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An Investigation about Stability in Waves of Large Pleasure Yachts

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Abstract: The IMO's second-generation intact stability criteria (SGISc) have been applied to a set of seven megayacht units ranging from 40 m to 80 m. The application aims to evaluate their stability performance in a seaway. The assessment is based on two vulnerability levels, and the related criteria rely on the physics of the phenomena under investigation (dead ship condition, excessive acceleration, parametric rolling, pure loss of stability, and surf-riding). At the same time, SGISc provide methodological approaches to consider possible operational limitations related to the geographical area the vessel is meant to sail. Results of the comprehensive analysis carried out for the selected megayacht units are presented in term of limiting KG curves. Outcomes pointed out that inconsistencies among vulnerability levels still exist. Further comments about the relation of the investigated vessel typology and relevant operational profile have been reported. In addition, systematic analysis of the effect of the main design parameter on ship rules compliance has been carried out.

Keywords: stability in waves; second generation intact stability criteria; design for safety; megayacht; pleasure yacht; operational limitation

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1. Introduction

Yachts have undergone significant changes in size in recent decades. In fact, we can certainly say that, in just 20 years, the average length of yachts and their gross tonnage have more than tripled, from 30–40 m yachts of the late 1990s to the current units that exceed 120 m. This growth in size has gone hand in hand with an evolution of the intended use: from mainly coastal use with short crossings, to longer crossings in open seas, therefore with possibly demanding weather conditions. Furthermore, while the first yachts were intended for private use, recently we witnessed the development of the charter mode, implying the guests pay for the temporary usage of the yacht, creating a condition similar to passenger ship commercial exploitation. Moreover, since they are meant to be luxury assets, yachts offer increasingly versatile and elegant layouts together with technologically demanding performance, e.g., the Ice Class features are used if guests want to enjoy a cruise in seas with the presence of ice. This rapid development from both a commercial and a technological point of view has forced rule-making bodies to consistently upgrade safety rules in order to guarantee adequate safety standards [1]. From this perspective, standards related to intact and damaged stability have been addressed and, at present, they are basically in line with SOLAS requirements. Following this trend, as already examined in previous works Annex 9 of [2], it seems appropriate to investigate the compliance of modern yacht units to the Second Generation Intact Stability criteria (SGISc) established by the International Maritime Organization (IMO) [3]. This innovative stability rule framework focuses on the influence of waves on vessel stability, overcoming the limitations of the traditional criteria based on stability assessment in calm water. A further reason for the investigation is the evidence that yacht speed may be very close to $Fn = 0.4$, representing a possibly critical situation for ship sailing in following seas [4].

The growing interest in large pleasure yachts is also reflected among researchers; in fact, many studies have been published in recent years focusing on several aspects. In [5], an investigation into air pollutant emission of yacht transfer is presented, and in [6], the enhancement of safety through an integrated methodology applied to an on-board system is presented. Stability and seakeeping aspects have been addressed as well, with particular reference to comfort-related problems during navigation. Studies on anti-rolling devices such as fins and gyroscopes applied to pleasure yachts can be found in the literature [7,8]. Dynamic stability in the waves of a large sailing yacht is studied in [9,10]. With regard to the intact stability of a large motor yacht, relevant work has been done in [11,12], where a method to identify the main stability parameters at early design stages is proposed. However, it seems that the application of SGISc to motor yachts is missing except for the sample calculations carried out by the Superyacht Builder Association (SYBASS) in Annex 9 of [2].

An overview of the intact stability criteria for pleasure yachts, with a focus on SGISc, is given in Section 2. In Section 3, a description of the undertaken investigation and of the sample of the analyzed yachts is reported. In Section 4, results of the comprehensive analysis have been reported for the first investigated vessel, in a standardized format. A focus on the influence of specific parameters on dynamic stability behavior has been carried out in Section 5. Finally, comments on the outcomes are given in Section 6.

2. Rule Context

Although these vessels are not merchant ships, they are nevertheless characterized by a significant safety rule framework that, in some cases, is strongly connected to IMO rules. In the following paragraphs, an overview of the rule context for motor yachts is given, and an introduction to the SGISc is provided as well.

2.1. Overview of Present Safety Rules for Yacht Units

The safety rules framework for yachts has been in continuous evolution as a consequence of the above-mentioned growth in size and service. It followed the evolution of the market: in the 1980s and the beginning of the 1990s, the use of the vessel as a private yacht, i.e., for the exclusive use of the owner, was the typical situation. At the end of the 1990s, the yacht market developed into charter mode, i.e., the possibility of renting out the yacht to people different from the owner, thus making a profit. Due to the limitation of 12 passengers (in this situation, paying guests), the result of the charter mode was the birth of a series of rules for charter yachts developed by different flag administrations and then classification societies, in order to set adequate standards for yacht safety. In parallel, the average size of yachts increased: in the 1990s, the largest yacht built in Italy, the Nabila,had a length less than 85 m. Only 10 years later, yachts over 80 m were under construction everywhere in the most important yacht-producing countries (Italy, Germany, and The Netherlands). Today, yachts exceeding 100 m in length number in the dozens. Reflecting this evolution, the Large Yacht (LY) Code has been introduced by the UK's Maritime and Coastguard Agency (UK-MCA). The LY1, or Code of Practice for the Safety of Large Commercial Sailing and Motor Vessels, was introduced in 1998, covering vessels in commercial use for sport or pleasure that are at least 24 m in load line length. The subsequent edition, LY2, The Large Commercial Yacht Code, came into effect on 24 September 2004, characterized by an increased attention to the charter mode. In 2013, the LY2 was replaced by the LY3, an updated version. Finally, in 2019, the Code changed again, merging the rules addressing the possibility of carrying up to 36 passengers, obviously reflecting the increased size of vessels [13].In the rules evolution described above, the main features in terms of the Intact Stability Code were basically: the introduction of additional criteria that considered the crowding of passengers on a side; and the launch of tenders with consequent heeling moment due to the crane disembarking the tender.

2.2. Second Generation Intact Stability Criteria

In recent years, IMO worked on an improvement to the intact stability regulations for merchant ships contained in the Intact Stability (IS) Code, which was last revised more than 10 years ago [14]. In the preamble of the IS code, three dynamic phenomena have been identified that may lead to a set of dangerous stability failures. Therefore, an IMO working group was established to study and to develop safety criteria concerning these stability failures. The identified stability failure modes are parametric rolling (PR), pure loss of stability (PL), dead ship condition (DS), excessive acceleration (EA), and surf-riding/broaching-to (SR). The phenomena are quite complex, and many valuable studies can be found in the literature [15–17]. Finally, in 2020, the interim guidelines for the SGISc were issued by [3]. Two years later, the explanatory notes to the interim guidelines were also finalized [18]. The SGISc rely on a multilayered approach: three different levels have been defined for each stability failure, with increasing accuracy but also with higher complexity. Although this approach was adopted based on a bottom-up sequential approach, the latest version of the criteria explicitly notes that there is no hierarchy among levels. This means that, according to the rules, a loading condition is deemed not vulnerable to a stability failure if at least one level is met. A graphical representation of the multilayered approach adopted in the framework of SGISc is given in Figure 1.

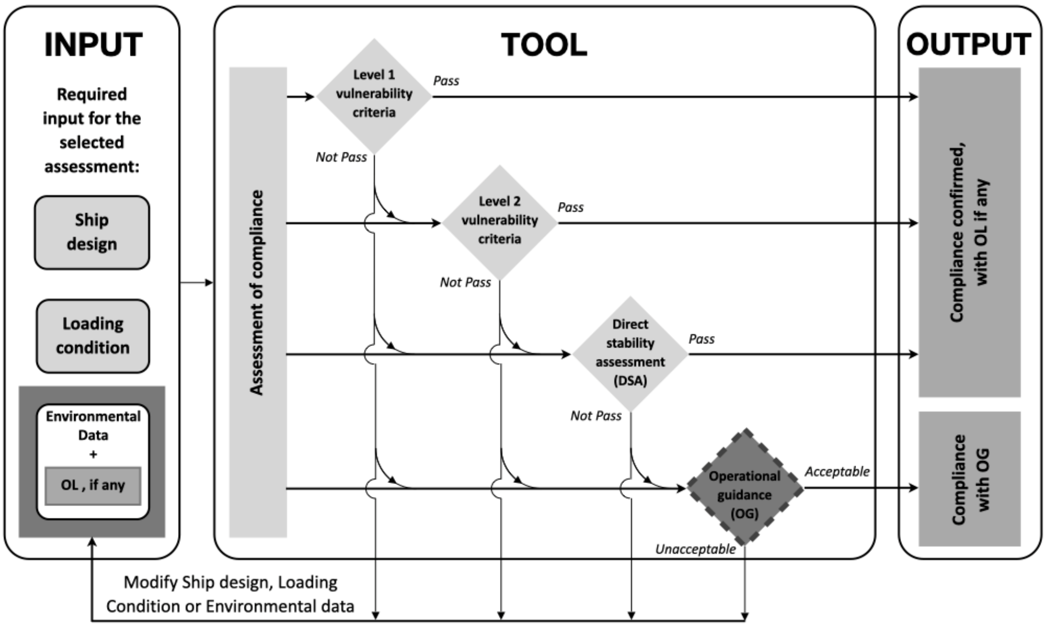


Figure 1. Graphical representation of the multilayered approach adopted in the framework of SGISc.

The first level (Lv1) and the second level (Lv2) are called vulnerability levels. Several applications and studies on vulnerability levels can be found in the literature [19–21]. The third level is called the direct stability assessment (DSA): it requires an enhanced time-domain non-linear numerical tool or a model tank test. The DSA should represent the highest level of accuracy; however, it is highly time-consuming. Interesting work on the DSA has been published by [22,23] and other authors [24,25]. Besides the vulnerability level implications during the design phase, SGISc introduce the operational aspects related to the navigation by operational measures. Operational measures can be divided into operational limitation (OL) and operational guidance (OG). The former sets restrictions on the navigation related to the environmental conditions; the latter provides suggestions to the master on how safely handle the vessel in dangerous sailing conditions (i.e., a combination of sea state, route, and speed). Applications of OL and OG can be found in the literature [26–28].

2.2.1. Structure of the First Vulnerability Levels

The first vulnerability levels have been developed in order to roughly identify a vessel's vulnerability to a stability failure using a relatively quick and simple tool. However, the simplifications imply that these criteria are highly conservative. A detailed description of the first vulnerability criteria reported herein can be found in the MSC.1/Circular 1627 [3] and related Explanatory Notes [18]. In Lv1, PR and PL are assessed through an analysis of waterplane variation due to the wave profile. In particular, the PL criterion deems a loading condition not vulnerable if (1) is satisfied:

$$GM_{min} \geq 0.05\,\text{m}, \quad (1)$$

where GM_{min} is the metacentric height evaluated considering a hydrostatic passing through the wave trough. It is considered a regular longitudinal wave with a length equal to the ship length and a steepness S_w equal to 0.0334. According to the PR criterion, a loading condition is deemed not vulnerable if (2) is satisfied:

$$\frac{\Delta GM}{GM} \leq R_{PR}, \quad (2)$$

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 passing through the wave trough and crest. It is considered a regular longitudinal wave with a length equal to the ship length and a steepness S_w equal to 0.0167. Both PL and PR Lv1 should comply with the criterion about hull shape reported in (3):

$$C_{\nabla} = \frac{\nabla_D - \nabla}{A_{wl} \cdot (D - d)} \leq 1.0, \quad (3)$$

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_{wl} is the waterplane area. The criterion for DS Lv1 corresponds to the so-called weather criterion defined in the IS code [14]. A minor modification has been introduced: the table representing the relationship between the natural roll period and the wave steepness has been replaced by the corresponding table defined in the guidelines within MSC.1/Circular 1200 [29]. The EA Lv1 criterion considers a loading condition not vulnerable if (4) is met:

$$C_{EA} = \varphi \cdot k_L \cdot \left(g + \frac{4\pi^2 \cdot h_r}{T_{nat}^2} \right) \leq 4.64\,\text{m} \cdot \text{s}^{-2}, \quad (4)$$

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 gravity acceleration; 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. Finally, the Lv1 criterion for SR considers a loading condition not vulnerable if (5) is satisfied:

$$Fn \leq 0.30 \quad \text{and} \quad L > 200\,\text{m}, \quad (5)$$

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

2.2.2. Structure of the Second Vulnerability Levels

Second vulnerability levels have been developed, adopting a long-term analysis over a selected set of sea states. The long-term criteria C_{LT} of Lv2 share a similar structure as defined in (6):

$$C_{LT} = \sum_{i=1}^{N} W_{S_i} \cdot C_{ST_i}, \quad (6)$$

where N is the total amount of considered sea states; W_S is the statistical weight of a single sea state defined by a wave scatter table; and C_{ST} is the short-term criterion of the considered sea state. A loading condition is deemed not vulnerable to a stability failure if the long-term criterion is equal to or lower than a standard R. The definition of the short-term criterion and standard is different for each stability failure. A technical description of the short-term criteria is not provided here, but it can be found in the MSC.1/Circular 1627 [3]. For PL and PR, two long-term criteria are to be evaluated. In PL, the short-term criteria rely on geometric analysis, considering the effect of several wave profiles on hull stability, aimed at identifying the vanishing angles and stable heel angle. The short-term criteria for PR have a different approach: one criterion studies the effect of several wave profiles on the metacentric height variation, while the second criterion assesses the maximum roll angle achieved by a simplified one-degree-of-freedom time-domain simulation. For SR, the short-term criterion is computed by an iterative procedure involving the hull resistance curve, the propeller characteristics curves, and the wave surging force. The DS short-term criterion is obtained by an analysis of the roll moment response spectrum considering the effects of waves and wind. Finally, for EA, the criterion is evaluated by the study of the response amplitude operator for lateral accelerations.

3. Case Study

In this section, the investigated vessels are identified, and the process of investigation is described.

