Surf-riding Operational Measures for Fast Semidisplacement Naval Hull Form

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Abstract
Surf-riding/broaching failure mode is one of the Second Generation Intact Stability Criteria (*SGISC*) dealt by *IMO*. The *SGISC* are structured with a multi-tiered approach: Level 1, Level 2 and Direct Stability Assessment (*DSA*). When a ship does not verify one level, the next once must be applied, or the ship design must be modified. If ship changes are not feasible, Operational Measures (*OM*) can be provided to avoid dangerous situations and reduce the likelihood of stability failures. The *OM* are divided into Operational Limitations (*OL*) related to areas or routes and related to maximum significant wave heights and Operational Guidance (*OG*).
The surf-riding criterion has been applied on the parent hull of the Systematic Series D, a fast semi-displacement naval hull with forms typically vulnerable to surf-riding phenomenon. The 90 m length ship results vulnerable to Level 1 and 2, therefore Operational Measures have been discussed and provided for a hypothetical route in the Mediterranean Sea (Area 26).
Following the *OL*, in considered Area 26 the ship operations are limited when significant wave heights exceed 3.8 m. The simplified *OG* define critical ship speeds to be avoided for each considered sea state.

Keywords. Surf-riding, Operational Measures, Systematic Series D, Second Generation Intact Stability Criteria

Acronyms

Symbol	definition
DSA	Direct Stability Assessment
DSC	Dead ship condition
EA	Excessive acceleration
IMO	International Maritime Organization
L1	Level 1
L2	Level 2
LS	Level Set
OG	Operational Guidance
OL	Operational Limitations
OM	Operational Measures
SDC	Sub-Committee on Ship Design and Construction
SGISC	Second Generation Intact Stability Criteria

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Nomenclature

Symbol	unit	definition
C	-	long-term prediction index of Level 2
$C2_{ij}$	-	Level 2 coefficient equal to 1 or 0 for surf-riding occurrence
c_{HT}	-	coefficient of 1 or 2 in Level 2
Fn	-	Froude number
H_S	m	significant wave height
$H_{S,UL}$	m	upper limit of the significant wave heights
$H_{S,UL\text{-}20\%}$	m	upper limit of the H_S for which the ratio of the total duration of all situations which should be avoided to the total operational time is equal to 0.2
$H_{S,UL(marg)}$		marginal value of the upper limit of wave heights
L	m	length of the ship
λ	m	wave length
T_Z	s	zero crossing period
w_{ij}	-	statistical weight for joint probability density function of local steepness and local wavelength under the stationary wave state with a Pierson-Moskowitz type wave spectrum

1. Introduction

The Second-Generation Intact Stability Criteria (*SGISC*) started to develop in 2002, after having found the actual criteria inadequate. The new generation of criteria is based on "realistic failure modes" that analyze the nonlinear dynamic behavior of ships in waves. Their aim is to prevent loss of stability that may lead to capsizing or endanger passengers, crew and cargo when ships are sailing in dangerous weather conditions. During the 7th session of the International Maritime Organization (*IMO*) sub-committee on Ship Design and Construction (*SDC*) in 2020 they have been finalized, with a view to approval in 2021.

The five stability failure modes dealt by *IMO* Intact Stability working group are: Parametric roll, Pure loss of stability, Surf-riding/broaching, Dead ship condition and Excessive accelerations. Due to the complexity of the physical modelling the SGISC are structured with a multi-tiered approach: Level 1 (*L*1) is simple and conservative; Level 2 (*L*2) is based on simplified physical models to reduce computational effort; the Direct Stability Assessment (*DSA*) is performed with the most advanced state of art methodology. The three levels have been adopted without any hierarchy, and, in a given loading condition, if the ship is found vulnerable to one level the next one has to be applied otherwise the ship design has to be modified. When ship changes are not feasible, Operational Measures (*OM*) can be provided to avoid dangerous situations and to reduce the likelihood of stability failure.

Many studies have been made and reported for the application of the first 2 levels, while Operational Measures performances are rare.

Backalov et al. [1] in 2015 investigated Operational Limitations of river-sea ships for the dead ship condition (*DSC*) and excessive accelerations (*EA*) criteria. The *OL* procedure followed the Level 2 vulnerability assessment and the limits have been

reported for different bilge keels, drafts and metacentric heights. The results of the analysis have been found generally in good agreement with the operational experience and lower metacentric heights had a positive effect on the behavior of the examined vessel.

