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Assessment of cargo handling operation efficiency in the Clarion-Clipperton Zone for standard bulk carriers in the view of significant amplitudes of roll as a limiting criterion

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Abstract
Experienced ship roll during loading is the easiest parameter to observe and measure on board of a loaded ship. Therefore, the ship's significant roll amplitudes should be the key limiting factor in view of the safety and efficiency of cargo handling operations at sea. For the example of three standard bulk carriers, the authors prepared a method of assessment of bulk carrier suitability to perform safe and efficient cargo handling operations in the Clarion-Clipperton Zone in view of significant amplitudes of roll. Via a calculation of the efficiency index for a set of limiting amplitudes of roll during loading simulation, we are able to analyze ship effectiveness. The application of the above-mentioned method can be employed as a useful tool to predict the lowest allowable significant amplitudes of roll when the required efficiency level is specified. Additionally, a calculation is made for the operable days where cargo operations are possible. Investigations show that, according to applied criteria, the effectiveness drops, and not every bulk carrier can perform safe cargo handling operations at sea.

Introduction

One of the most characteristic and prospective occurrences of nodules is a vast area in the Easter Pacific Ocean, which is located between two fracture zones: Clarion and Clipperton, i.e., the so-called Clarion-Clipperton Zone. Polymetallic nodules are rich in metals such as manganese, nickel, copper, cobalt etc., which belong to the deep seabed minerals. Nodules occur at depths of 3700–5500 meters (Dreiseitl, 2017; Kozłowska-Roman & Mikulski, 2021).

In general, maritime transport requires minimum time for loading and unloading. If the ship movements experienced are too large, cargo handling operations will slow down or even lead to damage to the ship. Considering that the loading of nodules has to occur in open seas, and both the transport vessel and mining vessel have other sea-keeping characteristics, it forces us to investigate the sea-keeping characteristics of a transport ship and establish reasonable safe ship motions for safe and efficient working conditions. Nodules can be transported in dry or wet conditions, while condition of nodule implies a method of cargo transfer and the type of ship. If nodules are dry, they can then be loaded onto a "standard" bulk carrier (Vrij & Boel, 2020).

Most of the research completed previously (Sharma, 2011; Agarwal et al., 2012; van Nijen, van Passel and Squires, 2018) agreed that the most suitable transportation unit for dry nodules is a bulk carrier or ore carrier. Research (DeepGreen Metals Inc, 2021) has assumed that chartered vessels would be used to transport the dewatered nodules, and the

Table 1. Ship-to-ship transfer in tandem and alongside (Vrij and Boel, 2020)

Mooring in tandem		Mooring alongside	
Advantages	Disadvantages	Advantages	Disadvantages
No DP required	Space for transport systems is limited on both bulk carrier and mining vessel	No distribution systems are required on bulk carrier	DP required
Easier to control the position of both vessels when towing	Distribution system required on bulk carrier	More possibilities to position the ship-to-ship transfer systems	Not possible to weathervane together
Possibility to weathervane together		Mining possible during ship-to-ship transfer	

vessels would be converted onto bulk mineral carriers with dynamic positioning (DP). According to earlier work (Vercruijsse & Kovacs, 2018), transport ships may be equipped with DP to conduct safe cooperation with mining ships. Table 1 lists the advantages and disadvantages of the selected discharging method and indicates where the use of DP on bulk carriers is required. In the case of side-to-side offloading operation of dry nodules to bulk carriers, this can be achieved by, for example, a conveyor belt (van Laar, 2021).

There is wide experience in ship-to-ship transshipment of bulk cargoes, notably for the lightering of large bulk carriers using barges close to the destination ports. The main reasons are the shallow water/port access limitations for large draught ships. However, such operations usually occur near ports in safe or protected sea areas where weather and nautical conditions are reasonable. There is no experience in using these technologies in the open ocean (DG Maritime Affairs and Fisheries, 2014).