3.1. Description of the Investigated Vessels

The selection of the motor yacht units for the investigation is based on a series of considerations: the range, spanning from 40 m to 77 m, allows for covering a large quantity of motor yachts produced over the last three decades. In Figure 2, a three-dimensional view of one of the investigated units is shown.

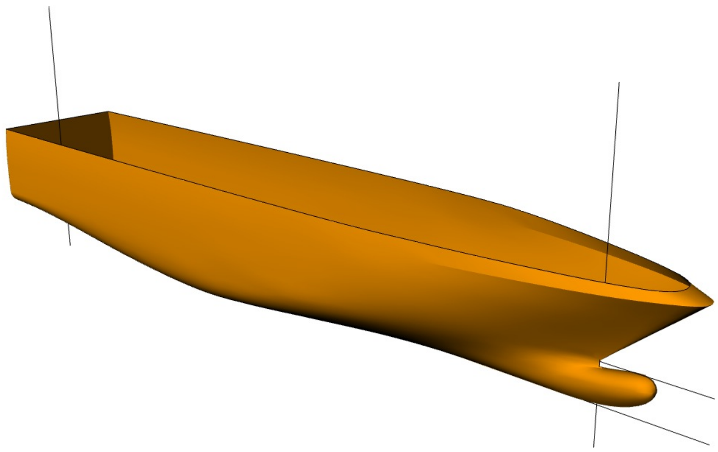


Figure 2. Three-dimensional view of the unit Y06.

Furthermore, these sizes are interesting from the scientific approach due to their interaction with sea conditions that typically characterize the Mediterranean area. It is also important to note that, due their dimensions, vessels in this range usually show a ratio between the KG and D, which offers the opportunity for interesting considerations of the stability performances [4]. The main dimensions of the considered vessels, as well as the propeller diameter $D_{Prop.}$, are reported in Table 1. Moreover, a graphical representation of the parameters constituting the metacentric height (i.e., BMT, KB, and KG) along the whole range of investigated yachts is reported in Figure 3.

Table 1. Main characteristics of the investigated motor yacht units.

Megayachts	L_{OA} (m)	L_{wl} (m)	B_{max} (m)	B_{wl} (m)	D (m)	V_S (kn)	Δ_{full} (t)	LCG (m)	KG (m)	C_B -	C_M -	C_{VP} -	$D_{Prop.}$ (m)
Y01	42.65	38.00	8.21	8.17	4.80	15.0	400	17.02	3.28	0.451	0.697	0.582	1.40
Y02	44.70	42.10	8.60	8.01	4.30	20.0	330	17.09	3.37	0.495	0.791	0.618	1.60
Y03	47.00	42.40	9.00	8.62	4.80	13.0	460	17.08	3.71	0.475	0.773	0.612	1.40
Y04	65.00	58.68	11.31	11.30	6.00	15.0	1360	22.71	5.18	0.548	0.800	0.643	1.91
Y05	67.50	60.31	11.02	11.01	5.20	15.0	940	22.75	4.63	0.411	0.746	0.545	1.94
Y06	74.40	66.74	13.20	12.97	7.50	17.5	1580	31.74	5.50	0.539	0.903	0.653	1.90
Y07	77.70	67.93	13.00	12.32	7.00	15.0	1410	30.05	5.55	0.397	0.677	0.527	1.90

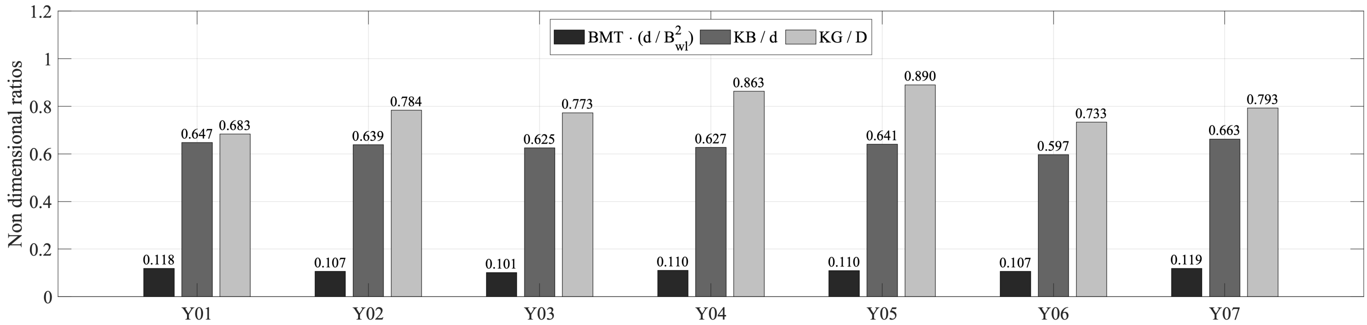


Figure 3. Bar plot of the parameters constituting the metacentric height along the whole range of investigated yachts.

3.2. Details on the Assessment Process

A comprehensive assessment activity in the framework of SGISc has been carried out on the selected set of vessels. As a first analysis, Lv1 and Lv2 vulnerability levels have been addressed for each stability failure. The complete assessment requires the knowledge of additional information other than the main particulars, such as the resistance curve in calm water, the characteristic curves of the propeller, and the general arrangements of the superstructure. For the selected units, this information is not always completely available; therefore, the following assumptions have been made. The resistance curves of each unit have been obtained by given experimental tank tests, except for Y02, Y03, and Y06. The resistance curve of these vessels has been computed by the application of the approximate method of [30]. Concerning the propeller characteristics, since only the propeller diameter was known, the Wageningen B-series [31] data have been adopted for all vessels to obtain the further necessary details. Afterward, when applicable, the limiting KG curves have been drawn for all vulnerability levels. In this kind of analysis, the SR stability failure mode has not been addressed because its structure does not directly depend on the KG value. The second check of Lv2 of PR has not been considered within the KG limiting curves due to its strongly dynamic-based nature. For this specific stability failure, a representation of results by matrix calculation is deemed more suitable, e.g., as done by [32] or [33]. To prove the susceptibility of the main stability parameters to the wave profile, the effect of the wave crest position along the hull has been investigated as well. As an additional insight, the impact of geographical restrictions on the vulnerability outcomes has been studied, taking into account the typical operational area of the selected vessels. Following the SGISc guidelines, an OL procedure has been applied considering the wave scatter diagram for the central Mediterranean Sea. This kind of OL can be applied by making reference to all Lv2 and to Lv1 of PR and PL. The formulations of criteria for the other stability failures do not depend on a change in environmental conditions. A graphical summary of the analysis carried out in this work is provided in Figure 4.

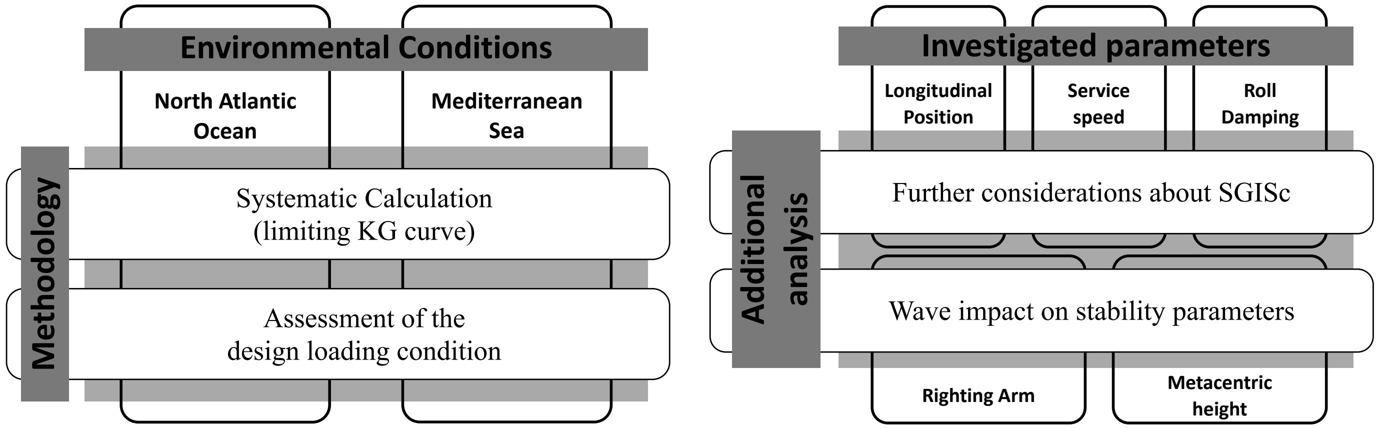


Figure 4. Graphical summary of the analysis carried out in this work.

The investigations described above were carried out using a computational tool developed in-house in MATLAB software. The tool has been used extensively in the authors' previous works [20]. The investigations required approximately three weeks of working hours for all seven units, including data preprocessing, computational time, and results post-processing.

4. Results Overview

In this section, the results of the comprehensive assessment are presented. As a reference case, the complete outcomes are shown in Section 4.1, only for the first unit (Y01). In Section 4.2, the outcomes of the additional analyses of the impact of wave profile on the main stability parameters are presented. Finally, a short summary of the results comprising all investigated vessels is given in Section 4.3.

4.1. Example of the Complete Outcomes for Y01

In this section, a standardized format is proposed for results presentation of a comprehensive stability analysis based on SGISc.

4.1.1. Outcomes of the Vulnerability Assessment

Due to the large amount of data and tables, a complete and exhaustive report is given only for Y01. However, the complete assessment has been carried out for all the selected vessels and summarized in Section 3. In Table 2, the results of the complete assessment of vulnerability levels for the loading conditions of Y01 are presented.

Table 2. Outcomes of the SGISc application to the loading conditions for Y01.

	Level 1 Criterion	Loading Condition Arrival	Mid-Voyage	Departure		Level 2 Criterion	Loading Condition Arrival	Mid-Voyage	Departure
PR	$\Delta GM/GM \leq R_{PR}$	0.431	0.305	0.192	PR	$C1 \leq 0.06$	0.000	0.000	0.000
	Check ≥ 1	1.128	1.113	1.078		$C2 \leq 0.025$	0.000	0.000	0.000
PL	$GM_{min} \geq 0.05$ m	−0.018	0.290	0.639	PL	$CR1 \leq 0.06$	0.000	0.000	0.000
	Check ≥ 1	1.128	1.113	1.078		$CR2 \leq 0.06$	0.104	0.098	0.036
DS	$b/a \geq 1$	0.206	0.654	7.986	DS	$C_{DS} \leq 0.06$	0.502	0.369	0.094
EA	$C_{EA1} \leq 4.94\ m \cdot s^{-2}$	6.914	7.169	7.813	EA	$C_{EA} \leq 3.9 \times 10^{-4}$	2.50×10^{-4}	5.11×10^{-4}	1.90×10^{-3}
SR	$Fn \geq 0.30$	0.402	0.402	0.402	SR	$C_{SR} \leq 0.005$	0.0713	0.0687	0.0702
	$L \geq 200$ m	37.307	37.367	37.510					

According to MSC.1/Circ.1627 [3], a ship is considered not vulnerable to a stability failure if compliant with at least one vulnerability level. Therefore, in Table 3, the final outcomes of the assessment for the loading conditions of Y01, merging the results of the two vulnerability levels, are reported.

Table 3. Summary of the vulnerability assessment for Y01.

Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
PR	MET	MET	MET
PL	NOT MET	MET	MET
DS	NOT MET	NOT MET	MET
EA	MET	NOT MET	NOT MET
SR	NOT MET	NOT MET	NOT MET

Once the comprehensive assessment was completed, the limiting *KG* curve was defined. It is worth noting that the limiting curves for PR, PL, and DS identify an upper limit (i.e., maximum *KG* value), while the EA criterion identifies a lower limit (i.e., minimum *KG* value); this is related to the physics of the phenomenon addressed by the EA stability failure. Adopting the same principle of no hierarchy among levels mentioned above, the highest maximum (or lowest minimum) *KG* value is selected between Lv1 and Lv2 for each stability failure. The final limiting *KG* curves for Y01, considering both levels, are reported in Table 4. In Figure 5, a graphical representation of limiting *KG* curves is given; on the horizontal axis, the draft is measured, while the limiting *KG* is reported on the vertical axis. Continuous lines indicate the maximum *KG* curves, and the *KG* minimum curve is represented by a dashed line; black crosses show the investigated loading conditions. When applicable, the gray shaded area shows the design domain (i.e., combination of *KG* and draft) where all stability failure modes are met.

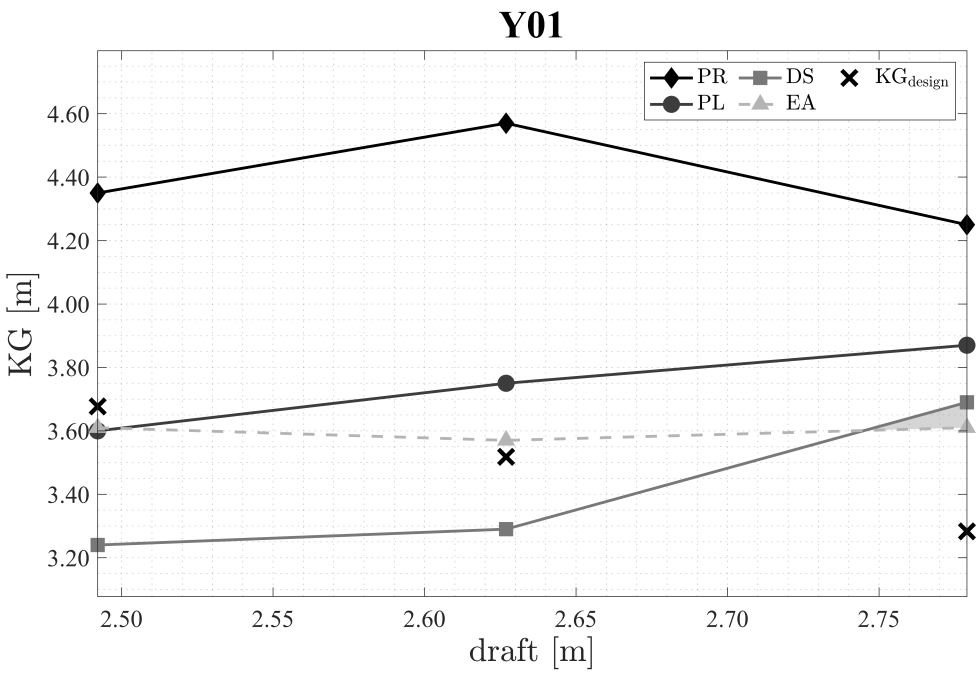


Figure 5. Limiting *KG* curves for Y01.