A detailed description and discussion on Operational Measures is reported in Petacco et al. (2020) [2] together with an application of Operational Limitations of Ro-Ro pax ferry for pure loss of stability, dead ship condition and excessive acceleration criteria.

In this paper the Operational Measures for the surf-riding criteria are provided for the parent hull D1, of the fast semi-displacement Systematic Series D, representative of European naval ships built in the nineties. Operational Limitations and Operational Guidance are applied considering a possible route in the Mediterranean Sea. *OL* are represented together with Level 2 surf-riding assessment in terms of speed limits and *OG* are provided by defining maximum allowable ship speeds for different seas states.

2. Surf-riding/broaching Criterion within *SGISC*

Surf-riding phenomenon may occur when a ship is sailing in developed quartering to following seas and gets accelerated to wave celerity. Although not dangerous, surf-riding may lead to a broaching phenomenon, an uncontrollable turn which may cause stability loss. Since surf-riding dynamics is less complex than broaching, its occurrence, under any initial conditions (over 2nd threshold), is studied as the predictor for surf-riding/broaching failure mode within the *IMO SGISC* [3].

2.1. Level 1 and Level 2 Vulnerability Assessment

Level 1 is defined as a simple verification of ship speed and length. The ship is found vulnerable if the Froude number $Fn > 0.3$ and the ship length is $L < 200$ m.

Level 2 vulnerability assessment defines a long-term probability Index C, based on the identification of the surf-riding second threshold combined with the probability of encountering a local regular wave that causes this instability, given a certain sea state and weighted on the probability of occurrence of each sea state. The identification of surf-riding occurrence is obtained by solving the surge motion equation by Melnikov's method, as described in Spyrou (2006) [4], that identifies the critical number of revolutions for which surf-riding occurs at the second threshold, for a specific loading condition and sea state. The probability of wave occurrence of each sea state refers to the North Atlantic wave scatter diagram.

2.2. Operational Measures

When the ship is found vulnerable to *L2* or the *DSA*, the substantial change of ship design to avoid the phenomena can be prohibitive for both ship designers and owners because it increases shipbuilding costs or sacrifices cargo capacity. Therefore, a solution is to provide Operational Measures (*OM*) to avoid dangerous situations.

IMO guidelines *SDC*7/*WP*.6 [3] define two types of Operational Measures, Operational Limitations (*OL*) and Operational Guidance (*OG*), as shown in Figure 1.

The Operational Limitations define the limits on a ship's operation in a considered loading condition and are divided in:

- Operational Limitations related to areas or routes and seasons, that permit operations in specific operational areas or routes and seasons.

- Operational Limitations related to maximum significant wave heights, that permit operation in conditions up to maximum significant wave height.

The preparation of the Operational Limitations follows the design assessments of *L*1, *L*2 or *DSA*. For the limitations related to areas or routes and season the assessments are performed with a modified environmental condition, based on the respective wave scatter table. For the limitations related to maximum significant wave height, the assessments are performed with a specific environmental condition based on a limited scatter diagram obtained by the respective wave scatter table, limited to a H_S.

The Operational Guidance defines the sailing conditions, that are the combination of ship speeds and headings, not recommended or to be avoided in each sea state and support the master during the navigation in dangerous conditions. The preparation of the *OG* is based on 3 approaches: probabilistic, deterministic, and simplified motion criteria.

The probabilistic and deterministic approaches provide accurate and detailed recommendations for the ship forward speed and course in each sea state but require model tests or numerical methods of high accuracy.

The simplified approach for the surf-riding/broaching criterion defines either of the following two speed limits:

- the nominal speed equal or greater than $0.94 \cdot L^{1/2}$ should be avoided for waves with lengths, calculated on mean wave period, greater 80%*L* and with significant wave height higher than 4%*L* and heading angles less than 45 degrees;
- the critical nominal ship speed provided by the Level 2 vulnerability criteria or above value should be avoided in following to beam wave directions in sea states for which $c_{HT} > 0.005$, where:

$$c_{HT}(H_S, T_z) = \sum_{i=1}^{N_\lambda} \sum_{j=1}^{N_\alpha} w_{ij}(H_S, T_z) C2_{ij} > 0.005 \quad (1)$$

where w_{ij} and $C2_{ij}$ are calculated as Level 2 but in this calculation diffraction component in the wave force calculations have to be included.

