CoG	Center of gravity;
DS	Dead ship condition stability failure mode;
DSA	Direct stability assessment;
EA	Excessive acceleration stability failure mode;
IMO	International maritime organization;
IS code	Intact stability code;
ISWI	Intact stability in waves index;
Lv1	First vulnerability level;
Lv2	Second vulnerability level;
MSC	Maritime safety committee of IMO;
OG	Operational guidance;
OL	Operational limitations;
OM	Operational measures;
PL	Pure loss of stability stability failure mode;
PR	Parametric roll stability failure mode;
RAO	Response amplitude operator;
SDC	Ship design and construction sub-committee of IMO;
SGISc	Second generation intact stability criteria;
SR	Surf-riding stability failure mode.

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