Table 4. Final maximum and minimum limiting *KG* curves of each level for Y01.

Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
	maximum *KG* (m)		
PR	4.35	4.57	4.25
PL	3.60	3.75	3.87
DS	3.24	3.29	3.69
	minimum *KG* (m)		
EA	3.61	3.57	3.61

4.1.2. Outcomes of the Vulnerability Assessment with Operational Limitations

In addition to what is presented above, for all vessels, the very same analyses have been carried out considering the application of OL related to a specific geographical area. In this work, the central Mediterranean Sea has been considered and represented by the wave scatter table given in Appendix B. Again, as a reference case, only for Y01 is the complete analysis shown. Assessment outcomes for both levels are given in Table 5. The vulnerability assessment results for each stability failure are given in Table 6. Finally, the limiting *KG* curves are reported in Table 7. In Figure 6, a graphical representation of the *KG* limiting curves is given.

Table 5. Outcomes of the SGISc application to the loading conditions for Y01 considering OL related to the Mediterranean Sea.

	Level 1 Criterion	Arrival	Loading Condition Mid-Voyage	Departure		Level 2 Criterion	Arrival	Loading Condition Mid-Voyage	Departure
PR	$\Delta GM/GM \leq R_{PR}$	0.991	0.305	0.192	**PR**	$C1 \leq 0.06$	0.000	0.000	0.000
	Check ≥ 1	1.128	1.113	1.078		$C2 \leq 0.025$	0.000	0.000	0.000
PL	$GM_{min} \geq 0.05$ m	−1.785	0.290	0.639	**PL**	$CR1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.128	1.113	1.078		$CR2 \leq 0.06$	0.214	0.144	0.114
DS	$b/a \geq 1$	0.206	0.654	7.986	**DS**	$C_{DS} \leq 0.06$	0.313	0.273	0.128
EA	$C_{EA1} \leq 4.94\,\mathrm{m \cdot s^{-2}}$	6.914	7.169	7.813	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	3.90×10^{-4}	1.00×10^{-3}	4.80×10^{-3}
SR	$Fn \geq 0.30$	0.402	0.402	0.402	**SR**	$C_{SR} \leq 0.005$	0.1078	0.1064	0.1064
	$L \geq 200$ m	37.307	37.367	37.510					

Table 6. Summary of the vulnerability assessment for Y01 considering OL related to the Mediterranean Sea.

Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
PR	MET	MET	MET
PL	NOT MET	NOT MET	NOT MET
DS	NOT MET	NOT MET	MET
EA	NOT MET	NOT MET	NOT MET
SR	NOT MET	NOT MET	NOT MET

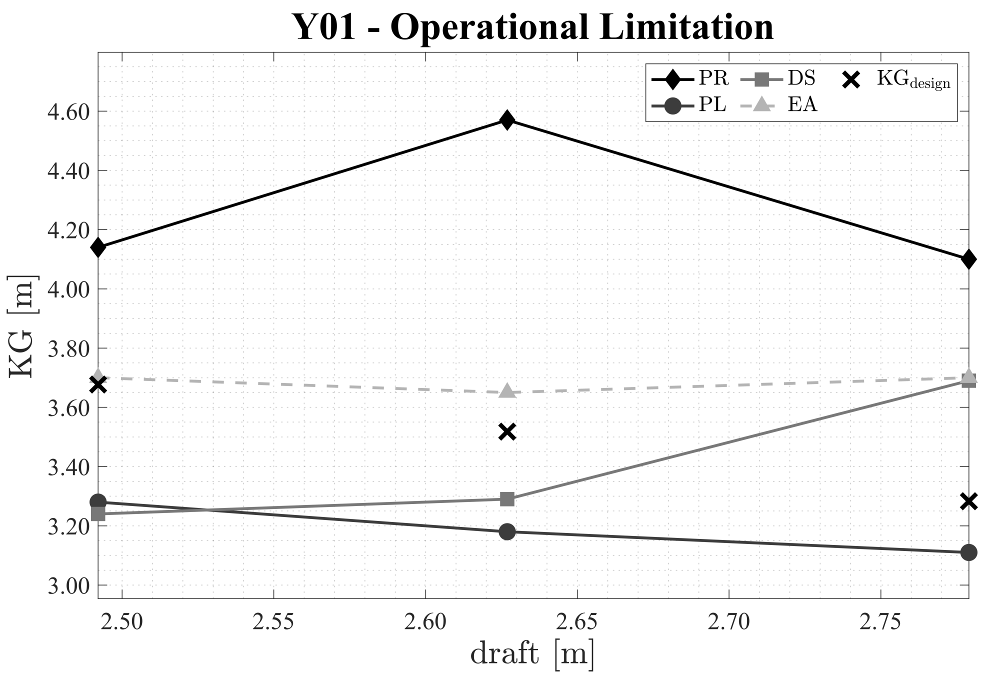


Figure 6. Limiting *KG* curves for Y01 considering OL related to the Mediterranean Sea.

Table 7. Final maximum and minimum limiting *KG* curves of each level for Y01 considering OL related to the Mediterranean Sea.

Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
	maximum ***KG*** **(m)**		
PR	4.14	4.57	4.10
PL	3.28	3.18	3.11
DS	3.24	3.29	3.69
	minimum ***KG*** **(m)**		
EA	3.70	3.65	3.70

4.2. Wave Profile Influence on the Intact Stability Parameters

In light of the outcomes of the SGISc application, it has been deemed noteworthy to conduct an additional investigation into the effect of the wave profile on the vessel. In particular, the impact of the wave profile on the righting arm *GZ* and on the transverse metacentric height *GM* as a function of the wave crest position has been investigated, as was done in the explanatory notes of the SGISc [18]. In Figure 7, the righting arm in wave divided by the maximum value is represented for all loading conditions of Y01. On the horizontal axis, the heel angle, measured in degrees, is reported. In Figure 8, the transverse metacentric height in waves divided by the *GM* in calm water is represented as a function of the wave crest position along the hull. The considered wave has a wavelength equal to the hull length and a steepness equal to 0.0334. These analyses point out a relevant susceptibility (e.g., a reduction of up to 20% of the absolute value is recorded in terms of both *GZ* and *GM*) of the main stability parameters for the wave profile, for all loading conditions of Y01. This conclusion is also applicable to all other analyzed motor yachts.

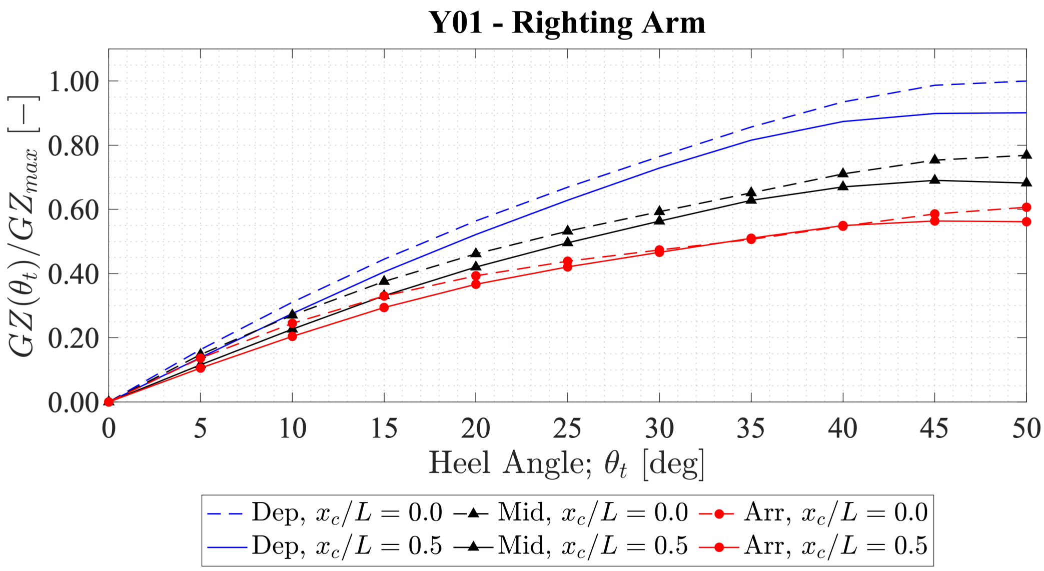


Figure 7. Righting arm in waves divided by its maximum value for all loading conditions of Y01. Continuous lines represent the wave crest amidship. Dashed lines represent the wave trough amidship.

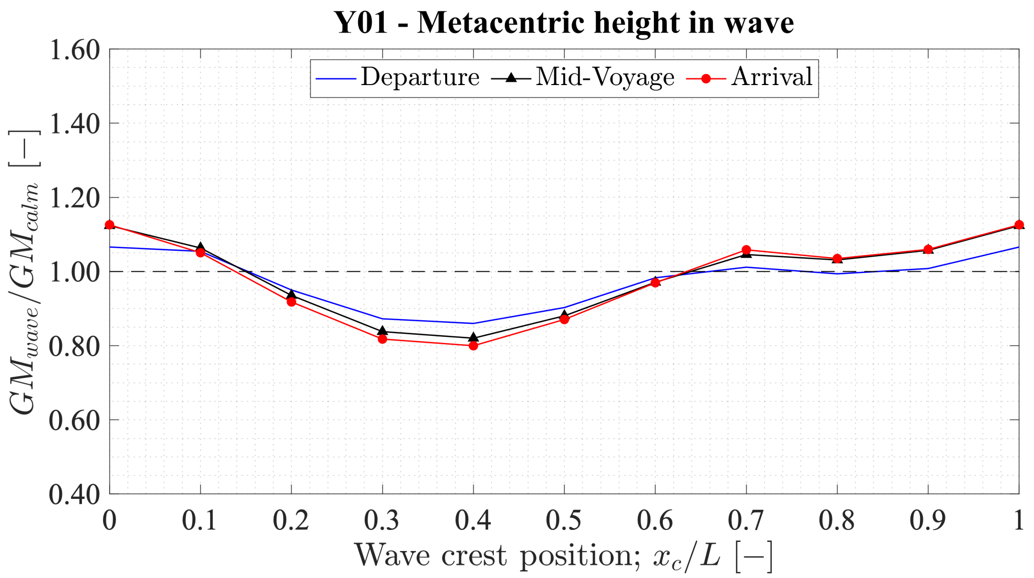


Figure 8. Transverse metacentric height in waves divided by GM in calm water for all loading conditions of Y01. On the horizontal axis, the wave crest position along the hull is reported.

4.3. Outcome Summary for All Vessels

Due to the large amount of data, the outcomes for all investigated vessels have been reported in Appendix A. In Table 8, a summary of the results is reported. The application of the vulnerability levels to a set of representative megayachts demonstrates that no loading conditions comply with all the criteria at the same time. Among 95 investigated cases (i.e., a combination of stability failure and vessel and loading conditions), about 56% of them are considered not vulnerable. All units are always deemed not vulnerable to the PR failure, while the SR criterion is met in 2 out of 19 investigated cases. The vulnerability assessment, taking into account OL, points out that less than 52% of cases among the 95 investigated cases are considered not vulnerable. Additionally, in this case, no loading conditions comply with all criteria at the same time. Again, the selected megayachts are always not vulnerable to the PR failure mode, and the SR criterion is met in 2 out of 19 investigated cases.

Table 8. Complete summary of the outcomes.

w/o OL Stability Failure	Across 19 Cases for Each Stability Failure			w/ OL Stability Failure	Across 19 Cases for Each Stability Failure		
	n° MET	n° NOT MET	% of MET		n° MET	n° NOT MET	% of MET
PR	19	0	100.0%	**PR**	19	0	100.0%
PL	15	4	78.9%	**PL**	8	11	42.1%
DS	6	13	31.6%	**DS**	9	10	47.4%
EA	11	8	57.9%	**EA**	11	8	57.9%
SR	2	17	10.5%	**SR**	2	17	10.5%

As a result of this investigation, it appears that the selected vessels suffer stability failure phenomena identified by the SGISc. This output had already been highlighted previously by SYBAss (Annex 9 of [2]). Moreover, it appears that applying the OL related to the Mediterranean Sea causes a worsening of the outcomes; in fact, the number of loading conditions not meeting the criteria increases. This may be related to the limited dimensions of the investigated vessels (L_{OA} < 80 m), which are comparable to the mean wavelength of the Mediterranean Sea wave scatter table, i.e., about λ_{mean} = 65 m. Considering the *KG* limiting curves, it appears that the four larger yachts have a sufficient design domain, i.e., the region of loading conditions (as a combination of draft and *KG*) fulfills all SGISc at the same time. From the design domain perspective, the application of OL related to the Mediterranean Sea enlarges the design domain for the largest yachts, i.e., L_{OA} > 65 m. On the contrary, the design domain of smaller yachts is negatively affected by the application of OL. As a further comment, it is worth mentioning that inconsistencies between vulnerability levels have been identified for the PL and DS stability failure modes among 4 out of 7 investigated yachts. In the SGISc framework, an inconsistency is defined as the case where a loading condition is deemed not vulnerable in one level but, at the same time, the higher level is not met.