The Operational Measures can be combined applying for example the Operational Limitations up to a certain significant wave height and the Operational Guidance for greater significant wave heights.

While Operational Limitations related to areas or routes do not require specific planning, for the Operational Limitations related to maximum wave height and the Operational Guidance weather forecast are to be available and referred to on board.

A loading condition, tested for *OL* related to maximum H_S and *OG*, is not acceptable if the ratio of the total duration of all situations which should be avoided to the total operational time, is greater than 0.2.

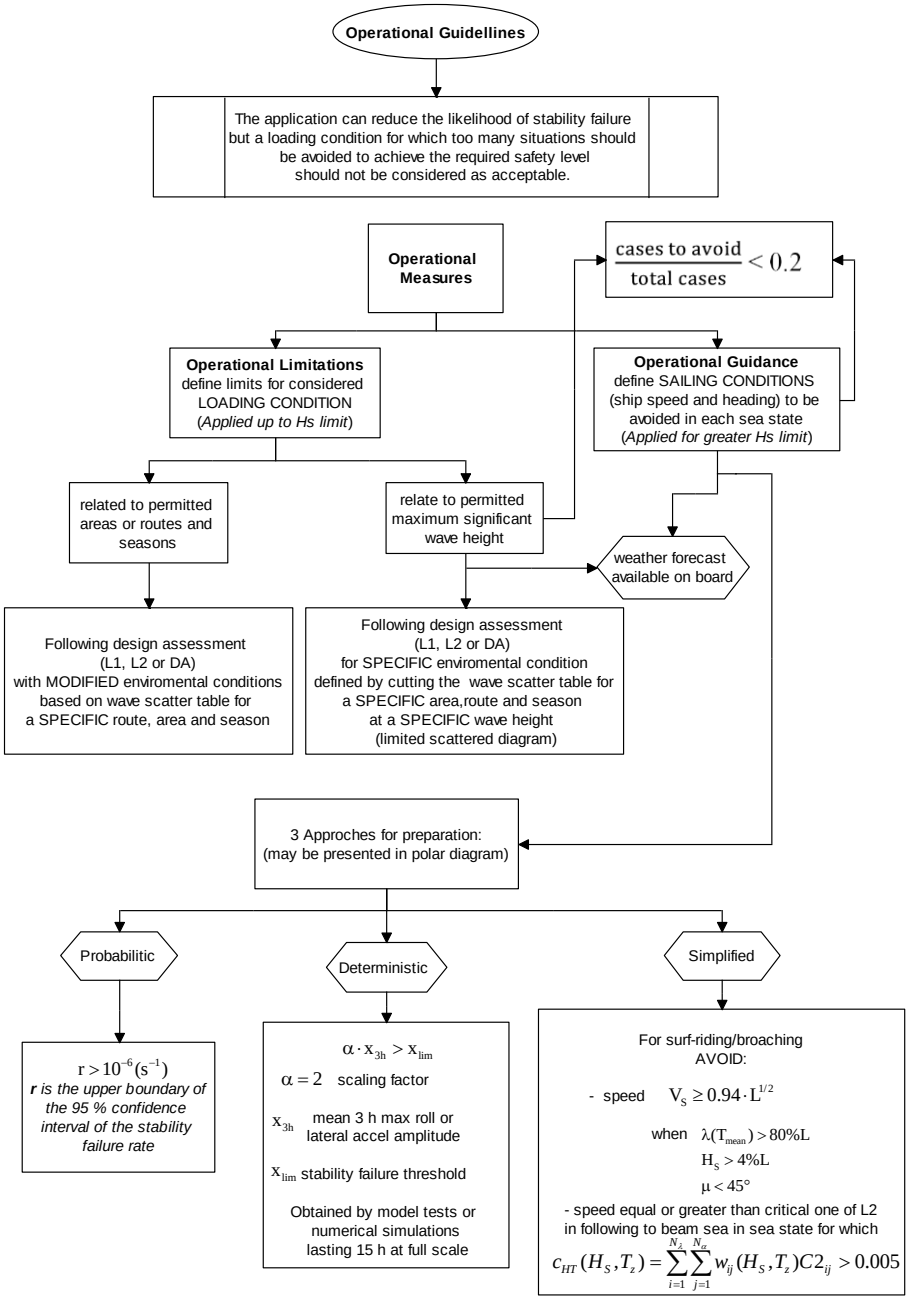

Figure 1. Operational Measures flow chart.