When planning ship-to-ship (STS) offloading operations, the following issues should be considered:

a. present and forecasted weather conditions,
b. availability of weather reports for the areas.

Therefore, before planning the operations, the operator should obtain forecasts for the STS transfer area of the anticipated period of the operation. In the case of oil tankers (OCIMF, 2013), ship-to-ship operations should be suspended when:

a. under adverse weather and/or sea conditions,
b. movement of alongside oil tankers reaches the maximum permissible.

Because the loading of nodules occurs at sea, we can implement general rules of STS operations also for dry cargo transfer at sea due to the similarities of the process.

The most important factor is that, during loading operations, a vessel changes its own general mass properties, which leads to a change in the ship's movements during the entire loading process. Before the sending of any bulk carrier to perform the loading of nodules at sea, a vessel should be analyzed in terms of sea-keeping characteristics that may affect loading at sea.

This study analyzed the three standard bulk carriers that perform the loading of nodules in the Clarion-Clipperton Zone in a dry state. The characteristics of bulk carriers are shown in Table 2. All the ships listed in Table 2 have unrestricted navigation and are specialized to carry heavy cargo.

Table 2. General particulars of bulk carriers for analysis

	Bulk carrier		
	A	B	C
Length between perpendiculars, LBP (m)	103.90	185.00	217.00
Molded breadth, B (m)	18.20	24.40	32.26
Design draught, T (m)	7.06	11.01	14.02
Deadweight, DWT (t)	7600	33 390	73 600
Number of holds	3	7	7

The main aim of this research is to analyze roll motion using the example of three bulk carriers during the loading of nodules, which consider the waving condition existing in the Clarion-Clipperton Zone. The second part is a presentation of general effectiveness graphs of the suitability of bulk carriers to perform safe and effective loading in view of significant roll amplitudes as a limiting criterion. All the ships during the loading operations do not make any progress through the water (i.e., the vessel speed is 0 knt).

Research method

Calculation of significant amplitudes of roll by the use of linear strip theory

Determination of the wave-induced ship motions is a very important aspect of ship design. As the most practical approach for conventional ships, various two-dimensional methods (i.e., strip theory methods) are still widely used for the prediction of wave-induced ship motions. Strip methods can provide reasonably accurate results for ship motions (IACS, 2014). Nowadays, strip theory is a standard tool for sea-keeping computations (Arslan & Yavuz, 2021). Strip theory is a frequency domain method – which means that the problem is formulated as a function of frequency. Research completed previously (Tezdogan and Taylan, 2011; Chen et al., 2013; Ma et al., 2016; Nguyen and Tran, 2018) used the linear strip theory to perform sea-keeping analysis. As a result, they agreed that linear strip theory still remains a solid basis for sea-keeping calculations. In this study, a linear strip theory is used to calculate the ship's motion.

Wave-induced responses are often predicted by sea-keeping analysis based on linear theory through a description of the vessel characteristics utilizing a response amplitude operator (RAO) (Dudziak, 2008). Then, the ship roll motion energy spectrum is found from:

$$S_{\zeta_\eta}(\omega)d\omega = S_\zeta(\omega)d\omega\, Y_\eta^2(\omega) \tag{1}$$

where $S_\zeta(\omega)$ represents the ocean wave spectrum and $Y_\eta^2(\omega)$ is the response amplitude operator of roll. The variance of the ship roll is given by:

$$D_{uu}^2 = \int_0^\infty S_{\zeta_\eta}(\omega)d\omega \tag{2}$$

While the RMS of the ship roll is expressed as:

$$\mathrm{RMS} = \sqrt{D_{uu}^2} \tag{3}$$

The significant amplitudes of the roll are calculated via:

$$\varphi_{1/3} = 2\cdot\mathrm{RMS} \tag{4}$$

The ocean wave spectrum

A wave spectrum describes the energy distribution among wave components of different frequencies of a sea state. The Bretschneider spectrum is applicable to fully developed seas. This spectrum is also known as the ISSC spectrum (represented by a significant wave height H_S and characteristic period of wave T_0), which is the spectrum recommended for open-ocean wave conditions; for example, in the Atlantic Ocean (Riggs, Ertekin & Mills, 1998; American Bureau of Shipping, 2016). In this research, the Brettschneider wave spectrum is used.