5. Further Considerations for SGISc

In addition to the comprehensive assessment and to the definition of *KG* limiting curves, an insight into the criteria has been made for the set of investigated yachts. In particular, the following aspects have been investigated:

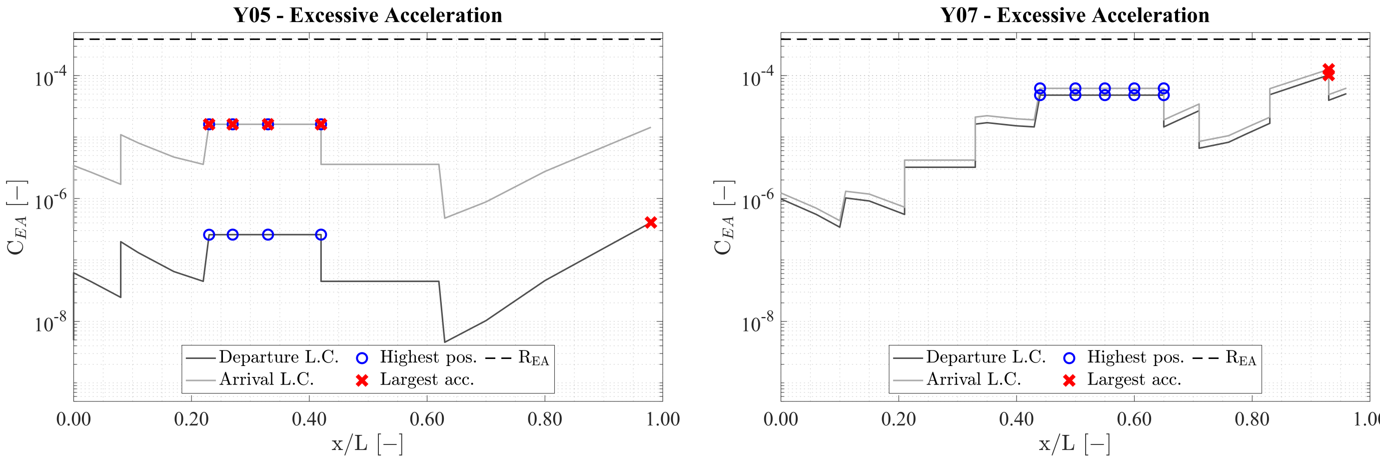
– The effects of the assessed longitudinal position on the EA criterion;
– The effect of the service speed on the surf-riding criterion;
– The effect of the experimental evaluation of the roll damping on PR, DS, and EA.

Outcomes of these further analyses are reported in the following sections.

5.1. Effects of the Longitudinal Position on the Excessive Acceleration Criterion

The EA assessment outcome is strictly related to the location on board that has been addressed for the investigation. The highest is the positions, while the largest is the lateral acceleration due to roll motion. However, if other ship motions are involved, such as pitch or yaw, this is not always true. To consider the combination of these motions (i.e., roll, pitch, and yaw), the regulation introduces the factor k_L as a function of the longitudinal position. Nevertheless, both Lv1 and Lv2 rule texts indicate to assess only the highest location where crew or passengers may be present, without any indication about the longitudinal position on board of the assessed location. Therefore, in this study, a sensitivity analysis has been carried out considering the highest location for a sample of positions along the longitudinal profile. In this work, the longitudinal position of the assessed location is defined as the distance from the aft perpendicular to the considered point on board selected for the EA assessment. It is usually expressed as a fraction of the length between perpendiculars.

Outcomes point out that, according to EA Lv2, 3 out of 19 loading conditions experience the largest lateral acceleration near the bow, although it is not the highest location on board. To show this issue, results for both loading conditions of units Y05 and Y07 are plotted in Figure 9. On the vertical axis, the EA Lv2 criterion is reported, while the non-dimensional longitudinal position is represented on the horizontal axis. The position where the largest acceleration occurs is highlighted by a cross for each loading condition. The highest positions are identified by a circle. As a reference, the standard threshold R_{EA} is represented by a horizontal dashed line.



(**a**) Unit Y05 (**b**) Unit Y07

Figure 9. Evaluation of the EA Lv2 criterion as a function of the non-dimensional longitudinal position from the aft perpendicular.

5.2. Effects of the Service Speed on the Surf-Riding Criterion

Since ship speed is one of the most important parameters affecting the SR phenomenon, a sensitivity analysis on this feature has been carried out. The second vulnerability level criterion has been considered, and all units have been analyzed. The service speed has been changed systematically as a function of the Froude number. Additionally, in this case, the OL related to the Mediterranean Sea has been applied as well. As a first attempt, the Froude number has been investigated in a range from $Fn = 0.2$ up to $Fn = 0.5$. The behavior of the criterion at a very high Froude number has been studied; however, it should be noted that, for longer vessels, this implies very large speeds that are actually far away from the design speed and practically unfeasible in the heaviest considered sea states. In Figure 10, the SR Lv2 criterion as a function of the Froude number is shown for each investigated ship, with and without the OL related to Mediterranean Sea. The horizontal straight line indicates the Lv2 maximum threshold, while the vertical line shows the design Froude number. Outcomes show that, for all vessels, above $Fn = 0.45$, the criterion assumes an asymptotic behavior around the value of 0.100. Below $Fn = 0.3$, for some units, the SR criterion increases, assuming an unstable trend. The understanding of this unstable behavior requires an additional insight that will be the subject of future work.

5.3. Effects of Experimental Evaluation of the Roll Damping

The effect of roll damping has been investigated as well. Experimental free roll decay model tests were available only for unit Y07. For the selected ship, the Lv2 of PR, DS, and EA has been applied, and the results have been compared to those obtained by the application of the methodology suggested in MSC.1/Circular 1627 [3], which relies on the simplified Ikeda method [34]. The loading conditions reported in Table 9 have been analyzed. Moreover, tests for both the loading conditions have been carried out with and without the presence of bilge keels.

The main goal of this analysis is to highlight the influence of the roll damping coefficient on the SGISc. Thus, the OL related to the Mediterranean Sea has not been applied. Outcomes of the comparison between the roll damping prediction methods (experimental tests vs. empirical methods) are reported in Table 10 and in Figure 11. When considering the experimental roll damping data instead of Ikeda's method, it appears that criteria compliance improves. Additionally, it seems that, using the experimental roll damping coefficient, all vulnerabilities detected by the criteria can be solved. Finally, as expected, the presence of the bilge keel has a relevant positive effect on the criteria.

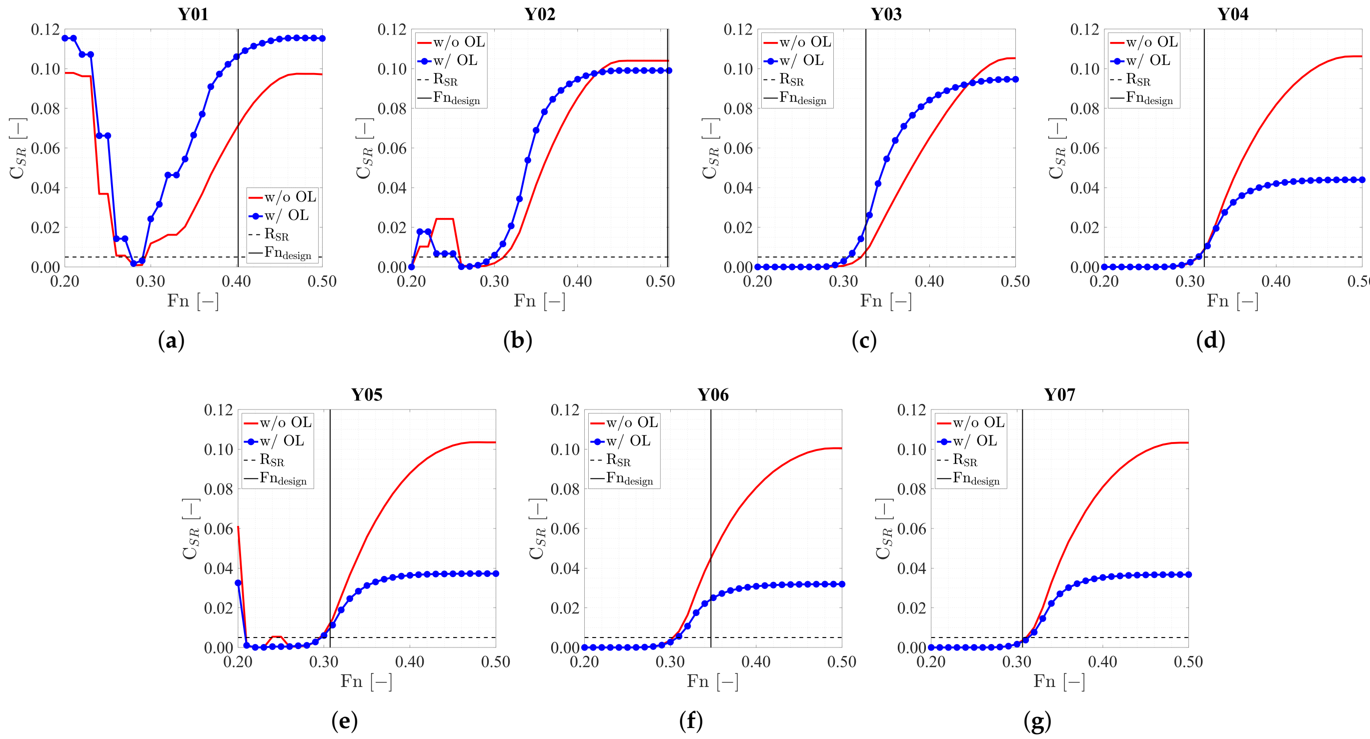


Figure 10. Analysis of the SR Lv2 on the ship speed.

Table 9. Loading conditions of Y07 considered in the roll damping investigation.

Loading Condition	Δ (t)	d (m)	KG (m)
LC01	860	3.10	5.12
LC02	920	3.20	4.91

Table 10. Comparison of the SGISc outcomes implementing different roll damping coefficient prediction methods.

Experimental Roll Damping Coefficient					Simplified Ikeda Method				
	Loading Condition					Loading Condition			
Stability Failure	**LC01 w/o BK**	**LC01 w/ BK**	**LC02 w/o BK**	**LC02 w/ BK**	**Stability Failure**	**LC01 w/o BK**	**LC01 w/ BK**	**LC02 w/o BK**	**LC02 w/ BK**
PR	1.44×10^{-3}	0.00	0.000	0.000	**PR**	3.06×10^{-3}	0.000	2.09×10^{-3}	0.000
DS	0.033	0.007	0.011	0.003	**DS**	0.584	0.057	0.509	0.032
EA	1.22×10^{-6}	6.31×10^{-11}	7.16×10^{-7}	3.04×10^{-9}	**EA**	5.34×10^{-3}	9.39×10^{-7}	7.73×10^{-3}	3.53×10^{-6}

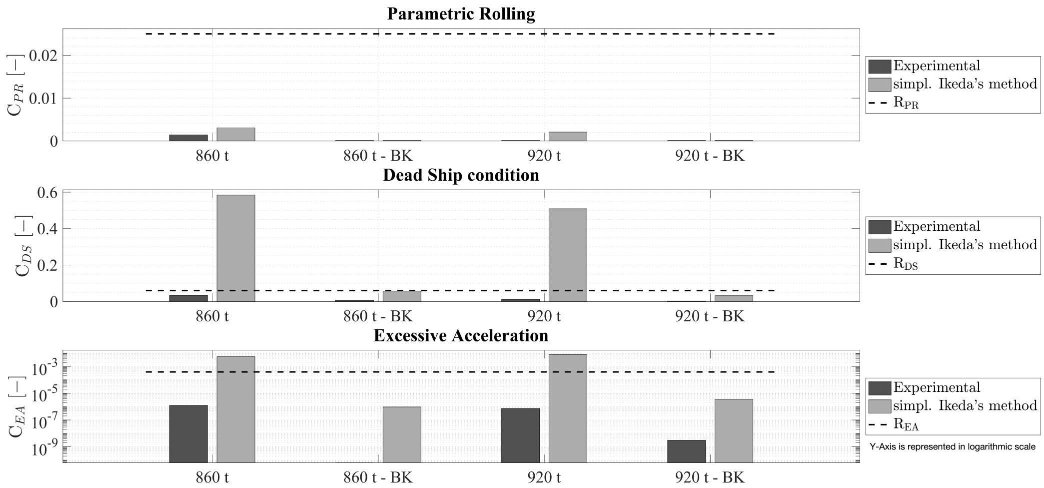


Figure 11. Comparison by bar plot of the roll damping evaluation methods for unit Y07.

6. Conclusions

A general overview on the evolution of motor yacht features in the last 30 years has been carried out. The development of specific regulations related to private or charter use of these units has been addressed as a collateral evolution, implying increasing scientific and technical competencies. The literature review on this topic points out that larger motor yachts may suffer from the stability failure phenomena newly identified at IMO and tackled by the SGISc. Therefore, a systematic and thorough assessment has been carried out on a set of seven representative motor yacht units by means of the application of all SGISc vulnerability levels. Finally, a selection of the SGISc has been deeply analyzed by a systematic variation in the main design parameters. In particular, the effect of the longitudinal position of the considered location for the EA assessment, the effects of ship service speed on SR, and the damping effect have been considered.

The outcomes achieved by the comprehensive analysis are reported as follows:

– Application of SGISc shows that all units are not vulnerable to PR failure, while vulnerability to SR failure affects almost all vessels under any investigated loading conditions. Actually, due to the relatively small dimension, vulnerability to SR was expected. Moreover, it is worth noting that, for this kind of vessel, the application of the weather criterion of the IS code is not mandatory. This is reflected in the results, when compliance with the DS failure mode is assessed.
– The OL related to the Mediterranean Sea has been applied, aimed at softening of the criteria compliance issues. This application points out that the expected improvement in terms of criteria compliance does not occur. In a general overview, OL reduces the vulnerability of loading conditions to DS and, in turn, vulnerability to PL seems to increase. Other stability failure modes are not affected by the application of OL related to the Mediterranean Sea.
– From the investigation carried out during the research activity, the important influence of the longitudinal position has been demonstrated as well, especially for the largest units. In such cases, the worst situation is spotted in a position near the bow, which is lower than the highest location on board. This is due to the coupling factor among motions related to lateral acceleration, i.e., roll, pitch, and yaw, and modeled in the criterion by the k_L factor. Nevertheless, it is an outcome to be considered in the refinement of the SGISc.
– As expected, the study of the effects of service speed on the SR criterion points out that, the greater the speed, the larger the criterion, although the criterion curve starts flattening over $Fn > 0.40$. Moreover, for some units at low speeds (i.e., $Fn < 0.30$), instabilities in the curve appear. This aspect requires further study because, in some cases, the unstable bounces may lead the unit to be considered vulnerable.