3. Surf-riding Criterion Applied on the D1 Hull Form

Surf-riding criterion has been performed on the parent hull of the Systematic Series D (Kracht and Jacobsen 1992) [5], originated from a semi-displacement, transom stern, twin-screw, round-bilge hull form, initially made by the German yard Howaldtswerke-Deutsche Werft. The D-Series has seven models, derived from a parent hull form D1 with narrow forms and fast service speed which are typical parameters of ships potentially vulnerable to surf-riding criterion.

The body plan of the parent hull D1 is shown in Figure 2 and a detailed description of the Series can be found in Begovic et al. (2018) [6].

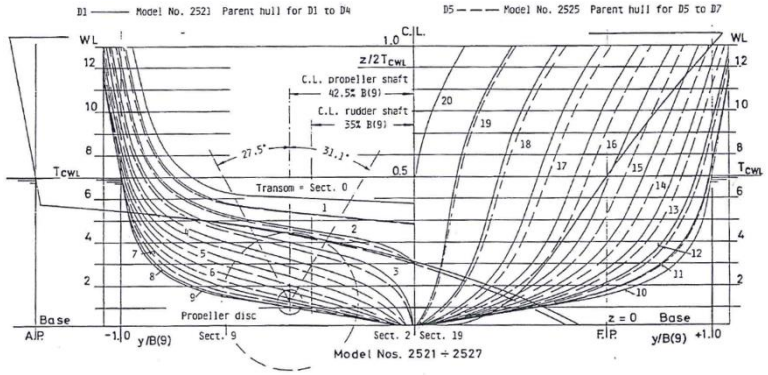

Figure 2. D1 hull form, after Kracht and Jacobsen [5].

3.1. Operational Limitations for D1 Hull

The parent hull D1 scaled to 90 m length ship at service speed of 25 kn, has the Froude number *Fn*=0.433, and it is vulnerable Level 1 and Level 2 surf-riding criterion, as reported in Begovic et al. (2018) [6]. Since no changes in ship design are possible, Operational Measures are provided for D1 hull sailing on a possible route in the Mediterranean Sea, reported in Table 1; which according to the Global Wave Statistics (Hogben et al. 1986) corresponds to Area 26 [7].

Operational Limitations have been evaluated by performing *L*2 assessment, including the diffraction component in the calculations of the wave surging force by software Hydrostar ®. In the procedure the North Atlantic scatter diagram is replaced with the one related to Area 26, for *OL* related to area, and with different limited wave scatter diagrams obtained by cutting the wave scatter diagram, related to Area 26, at different H_S, for *OL* related to maximum significant wave heights.

For the *OL* related to maximum significant wave height two types of situations have been considered:

- the ship always in operation normalizing the limited scatter diagrams;
- the ship safe in port when sea conditions should be avoided not normalizing the limited scatter diagrams.

The Index *C* values obtained for the total and for the limited scatter diagrams of Area 26, cut at different selected H_S, are shown in Figure 3 as function of *Fn*, where the curves with "N" define normalized diagrams. The value of the H_S that defines each

curve represents and includes the upper limit of the wave height interval from the wave scatter table.

The *OL* state that the hull D1 may operate in compliance with surf-riding criterion at service speed in Area 26 with H_S limited up to 3 m. As expected, the curves determined with normalized tables prove to be more conservative.

The *Fn* limit of *L*1 and the curves of Index *C* obtained by *L*2 assessment, with diffraction effect (*L*2 diffr) and without (*L*2), are compared with the curves obtained for the *OL* related to Area 26 and related to the maximum significant wave heights.

An increasing of ship speed limits can be observed when applying Level 2 with diffraction, and then the *OL*.