The formula for the Bretschneider ocean wave spectrum is determined as follows (American Bureau of Shipping, 2016):

$$S(\omega) = \frac{5\omega_m^4}{16\omega^5} H_{1/3}^2 e^{-5\omega_m^4/4\omega^4} \ (\mathrm{m^2/(rad/s)}) \tag{5}$$

where ω signifies the wave frequency (in units of rad/s) and $H_{1/3}$ is the significant wave height, which is defined as the mean of one-third of the highest waves, i.e.:

$$T_0 = \frac{2\pi}{\omega_m} \tag{6}$$

Here, ω_m is the peak wave frequency and T_0 is the characteristic wave period.

Operability assumptions

The limiting values of operability criteria are used in sea-keeping studies to validate ship response in different sea states. Exceeding limiting values leads to a reduction in ship operability. Operability limiting values represent a border between acceptable and unacceptable phenomena, such as the number of seafloor contacts in one minute or the amount of vertical acceleration on the fore perpendicular, etc. However, the mentioned border is hard to define. Data from service, therefore, has a priceless value. Statistical analysis of service data in comparison with sea-keeping calculations gives the best validation of operation limiting values (Mudronja, Vidan & Parunov, 2015).

For commercial ocean-going vessels, sea-keeping performance is addressed in terms of the following:

a. habitability – the ability of the vessel to carry out a mission with a minimum of discomfort,
b. operability – the ability to carry out a mission in all types of weather.

The third aspect of sea-keeping performance is survivability or seaworthiness. This aspect is usually not considered in detail by the designer and is generally assumed to be satisfied by adherence to appropriate classification rules, load line, and stability regulations. To ascertain operability, there is a need to establish limiting values or use existing ones.

The operative limiting criteria for ship operations were presented previously (Karppinen, 1987). Table 4 shows the criteria for acceleration and roll depending on the work performed on the ship. However, heavy manual work does not mean conducting cargo handling operations. Only one existing criterion to assess the safety of cargo handling operations in the function of experienced ship movements is

Table 3. Recommended motion criteria for safe cargo handling operations (Elzinga, Iribarren & Jensen, 1992)

Ship type	Cargo handling equipment	Surge (m)	Sway (m)	Heave (m)	Yaw (deg)	Pitch (deg)	Roll (deg)
General cargo	N/A	2.0	1.5	1.0	3	2	5

Table 4. Criteria for accelerations and roll (Karppinen, 1987)

Description	RMS vertical acceleration (g)	RMS lateral acceleration (g)	RMS roll motion (deg)
Light manual work	0.20	0.10	6.0
Heavy manual work	0.15	0.07	4.0
Intellectual work	0.10	0.05	3.0
Transit passenger	0.05	0.04	2.5
Cruise liner	0.02	0.03	2.0

presented in the literature (Elzinga, Iribarren & Jensen, 1992). In this study, general cargo ship criteria are used because the intended bulk carrier is without any cargo gear, and the ship is planned to be loaded by external loading gear. The authors of this research assumed that loading at sea cannot be extensively influenced by the ship's motion since it is limited in port and sheltered waters. Table 3 presents these limiting values.

The RMS, i.e., the square root of the mean square, in this study, signifies that the amplitudes of roll are twice the RMS value according to Equation (4). In Table 3, values are assumed as the maximum significant roll.