– The analysis of the damping coefficient demonstrates that the Ikeda simplified method seems to underestimate the damping coefficient compared to the free roll decay test. It is worth noting that the investigated unit is partially outside the applicability range of the Ikeda simplified method; thus, this may affect the final outcomes.

This work provides a comprehensive and detailed analysis of the wave stability performances of large motor yacht units. It aims to fill in the lack of expertise about SGISc applications for this kind of vessel. However, it is recognized that other assessments can be further developed on the megayacht typology, for instance, on the effect of the actual operational profile on the criteria. This aspect of the operational profile could open up an interesting progression in our work: the influence of the main routes followed by motoryachts and actual weather forecasts might be studied and combined to provide more accurate insight to the pleasure vessel framework. An enlargement of the database of investigated yachts and assessed environment conditions will be pursued as well. In addition, further insight to the criteria structure and how it influences the outcomes in relation to vessel typology will be analyzed in further works. The investigation of other environmental factors, such as the relationship among wind speed, sea state, and geographical area may trigger interesting research as well. As a final comment, it should be noted that, for several reasons, the DSA has not been carried out in this work. The availability of a proper numerical tool is a prerequisite but, in any case, the analysis would be time-consuming and costly. This may represent a limitation to the completion of the overall assessment of SGISc for motor yacht units. Additionally, simulations required by DSA will allow for superior accuracy in the actual impact of environmental loads on the evaluation of stability in waves. With regards to environmental loads, this work focuses directly on the influence of waves on ship stability. Nevertheless, it is recognized that other important related aspects have not been considered, such as structural integrity or ship propulsion (e.g., voluntary and/or involuntary speed reduction) and maneuvering in waves.

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Nomenclature and Acronyms

SYMBOL		**DEFINITION**
ΔGM	-	Metacentric height variation in wave according to PR Lv1
Δ_{full}	(t)	Ship displacement at full load condition
λ	(m)	Wave length
∇_D	(m^3)	Immersed volume at a draft equal to D
∇	(m^2)	Immersed volume at a draft equal to d
φ	-	Characteristic roll amplitude
A_{wl}	(m^2)	Waterplane area at a draft equal to d
a	(m rad)	Left-hand area below the GZ curve according to weather criterion in IS code
B_{max}	(m)	Maximum ship breadth
B_{wl}	(m)	Ship breadth at the design waterline
b	(m rad)	Right-hand area below the GZ curve according to weather criterion in IS code

BMT	(m)	Metacentric radius in calm water
C_{∇}	-	Criterion on hull shape according to PL and PR Lv1
C_B	-	Block coefficient: $\nabla/(L_{wl} \cdot B_{wl} \cdot d)$
C_{EA1}	(m s^{-2})	EA Lv1 criterion
C_{LT}	-	Long-term vulnerability criterion according to Lv2
C_M	-	Midship coefficient: $A_M/(B_{wl} \cdot d)$
C_{ST}	-	Shot-term vulnerability criterion according to Lv1
C_{VP}	-	Vertical prismatic coefficient: $\nabla/(A_{wl} \cdot d)$
D	(m)	Hull depth
$D_{\text{Prop.}}$	(m)	Propeller diameter
d	(m)	Draft
Fn	-	Froude number: $V_S/\sqrt{g \cdot L}$
g	(m s^{-2})	Gravity acceleration
GM_{min}	(m)	Minimum metacentric height in wave according to PL Lv1
GM	(m)	Metacentric height in calm water
GZ	(m)	Righting arm
GZ_{max}	(m)	Maximum value of the righting arm
H_w	(m)	Wave height
h_r	(m)	Vertical position above the roll axis where person may be present
k_L	-	Coupling factor considering simultaneous pitch, roll, and heave motions
KG	(m)	Vertical coordinate of the CoG
L_{OA}	(m)	Overall ship length
L_{wl}	(m)	Ship length at the design waterline
L	(m)	Ship length according to IS code
LCG	(m)	Longitudinal coordinate of the CoG
R_{PR}	-	Standard threshold of PR Lv1
S_w	-	Wave steepness: H_w/λ
T_{ϕ}	-	Natural roll period
V_S	(m s^{-1})	Ship service speed
KB	(m)	Vertical coordinate of the CoB
W_S	-	Statistical weight of a sea state

ACRONYM	**DEFINITION**
CoB	Center of Buoyancy
CoG	Center of Gravity
DS	Dead Ship condition failure mode
DSA	Direct Stability Assessment
EA	Excessive Acceleration failure mode
IMO	International Maritime Organization
IS code	Intact Stability code
Lv1	First vulnerability level
Lv2	Second vulnerability level
LY	Large Yacht code issued by the UK's Maritime and Coast-guard Agency
MSC	IMO Maritime Safety Committee
OG	Operational Guidance
OL	Operational Limitation
PL	Pure Loss of stability failure mode
PR	Parametric Rolling failure mode
SGISc	Second Generation Intact Stability criteria
SOLAS	Safety Of Life At Sea convention
SR	Surf-Riding/Broaching-to failure mode
SYBAss	Superyacht Builders Association

Appendix A

In this appendix, the complete outcomes for all investigated vessels (except for Y01), in the form of tables or figures, are reported. The structure of data and graphs has been described in Section 4.1.

Appendix A.1. Outcomes of the Complete Vulnerability Assessment

Table A1. Outcomes of the SGISc application to the loading conditions for Y02.

	Level 1 Criterion	Loading Condition Arrival	Mid-Voyage	Departure		Level 2 Criterion	Loading Condition Arrival	Mid-Voyage	Departure
PR	$\Delta GM/GM \leq R_{PR}$	0.206	0.183	0.192	**PR**	$C1 \leq 0.06$	0.115	0.000	0.000
	$C_{\nabla} \geq 1$	1.100	1.096	1.078		$C2 \leq 0.025$	3.77×10^{-4}	3.67×10^{-5}	7.24×10^{-6}
PL	$GM_{min} \geq 0.05$ m	0.409	0.543	0.639	**PL**	$CR1 \leq 0.06$	0.305	0.004	0.000
	$C_{\nabla} \geq 1$	1.100	1.096	1.078		$CR2 \leq 0.06$	0.090	0.053	0.039
DS	$b/a \geq 1$	0.986	1.393	7.986	**DS**	$C_{DS} \leq 0.06$	0.790	0.745	0.655
EA	$C_{EA1} \leq 4.94$ m s^{-2}	6.226	5.957	7.813	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	2.27×10^{-2}	2.43×10^{-2}	2.20×10^{-2}
SR	$Fn \geq 0.30$	0.508	0.508	0.402	**SR**	$C_{SR} \leq 0.005$	0.104	0.104	0.104
	$L \geq 200$ m	41.641	41.663	37.510					

Table A2. Outcomes of the SGISc application to the loading conditions for Y03.

	Level 1 Criterion	Loading Condition Arrival	Mid-Voyage	Departure		Level 2 Criterion	Loading Condition Arrival	Mid-Voyage	Departure
PR	$\Delta GM/GM \leq R_{PR}$	0.479	0.490	0.475	**PR**	$C1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.077	1.077	1.075		$C2 \leq 0.025$	0.000	0.000	0.000
PL	$GM_{min} \geq 0.05$ m	−0.041	−0.044	0.082	**PL**	$CR1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.077	1.077	1.075		$CR2 \leq 0.06$	0.009	0.013	0.029
DS	$b/a \geq 1$	0.769	0.675	0.704	**DS**	$C_{DS} \leq 0.06$	0.392	0.405	0.400
EA	$C_{EA1} \leq 4.94$ m s^{-2}	6.226	5.957	5.686	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	5.86×10^{-4}	3.79×10^{-4}	2.11×10^{-4}
SR	$Fn \geq 0.30$	0.326	0.326	0.326	**SR**	$C_{SR} \leq 0.005$	0.0079	0.0076	0.0078
	$L \geq 200$ m	45.515	45.270	42.864					

Table A3. Outcomes of the SGISc application to the loading conditions for Y04.

	Level 1 Criterion	Loading Condition Arrival	Mid-Voyage	Departure		Level 2 Criterion	Loading Condition Arrival	Mid-Voyage	Departure
PR	$\Delta GM/GM \leq R_{PR}$	0.245	0.195	0.109	**PR**	$C1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.120	1.108	1.102		$C2 \leq 0.025$	5.40×10^{-6}	8.87×10^{-5}	0.000
PL	$GM_{min} \geq 0.05$ m	0.100	0.055	0.517	**PL**	$CR1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.120	1.108	1.102		$CR2 \leq 0.06$	0.094	0.102	0.015
DS	$b/a \geq 1$	0.791	0.787	2.567	**DS**	$C_{DS} \leq 0.06$	0.127	0.097	0.024
EA	$C_{EA1} \leq 4.94$ m s^{-2}	5.206	3.830	4.356	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	1.72×10^{-6}	1.30×10^{-8}	8.10×10^{-7}
SR	$Fn \geq 0.30$	0.316	0.316	0.316	**SR**	$C_{SR} \leq 0.005$	0.0141	0.0105	0.0089
	$L \geq 200$ m	60.570	60.570	60.570					

Table A4. Outcomes of the SGISc application to the loading conditions for Y05.

	Level 1 Criterion	Loading Condition Arrival	Departure		Level 2 Criterion	Loading Condition Arrival	Departure
PR	$\Delta GM/GM \leq R_{PR}$	0.710	0.256	**PR**	$C1 \leq 0.06$	0.000	0.000
	$C_{\nabla} \geq 1$	1.217	1.185		$C2 \leq 0.025$	0.000	0.000
PL	$GM_{min} \geq 0.05$ m	−1.740	−1.399	**PL**	$CR1 \leq 0.06$	0.000	0.000
	$C_{\nabla} \geq 1$	1.217	1.185		$CR2 \leq 0.06$	0.020	0.002
DS	$b/a \geq 1$	0.227	3.424	**DS**	$C_{DS} \leq 0.06$	0.106	0.017
EA	$C_{EA1} \leq 4.94$ m s^{-2}	4.569	5.340	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	2.60×10^{-7}	1.62×10^{-5}
SR	$Fn \geq 0.30$	0.307	0.307	**SR**	$C_{SR} \leq 0.005$	0.0169	0.0121
	$L \geq 200$ m	64.230	64.230				

Table A5. Outcomes of the SGISc application to the loading conditions for Y06.

	Level 1 Criterion	Loading Condition Arrival	Mid-Voyage	Departure		Level 2 Criterion	Loading Condition Arrival	Mid-Voyage	Departure
PR	$\Delta GM/GM \leq R_{PR}$	0.506	0.408	0.299	**PR**	$C1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.043	1.050	1.092		$C2 \leq 0.025$	0.012	0.007	0.008
PL	$GM_{min} \geq 0.05$ m	−0.440	−0.116	0.176	**PL**	$CR1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.043	1.050	1.092		$CR2 \leq 0.06$	0.070	0.033	0.013
DS	$b/a \geq 1$	0.445	0.441	0.436	**DS**	$C_{DS} \leq 0.06$	0.213	0.183	0.161
EA	$C_{EA1} \leq 4.94$ m s^{-2}	7.042	7.379	7.470	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	2.01×10^{-4}	4.70×10^{-4}	7.91×10^{-4}
SR	$Fn \geq 0.30$	0.347	0.347	0.347	**SR**	$C_{SR} \leq 0.005$	0.0329	0.0320	0.0455
	$L \geq 200$ m	67.630	67.630	67.630					

Table A6. Outcomes of the SGISc application to the loading conditions for Y07.

	Level 1 Criterion	Loading Condition Arrival	Departure		Level 2 Criterion	Loading Condition Arrival	Departure
PR	$\Delta GM/GM \leq R_{PR}$	0.572	0.473	**PR**	$C1 \leq 0.06$	0.000	0.000
	$C_{\nabla} \geq 1$	1.039	1.031		$C2 \leq 0.025$	7.05×10^{-4}	6.10×10^{-4}
PL	$GM_{min} \geq 0.05$ m	−0.660	−0.491	**PL**	$CR1 \leq 0.06$	0.000	0.000
	$C_{\nabla} \geq 1$	1.039	1.031		$CR2 \leq 0.06$	0.139	0.102
DS	$b/a \geq 1$	0.998	1.184	**DS**	$C_{DS} \leq 0.06$	0.254	0.252
EA	$C_{EA1} \leq 4.94$ m s^{-2}	5.737	5.817	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	4.50×10^{-5}	6.20×10^{-5}
SR	$Fn \geq 0.30$	0.306	0.306	**SR**	$C_{SR} \leq 0.005$	0.0039	0.0034
	$L \geq 200$ m	64.540	64.540				

Table A7. Complete summary of the vulnerability assessment of all vessels, except for Y01.