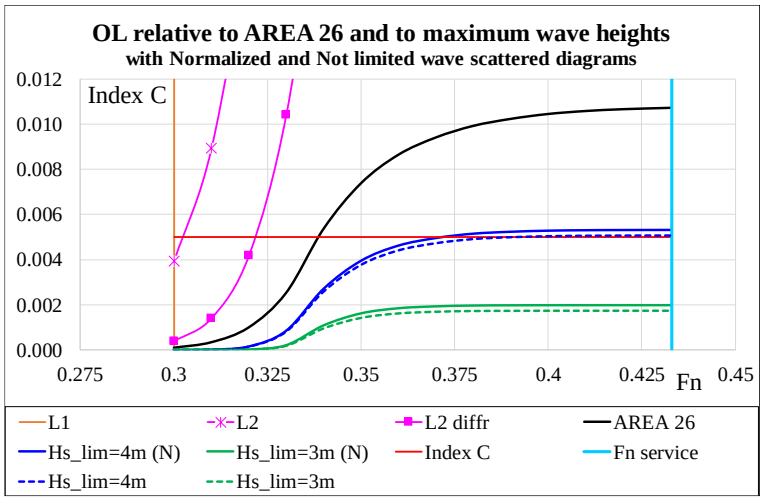

Figure 3. Comparison of Index C values obtained by the different methods.

The final step is the calculation of the total probability of all the sea states to be avoided when cutting the wave scatter diagram at different H_S, as given in Table 1. As mentioned, the probability of all sea states to be avoided has to be equal or less than 0.2 and the exact value of the upper limit of the significant wave height, $H_{S,UL\text{-}20\%}$, has been interpolated and results equal to 2.533 m.

Table 1. Determination of maximum H_S for acceptable loading condition for Area 26.

AREA 26		Tz [s] 3-4 **3.5**	4-5 **4.5**	5-6 **5.5**	6-7 **6.5**	7-8 **7.5**	8-9 **8.5**	9-10 **9.5**	10-11 **10.5**	11-12 **11.5**	12-13 **12.5**	13-14 **13.5**	Prob lim to Hs	Cdf	Prob of exceeding	Hs Upper Limit	
14-15	**14.5**	0	0	0	0	0	0	0	0	0	0	0	999	1	0	15	
13-14	**13.5**	0	0	0	0	0	0	0	0	0	0	0	999	1	0	14	
12-13	**12.5**	0	0	0	0	0	0	0	0	0	0	0	999	1	0	13	
11-12	**11.5**	0	0	0	0	0	0	0	0	0	0	0	999	1	0	12	
10-11	**10.5**	0	0	0	0	0	0	0	0	0	0	0	999	1	0	11	
9-10	**9.5**	0	0	0	0	0	0	0	0	0	0	0	999	1	0	10	
8-9	**8.5**	0	0	0	0	0	0	0	0	0	0	0	999	1	0	9	
7-8	**7.5**	0	0	1	1	1	0	0	0	0	0	0	999	1	0	8	
6-7	**6.5**	0	0	1	2	1	1	0	0	0	0	0	996	0.997	0.003	7	
5-6	**5.5**	0	1	3	4	2	1	0	0	0	0	0	991	0.992	0.008	6	
4-5	**4.5**	0	3	8	9	5	2	1	0	0	0	0	980	0.981	0.019	5	$Hs_{,UL}$ (20%)
3-4	**3.5**	1	9	24	23	11	4	1	0	0	0	0	952	0.953	0.047	4	
2-3	**2.5**	3	32	66	50	20	6	1	0	0	0	0	879	0.880	0.120	3	2.552
1-2	**1.5**	15	96	138	77	24	5	1	0	0	0	0	701	0.702	0.298	2	
0-1	**0.5**	60	140	102	35	7	1	0	0	0	0	0	345	0.345	0.655	1	
													999	0.000	1.000	0	

Hs [m]

In Figure 4, the Index *C* values have been represented as function of the upper limit of the significant wave height, $H_{S,UL}$, of the limited scatter diagram for different *Fn*. The curves have a range of operability limited by the area crossed with red oblique lines, defined by the $H_{S,UL\text{-}20\%}$ as calculate above, and by the value of 0.005 over which the Index *C* is not in compliance with *L*2 assessment.