Y02 Stability Failure	**Loading Condition Arrival**	**Mid-Voyage**	**Departure**	**Y03 Stability Failure**	**Loading Condition Arrival**	**Mid-Voyage**	**Departure**
PR	MET	MET	MET	**PR**	MET	MET	MET
PL	MET	MET	MET	**PL**	MET	MET	MET
DS	NOT MET	MET	MET	**DS**	NOT MET	NOT MET	NOT MET
EA	NOT MET	NOT MET	NOT MET	**EA**	NOT MET	MET	MET
SR	NOT MET	NOT MET	NOT MET	**SR**	NOT MET	NOT MET	NOT MET
Y04 Stability Failure	**Loading Condition Arrival**	**Mid-Voyage**	**Departure**	**Y05 Stability Failure**	**Loading Condition Arrival**	**Departure**	
PR	MET	MET	MET	**PR**	MET	MET	
PL	MET	MET	MET	**PL**	MET	MET	
DS	NOT MET	NOT MET	MET	**DS**	NOT MET	MET	
EA	MET	MET	MET	**EA**	MET	MET	
SR	NOT MET	NOT MET	NOT MET	**SR**	NOT MET	NOT MET	
Y06 Stability Failure	**Loading Condition Arrival**	**Mid-Voyage**	**Departure**	**Y07 Stability Failure**	**Loading Condition Arrival**	**Departure**	
PR	MET	MET	MET	**PR**	MET	MET	
PL	NOT MET	MET	MET	**PL**	NOT MET	NOT MET	
DS	NOT MET	NOT MET	NOT MET	**DS**	NOT MET	MET	
EA	MET	NOT MET	NOT MET	**EA**	MET	MET	
SR	NOT MET	NOT MET	NOT MET	**SR**	MET	MET	

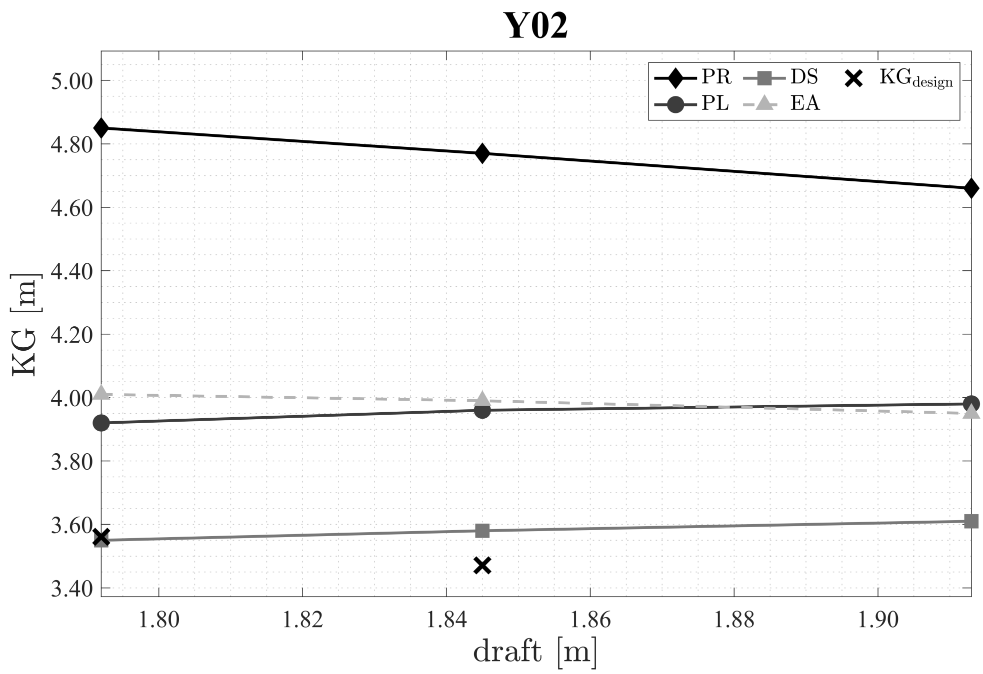

Figure A1. Limiting *KG* curves for Y02.

Table A8. Final maximum and minimum limiting *KG* curves of each level for Y02.

Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
	maximum *KG* **(m)**		
PR	4.85	4.77	4.66
PL	3.92	3.96	3.98
DS	3.55	3.58	3.61
	minimum *KG* **(m)**		
EA	4.01	3.99	3.95

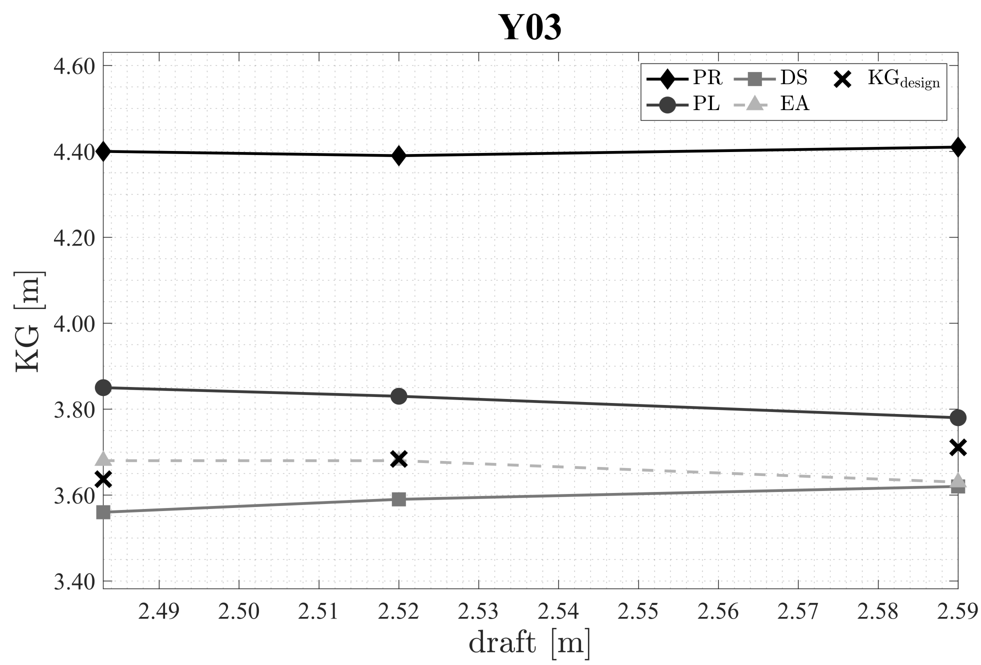

Figure A2. Limiting *KG* curves for Y03.

Table A9. Final maximum and minimum limiting *KG* curves of each level for Y03.

Stability Failure	Arrival	Loading Condition Mid-Voyage	Departure
	maximum *KG* (m)		
PR	4.40	4.39	4.41
PL	3.85	3.83	3.78
DS	3.56	3.59	3.62
	minimum *KG* (m)		
EA	3.68	3.68	3.63

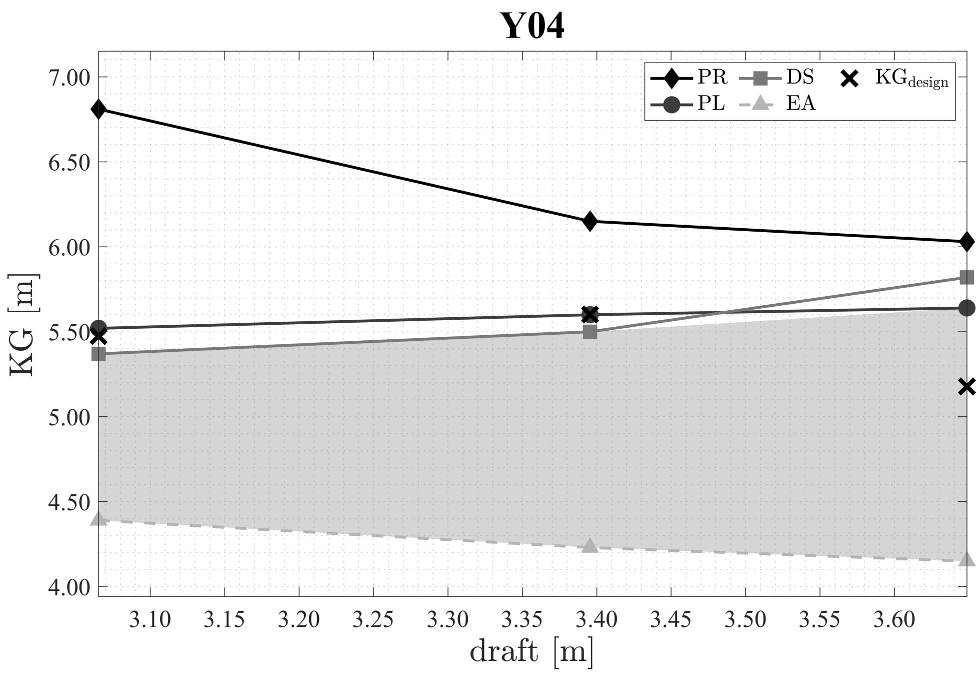

Figure A3. Limiting *KG* curves for Y04.

Table A10. Final maximum and minimum limiting *KG* curves of each level for Y04.

Stability Failure	Arrival	Loading Condition Mid-Voyage	Departure
	maximum *KG* (m)		
PR	6.81	6.15	6.03
PL	5.52	5.60	5.64
DS	5.37	5.50	5.82
	minimum *KG* (m)		
EA	4.39	4.23	4.15

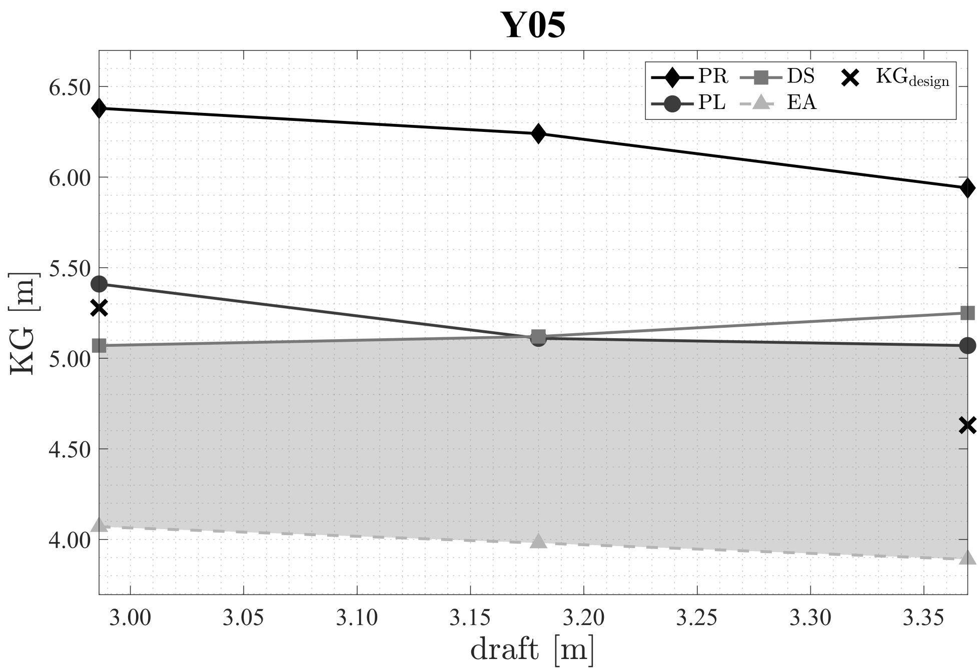

Figure A4. Limiting *KG* curves for Y05.

Table A11. Final maximum and minimum limiting *KG* curves of each level for Y05.

Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
	maximum *KG* **(m)**		
PR	6.38	6.24	5.94
PL	5.41	5.11	5.07
DS	5.07	5.12	5.25
	minimum *KG* **(m)**		
EA	4.07	3.98	3.89

Table A12. Final maximum and minimum limiting *KG* curves of each level for Y06.

Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
	maximum *KG* **(m)**		
PR	7.70	7.58	7.41
PL	5.92	5.85	5.75
DS	5.82	5.90	5.98
	minimum *KG* **(m)**		
EA	5.79	5.75	5.69

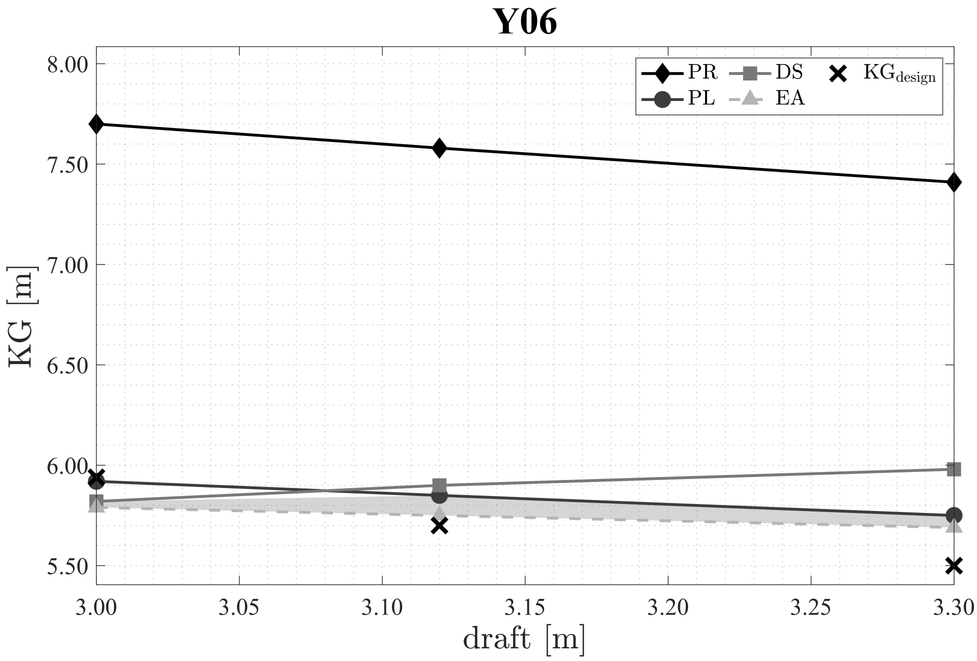

Figure A5. Limiting *KG* curves for Y06.