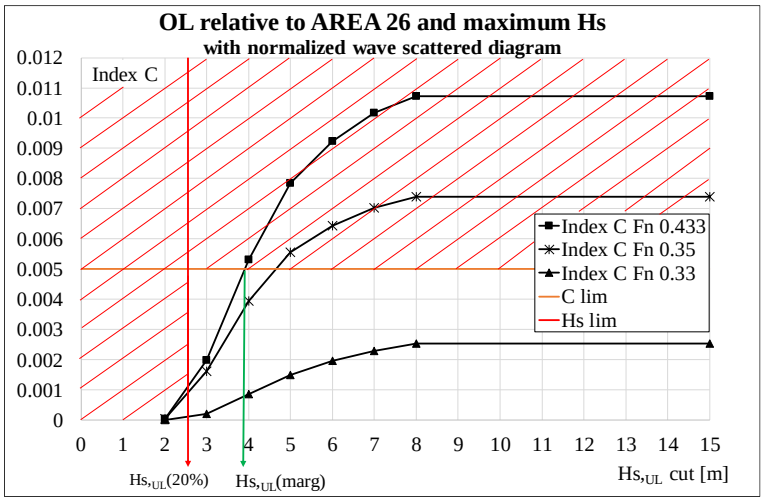

Figure 4. Operational Limitations relative to maximum wave height in Area 26.

It can be seen that by linear interpolation the marginal value of the upper limit of wave heights, $H_{S,UL(marg)}$ reaches a value around 3.8 m, which is higher than the limit found by analysing Figure 3.
Besides the significant improvement of *L*2 assessment performed with the diffraction effect, overall results show that the ship will have speed limitations in Area 26 for H_S higher than 3.8 m to comply with surf-riding *OL*.

3.2. Operational Guidance for D1 Hull

The simplified Operational Guidance, applied on the D1 hull, state that when the ship encounters sea state with H_S greater than 3.6 m and wave length, λ, greater than 72 m, ship speeds higher than 8.92 m/s (17.34 kn) should be avoided.

The second simplified approach for the OG has been performed defining, for each sea state (combination of H_S and T_Z), the critical nominal Froude number whose value or above should be avoided in following to beam wave when the index c_{HT} is equal or greater to 0.005, as reported in Table 2.

The table has been colored to highlight the following:

- **green** if the sea states are not critical, critical Froude number > *Fn* service
- **from yellow to red**, corresponding to decreasing values, if the sea states are critical and the corresponding critical Froude number must be avoided;

Table 2. Simplified Operational Guidance: critical nominal Froude number for each sea state.

Critical Fn	Tz															
	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
0.5	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433
1.5	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433
2.5	> 0.433	> 0.433	> 0.433	0.335	0.333	0.337	0.359	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433
3.5	> 0.433	0.346	0.330	0.322	0.321	0.324	0.332	0.342	0.376	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433
4.5	> 0.433	0.332	0.321	0.312	0.311	0.314	0.322	0.331	0.341	0.363	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433	> 0.433
5.5	0.340	0.324	0.312	0.304	0.302	0.306	0.313	0.323	0.332	0.342	0.362	0.411	> 0.433	> 0.433	> 0.433	> 0.433
6.5	0.333	0.318	0.305	0.297	0.294	0.299	0.306	0.315	0.325	0.334	0.345	0.365	0.407	> 0.433	> 0.433	> 0.433
7.5	0.328	0.312	0.300	0.291	0.288	0.292	0.300	0.310	0.320	0.328	0.337	0.349	0.370	0.410	> 0.433	> 0.433
Hs 8.5	0.323	0.306	0.293	0.285	0.283	0.286	0.293	0.303	0.313	0.323	0.332	0.341	0.354	0.376	0.416	> 0.433
9.5	0.318	0.302	0.289	0.282	0.280	0.282	0.289	0.298	0.308	0.318	0.327	0.335	0.345	0.360	0.384	0.425
10.5	0.314	0.297	0.285	0.280	0.277	0.280	0.284	0.293	0.303	0.313	0.323	0.331	0.340	0.351	0.367	0.393
11.5	0.310	0.293	0.282	0.277	0.275	0.277	0.282	0.289	0.299	0.309	0.319	0.327	0.335	0.345	0.357	0.375
12.5	0.306	0.290	0.281	0.276	0.274	0.275	0.280	0.285	0.294	0.304	0.314	0.323	0.332	0.340	0.350	0.364
13.5	0.302	0.287	0.280	0.275	0.274	0.274	0.278	0.283	0.291	0.301	0.311	0.320	0.328	0.336	0.345	0.357
14.5	0.300	0.285	0.279	0.275	0.273	0.274	0.277	0.281	0.288	0.297	0.307	0.316	0.325	0.333	0.341	0.351
15.5	0.297	0.284	0.278	0.274	0.273	0.274	0.276	0.281	0.285	0.294	0.303	0.313	0.322	0.330	0.338	0.347
16.5	0.295	0.283	0.277	0.274	0.273	0.273	0.275	0.280	0.283	0.291	0.301	0.310	0.319	0.327	0.335	0.344
T [s]	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
λ/L	0.212	0.351	0.525	0.733	0.975	1.253	1.565	1.912	2.293	2.71	3.161	3.646	4.166	4.721	5.311	5.935