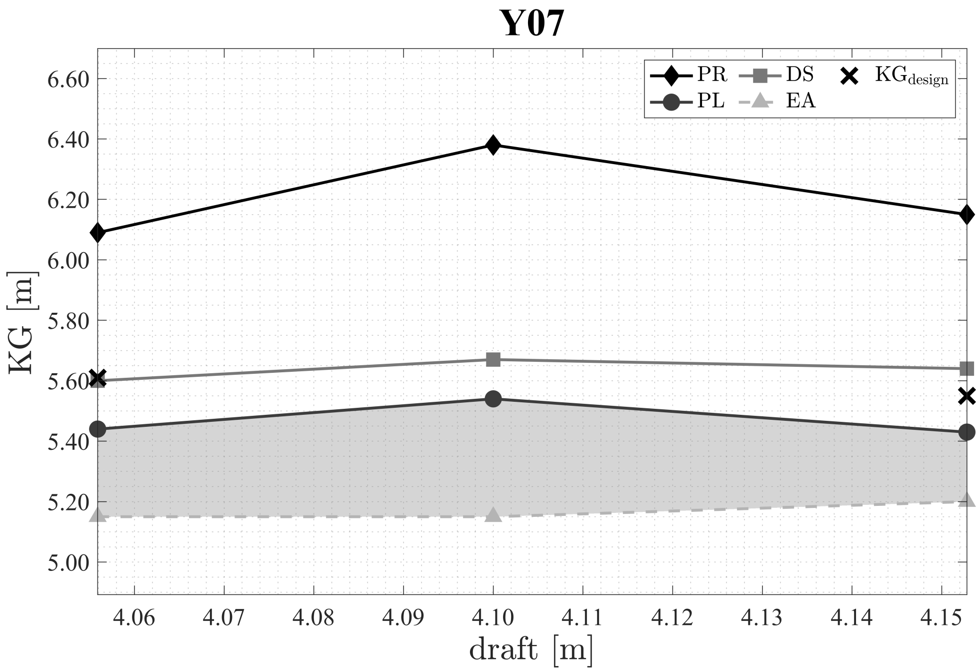

Figure A6. Limiting *KG* curves for Y07.

Table A13. Final maximum and minimum limiting *KG* curves of each level for Y07.

Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
	maximum *KG* (m)		
PR	6.09	6.38	6.15
PL	5.44	5.54	5.43
DS	5.60	5.67	5.64
	minimum *KG* (m)		
EA	5.15	5.15	5.20

Appendix A.2. Outcomes of the Complete Vulnerability Assessment with Operational Limitations Related to the Mediterranean Sea

Table A14. Outcomes of the SGISc application to the loading conditions for Y02 considering OL related to the Mediterranean Sea.

	Level 1 Criterion	Loading Condition Arrival	Mid-Voyage	Departure		Level 2 Criterion	Loading Condition Arrival	Mid-Voyage	Departure
PR	$\Delta GM/GM \leq R_{PR}$	0.973	0.875	0.717	**PR**	$C1 \leq 0.06$	0.899	0.027	0.000
	$C_{\nabla} \geq 1$	1.100	1.096	1.091		$C2 \leq 0.025$	1.50×10^{-3}	5.51×10^{-4}	2.12×10^{-4}
PL	$GM_{min} \geq 0.05$ m	−2.152	−2.021	−1.867	**PL**	$CR1 \leq 0.06$	0.282	0.027	0.000
	$C_{\nabla} \geq 1$	1.100	1.096	1.091		$CR2 \leq 0.06$	0.144	0.116	0.076
DS	$b/a \geq 1$	0.986	1.393	1.858	**DS**	$C_{DS} \leq 0.06$	0.652	0.635	0.581
EA	$C_{EA1} \leq 4.94$ m s^{-2}	6.226	5.957	5.686	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	2.69×10^{-2}	2.89×10^{-2}	2.72×10^{-2}
SR	$Fn \geq 0.30$	0.508	0.508	0.508	**SR**	$C_{SR} \leq 0.005$	0.0991	0.0993	0.0991
	$L \geq 200$ m	41.641	41.663	41.690					

Table A15. Outcomes of the SGISc application to the loading conditions for Y03 considering OL related to the Mediterranean Sea.

	Level 1 Criterion	Loading Condition Arrival	Mid-Voyage	Departure		Level 2 Criterion	Loading Condition Arrival	Mid-Voyage	Departure
PR	$\Delta GM/GM \leq R_{PR}$	1.058	1.088	1.001	**PR**	$C1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.077	1.077	1.075		$C2 \leq 0.025$	0.000	0.000	0.000
PL	$GM_{min} \geq 0.05$ m	−1.762	−1.786	−1.767	**PL**	$CR1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.077	1.077	1.075		$CR2 \leq 0.06$	0.028	0.038	0.076
DS	$b/a \geq 1$	0.769	0.675	0.704	**DS**	$C_{DS} \leq 0.06$	0.218	0.208	0.205
EA	$C_{EA1} \leq 4.94$ m s^{-2}	6.226	5.957	5.686	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	5.00×10^{-4}	2.63×10^{-4}	1.12×10^{-4}
SR	$Fn \geq 0.30$	0.326	0.326	0.326	**SR**	$C_{SR} \leq 0.005$	0.0179	0.0177	0.0208
	$L \geq 200$ m	45.515	45.270	42.864					

Table A16. Outcomes of the SGISc application to the loading conditions for Y04 considering OL related to the Mediterranean Sea.

	Level 1 Criterion	Loading Condition Arrival	Mid-Voyage	Departure		Level 2 Criterion	Loading Condition Arrival	Mid-Voyage	Departure
PR	$\Delta GM/GM \leq R_{PR}$	0.872	0.953	0.560	**PR**	$C1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.120	1.108	1.102		$C2 \leq 0.025$	4.24×10^{-5}	4.45×10^{-4}	0.000
PL	$GM_{min} \geq 0.05$ m	−3.075	−2.944	−2.323	**PL**	$CR1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.120	1.108	1.102		$CR2 \leq 0.06$	0.082	0.106	0.028
DS	$b/a \geq 1$	0.791	0.787	2.567	**DS**	$C_{DS} \leq 0.06$	0.058	0.015	0.008
EA	$C_{EA1} \leq 4.94$ m s^{-2}	5.206	3.830	4.356	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	1.09×10^{-6}	9.43×10^{-12}	5.40×10^{-8}
SR	$Fn \geq 0.30$	0.316	0.316	0.316	**SR**	$C_{SR} \leq 0.005$	0.0127	0.0098	0.0085
	$L \geq 200$ m	60.570	60.570	60.570					

Table A17. Outcomes of the SGISc application to the loading conditions for Y05 considering OL related to the Mediterranean Sea.

	Level 1 Criterion	Loading Condition Arrival	Departure		Level 2 Criterion	Loading Condition Arrival	Departure
PR	$\Delta GM/GM \leq R_{PR}$	1.684	0.957	**PR**	$C1 \leq 0.06$	0.000	0.000
	$C_{\nabla} \geq 1$	1.217	1.185		$C2 \leq 0.025$	0.000	0.000
PL	$GM_{min} \geq 0.05$ m	−3.711	−3.426	**PL**	$CR1 \leq 0.06$	0.000	0.000
	$C_{\nabla} \geq 1$	1.217	1.185		$CR2 \leq 0.06$	0.030	0.006
DS	$b/a \geq 1$	0.227	3.424	**DS**	$C_{DS} \leq 0.06$	0.046	0.021
EA	$C_{EA1} \leq 4.94$ m s^{-2}	4.569	5.340	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	7.96×10^{-8}	2.82×10^{-5}
SR	$Fn \geq 0.30$	0.307	0.307	**SR**	$C_{SR} \leq 0.005$	0.0130	0.0097
	$L \geq 200$ m	64.230	64.230				

Table A18. Outcomes of the SGISc application to the loading conditions for Y06 considering OL related to the Mediterranean Sea.

	Level 1 Criterion	Loading Condition Arrival	Mid-Voyage	Departure		Level 2 Criterion	Loading Condition Arrival	Mid-Voyage	Departure
PR	$\Delta GM/GM \leq R_{PR}$	1.149	0.971	0.820	**PR**	$C1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.043	1.050	1.092		$C2 \leq 0.025$	7.70×10^{-3}	5.00×10^{-3}	5.40×10^{-3}
PL	$GM_{min} \geq 0.05$ m	−2.491	−2.217	−1.963	**PL**	$CR1 \leq 0.06$	0.000	0.000	0.000
	$C_{\nabla} \geq 1$	1.043	1.050	1.092		$CR2 \leq 0.06$	0.041	0.031	0.024
DS	$b/a \geq 1$	0.445	0.441	0.436	**DS**	$C_{DS} \leq 0.06$	0.087	0.087	0.083
EA	$C_{EA1} \leq 4.94$ m s^{-2}	7.042	7.379	7.470	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	2.27×10^{-2}	2.43×10^{-2}	2.20×10^{-2}
SR	$Fn \geq 0.30$	0.347	0.347	0.347	**SR**	$C_{SR} \leq 0.005$	0.0204	0.0200	0.0245
	$L \geq 200$ m	67.630	67.630	67.630					

Table A19. Outcomes of the SGISc application to the loading conditions for Y07 considering OL related to the Mediterranean Sea.

	Level 1 Criterion	Loading Condition Arrival	Departure		Level 2 Criterion	Loading Condition Arrival	Departure
PR	PR $\Delta GM/GM \leq R_{PR}$	1.077	0.982	**PR**	$C1 \leq 0.06$	0.000	0.000
	$C_{\nabla} \geq 1$	1.039	1.031		$C2 \leq 0.025$	$1.50 \times 10-3$	1.20×10^{-2}
PL	$GM_{min} \geq 0.05$ m	−2.636	−2.450	**PL**	$CR1 \leq 0.06$	0.000	0.000
	$C_{\nabla} \geq 1$	1.039	1.031		$CR2 \leq 0.06$	0.106	0.106
DS	$b/a \geq 1$	0.998	1.184	**DS**	$C_{DS} \leq 0.06$	0.098	0.108
EA	$C_{EA1} \leq 4.94$ m s^{-2}	5.737	5.817	**EA**	$C_{EA} \leq 3.9 \times 10^{-4}$	2.60×10^{-5}	3.82×10^{-5}
SR	$Fn \geq 0.30$	0.306	0.306	**SR**	$C_{SR} \leq 0.005$	0.0032	0.0029
	$L \geq 200$ m	64.540	64.540				

Table A20. Complete summary of the vulnerability assessment of all vessels, except for Y01, considering OL related to the Mediterranean Sea.

Y02 Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure	Y03 Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
PR	MET	MET	MET	**PR**	MET	MET	MET
PL	NOT MET	NOT MET	NOT MET	**PL**	MET	MET	NOT MET
DS	NOT MET	MET	MET	**DS**	NOT MET	NOT MET	NOT MET
EA	NOT MET	NOT MET	NOT MET	**EA**	NOT MET	MET	MET
SR	NOT MET	NOT MET	NOT MET	**SR**	NOT MET	NOT MET	NOT MET
Y04 Stability Failure	**Loading Condition Arrival**	**Mid-Voyage**	**Departure**	**Y05 Stability Failure**	**Loading Condition Arrival**	**Departure**	
PR	MET	MET	MET	**PR**	MET	MET	
PL	NOT MET	NOT MET	MET	**PL**	MET	MET	
DS	MET	MET	MET	**DS**	MET	MET	
EA	MET	MET	MET	**EA**	MET	MET	
SR	NOT MET	NOT MET	NOT MET	**SR**	NOT MET	NOT MET	
Y06 Stability Failure	**Loading Condition Arrival**	**Mid-Voyage**	**Departure**	**Y07 Stability Failure**	**Loading Condition Arrival**	**Departure**	
PR	MET	MET	MET	**PR**	MET	MET	
PL	MET	MET	MET	**PL**	NOT MET	NOT MET	
DS	NOT MET	NOT MET	NOT MET	**DS**	NOT MET	MET	
EA	MET	MET	NOT MET	**EA**	MET	MET	
SR	NOT MET	NOT MET	NOT MET	**SR**	MET	MET	

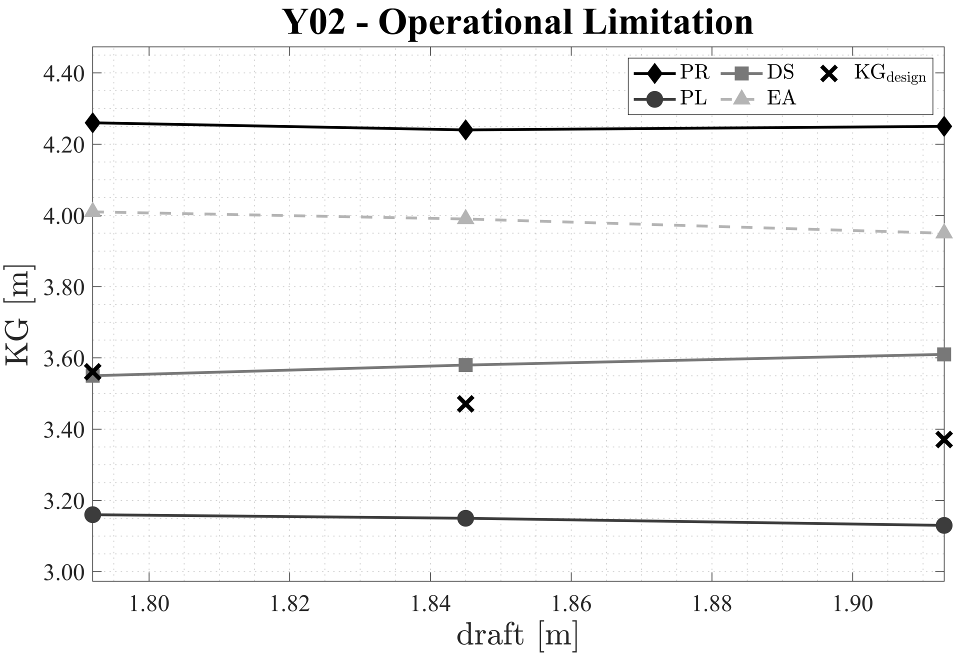

Figure A7. Limiting *KG* curves for Y02 considering OL related to the Mediterranean Sea.

Table A21. Final maximum and minimum limiting *KG* curves of each level for Y02 considering OL related to the Mediterranean Sea.