It can be observed that under wave heights equal to 2.5 m there are no limitations for ship speeds and the critical ship decreases together with wave heights for wave periods corresponding to wave lengths comparable to ship lengths, i.e. λ/L around 1.

The probability of encountering each sea state has been multiplied by two coefficients, corresponding to a heading and speed weight, defined as follows:

$$\Pr(T_Z, H_S) \times \text{heading(range)} \times \frac{Fn_{service} - Fn_{critical}}{Fn_{service}} \tag{2}$$

This value defines the probability of unacceptable situations for the corresponding sea state, range of heading and service speed. The sum of all the probabilities of the unacceptable cases gives the Total probability of the cases to be avoided, whose value must be less than 0.2 in order to consider acceptable the loading condition for which the OG have been provided.

The Total probability of the cases to be avoided has been evaluated for the scatter diagram of Area 26, as represented in Table 3. The heading weight has been taken equal to 1/2, corresponding to uniformly distributed heading range from following to beam sea. The speed range has been considered uniformly distributed from 0 to service speed (Fn=0.433) and the critical Fn has been taken from Table 2.

The Total probability of cases to be avoided is equal to 0.024, less than 0.2, so the Operational Guidance, defined in Table 3, is in the compliance with the criterion and may be applied for hull D1 in the considered loading condition.

Table 3. Total Probability of the cases to be avoided with OG evaluate for the Area 26.

Hs [m]	Tz [s]										
	3.5	**4.5**	**5.5**	**6.5**	**7.5**	**8.5**	**9.5**	**10.5**	**11.5**	**12.5**	**13.5**
0.5	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0.005688	0.002313	0.000665	8.59E-05	0	0	0	0
3.5	0	0.000904	0.002848	0.002944	0.001424	0.000504	0.000117	0	0	0	0
4.5	0	0.00035	0.001038	0.001254	0.000705	0.000275	0.000128	0	0	0	0
5.5	0	0.000126	0.000418	0.000597	0.000303	0.000147	0	0	0	0	0
6.5	0	0	0.000148	0.000315	0.000161	0.000155	0	0	0	0	0
7.5	0	0	0.000154	0.000164	0.000167	0	0	0	0	0	0
8.5	0	0	0	0	0	0	0	0	0	0	0
9.5	0	0	0	0	0	0	0	0	0	0	0
10.5	0	0	0	0	0	0	0	0	0	0	0
11.5	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0
13.5	0	0	0	0	0	0	0	0	0	0	0
14.5	0	0	0	0	0	0	0	0	0	0	0
				PR_{TOT}		**0.024**					

4. Conclusions

A first application of surf-riding Operational Measures within the SGISC have been performed on the parent hull of the Systematic Series D sailing on a route in the Mediterranean Sea (Area 26). Operational Limitations, applied following Level 2 assessment with the diffraction effect included, limit the ship operations in the considered area when the significant wave height is higher than 3.8 m. Simplified Operational Guidance has been provided by defining critical ship speeds and headings for each sea state condition.

It is worth to underline that Operational Limitations are performed considering a long-term probability index, therefore the ship will not always operate in safe conditions below the selected significant wave height but the probability of occurring in surf-riding failure mode in low. Instead, the simplified Operational Guidance are based on a short-term index, therefore the sea state, for which the index is below the limit, is considered a safe condition for the ship to operate in.

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