Stability Failure	Arrival	Loading Condition Mid-Voyage	Departure
		maximum *KG* (m)	
PR	4.26	4.24	4.25
PL	3.16	3.15	3.13
DS	3.55	3.58	3.61
		minimum *KG* (m)	
EA	4.01	3.99	3.95

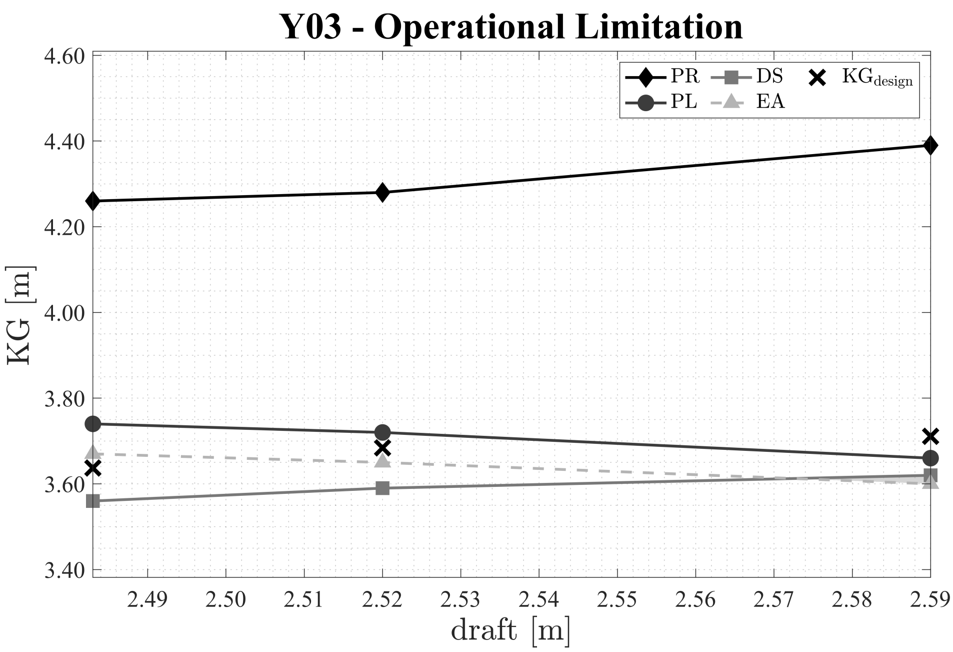

Figure A8. Limiting *KG* curves for Y03 considering OL related to the Mediterranean Sea.

Table A22. Final maximum and minimum limiting *KG* curves of each level for Y03 considering OL related to the Mediterranean Sea.

Stability Failure	Arrival	Loading Condition Mid-Voyage	Departure
		maximum *KG* (m)	
PR	4.26	4.28	4.39
PL	3.74	3.72	3.66
DS	3.56	3.59	3.62
		minimum *KG* (m)	
EA	3.67	3.65	3.60

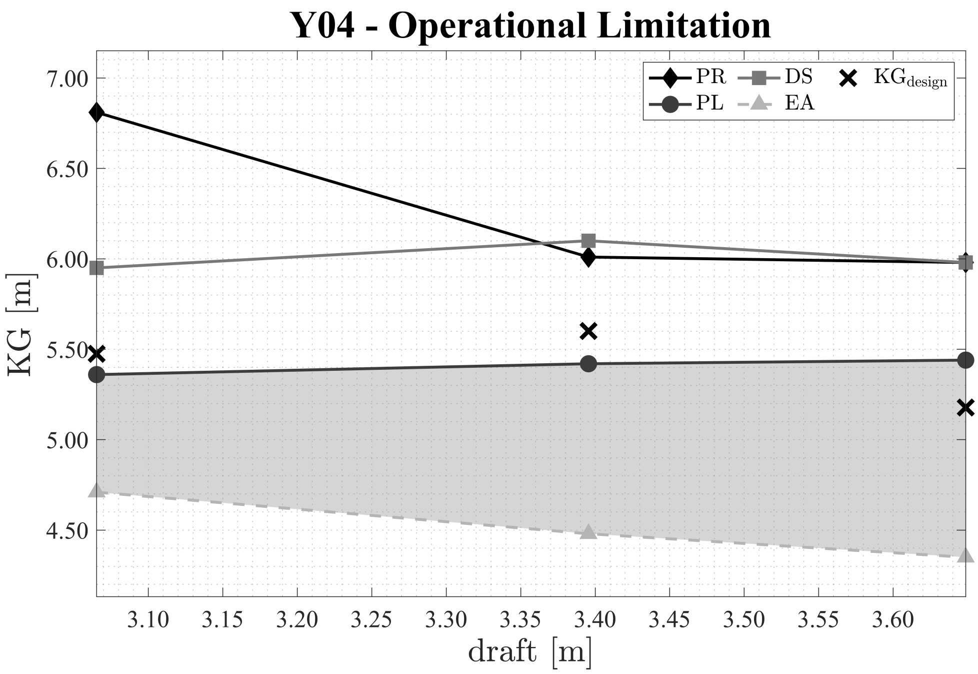

Figure A9. Limiting *KG* curves for Y04 considering OL related to the Mediterranean Sea.

Table A23. Final maximum and minimum limiting *KG* curves of each level for Y04 considering OL related to the Mediterranean Sea.

Stability Failure	Arrival	Loading Condition Mid-Voyage	Departure
		maximum *KG* (m)	
PR	6.81	6.01	5.98
PL	5.36	5.42	5.44
DS	5.95	6.10	5.98
		minimum *KG* (m)	
EA	4.71	4.48	4.35

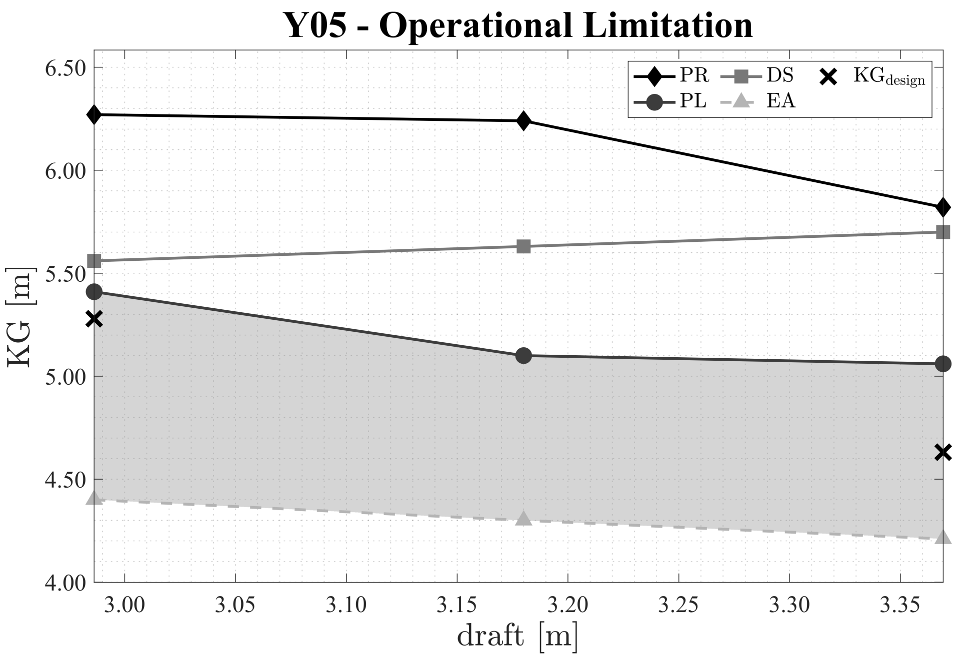

Figure A10. Limiting *KG* curves for Y05 considering OL related to the Mediterranean Sea.

Table A24. Final maximum and minimum limiting *KG* curves of each level for Y05 considering OL related to the Mediterranean Sea.

Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
	maximum ***KG*** **(m)**		
PR	6.27	6.24	5.82
PL	5.41	5.10	5.06
DS	5.56	5.63	5.70
	minimum ***KG*** **(m)**		
EA	4.40	4.30	4.21

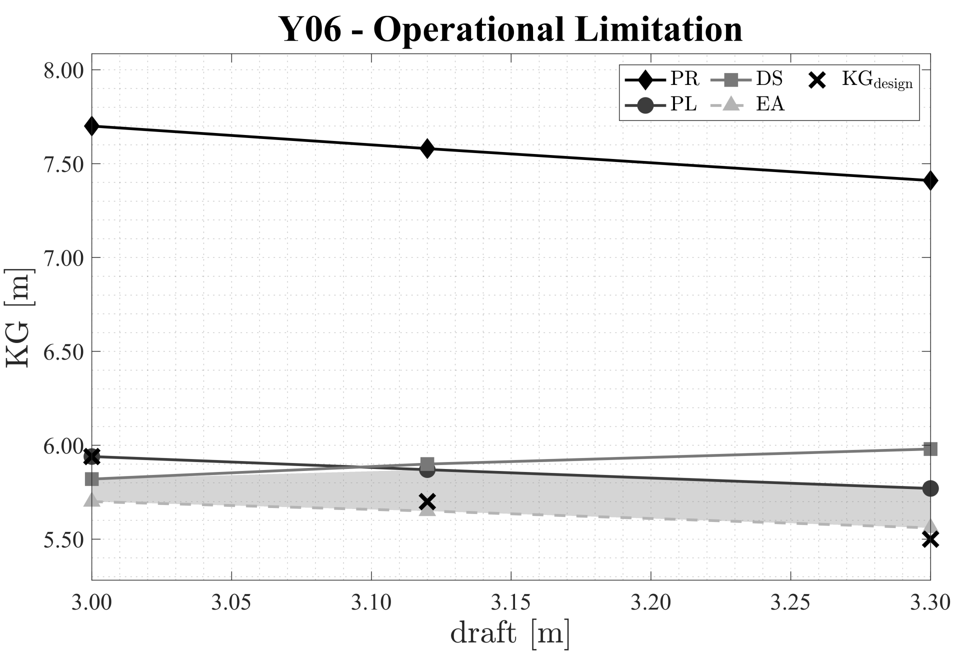

Figure A11. Limiting *KG* curves for Y06 considering OL related to the Mediterranean Sea.

Table A25. Final maximum and minimum limiting *KG* curves of each level for Y06 considering OL related to the Mediterranean Sea.

Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
	maximum *KG* (m)		
PR	7.70	7.58	7.41
PL	5.94	5.87	5.77
DS	5.82	5.90	5.98
	minimum *KG* (m)		
EA	5.70	5.65	5.56

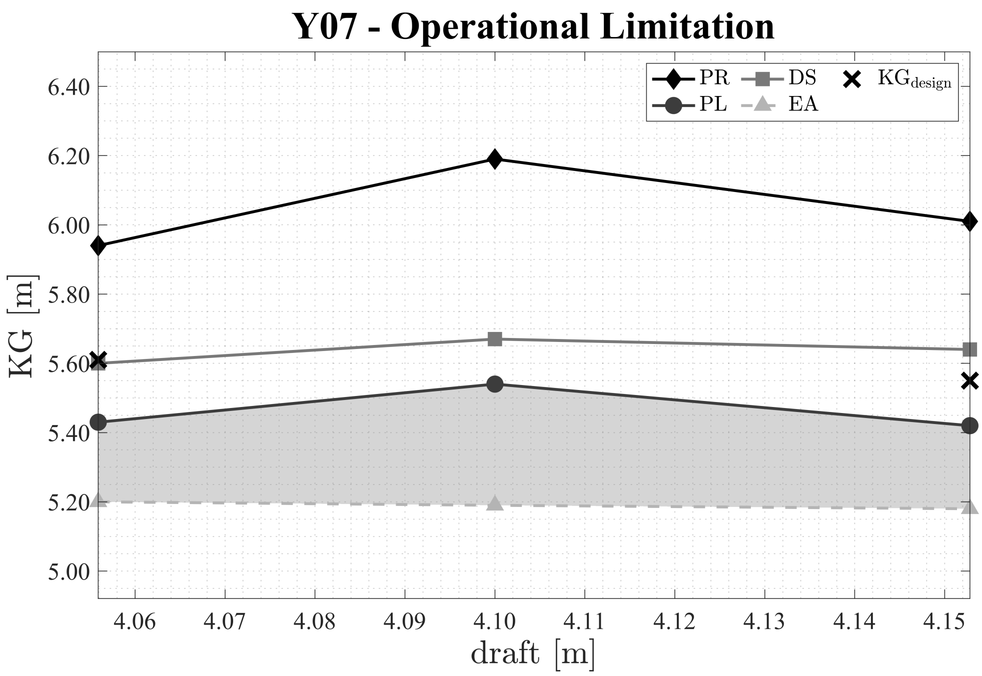

Figure A12. Limiting *KG* curves for Y07 considering OL related to the Mediterranean Sea.

Table A26. Final maximum and minimum limiting *KG* curves of each level for Y07 considering OL related to the Mediterranean Sea.

Stability Failure	Loading Condition Arrival	Mid-Voyage	Departure
	maximum *KG* (m)		
PR	5.94	6.19	6.01
PL	5.43	5.54	5.42
DS	5.60	5.67	5.64
	minimum *KG* (m)		
EA	5.20	5.19	5.18

Appendix B

In this appendix, the wave scatter table of the central Mediterranean Sea used in the investigation is presented in Table A27.

Table A27. Wave scatter table of the central Mediterranean Sea used in the investigation.

	T_Z (s)						
H_S (m)	**3.50**	**4.50**	**5.50**	**6.50**	**7.50**	**8.50**	**9.50**
0.50	0.0064	0.1485	0.1082	0.0350	0.0074	0.0011	0.0000
1.50	0.0159	0.1018	0.1463	0.0817	0.0255	0.0053	0.0011
2.50	0.0032	0.0339	0.0700	0.0530	0.0212	0.0064	0.0011
3.50	0.0010	0.0095	0.0255	0.0244	0.0117	0.0042	0.0011
4.50	0.0000	0.0032	0.0085	0.0095	0.0053	0.0021	0.0011
5.50	0.0000	0.0011	0.0032	0.0042	0.0021	0.0011	0.0000
6.50	0.0000	0.0000	0.0010	0.0021	0.0010	0.0011	0.0000
7.50	0.0000	0.0000	0.0010	0.0010	0.1000	0.0000	0.0000

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