Effectiveness index

The efficiency index was introduced by Karpinen in 1987 to estimate how long various ship operations would take in a given wave condition. In this study, the operational effectiveness index E_T shows the probability for which the significant roll amplitudes during loading do not exceed a limited level in given wave parameters. This is expressed as follows:

$$E_T = \sum_{H_S,T} P(\Gamma = 1) \tag{7}$$

where E_T represents the operational effectiveness index, H_S is the significant wave height, T_0 is the characteristic wave period, and P is the probability that a significant roll motion does not exceed a limited level. Moreover, $\varphi_{1/3}$ is the significant amplitude of roll for a given wave, $\varphi_{1/3\ \mathrm{limit}}$ is the limiting value for significant amplitudes of roll, and Γ is the bivalent function that has only two values in given wave conditions, i.e.:

- 0, when the ship's significant roll motions amplitudes exceed the acceptable level:

$$\Gamma(\varphi_{1/3} > \varphi_{1/3\ \mathrm{limit}}) = 0 \tag{8}$$

- 1, when the ship's significant roll motions amplitudes do not exceed the acceptable level:

$$\Gamma(\varphi_{1/3} < \varphi_{1/3\ \mathrm{limit}}) = 1 \tag{9}$$

The higher values of the E_T index correspond to the optimal sea-keeping properties of the ship. To obtain the E_T index, the following calculations have to be completed:

1. calculations of a wave occurrence in a given period of time,
2. calculation of significant amplitudes of roll for a given wave,
3. comparison of the significant roll motions with their limits,
4. calculation of the Γ function,
5. calculation of the E_T value as a sum of occurrence probability of significant wave height H_S and characteristic wave period T_0 (probabilities for which is $\Gamma = 1$) by the use of Equation (7).

Loading conditions

Loading conditions during the cargo handling operations, and the corresponding hydrostatic and hydrodynamic characteristics of the selected bulk carriers, have been used throughout this analysis. Before the commencement of any loading operation, there is a need to prepare a loading program. It should be noted that during the loading displacement D, the transverse metacentric height GM value is continually changing. The change of the GM value not only reduces the peak amplitudes but also shifts the resonant frequencies to higher values with no forward speed of the ship (Pesman, Bayraktar & Taylan, 2013). That is why there is a need to perform an overall analysis of the roll motion for each loading condition. The number of loading states is shown in Table 5. For bulk carriers B and C, the cargo is distributed by alternate hold loading conditions. This type of cargo distribution raises the ship's center of gravity, which eases the ship's rolling motion (Puchalski & Soliwoda, 2008; IACS,

Figure 1. A homogeneous hold loading condition and an alternate hold loading condition (IACS, 2018)

2018). For bulk carrier A, there was no possibility of adopting an alternate hold loading condition. In this case, bulk carrier A is loaded by a homogeneous hold loading condition due to the fact that heavy cargoes, such as iron ore, may be carried homogeneously on bulk carriers (IACS, 2018). A homogeneous hold loading condition and an alternate hold loading condition are shown in Figure 1.

Table 5. Number of loading conditions of bulk carriers

Ship	Loading conditions
Bulk carrier A	4
Bulk carrier B	4
Bulk carrier C	5

The sum of operable days – based on the efficiency index

The total number of loading hours, where the loading is possible, that is not affected by the statistical properties of the waves was presented in previous work (Cepowski and Kacprzak, 2019). In this research, the authors investigate the influence of the internal shear forces and the bending moments during the loading process. Based on the efficiency index, the authors calculated the total amount of cargo loading hours, which was a base of calculation of the total cargo loading efficiency throughout the year. In this research, the authors calculate the maximum operable days by use of the following formula:

$$D = E_{T\,\mathrm{min}} \cdot 365 \tag{10}$$

where D is the maximum operable days in the Clarion-Clipperton Zone, and the integer 365 is the total number of days of wave occurrence in the Clarion-Clipperton Zone, as stated in previous work (Lipton & Nimmo, 2016).

Statistical data

In this study, the wave parameters around the Clarion-Clipperton Fracture Zone for one year are used, as presented in earlier work (Lipton & Nimmo, 2016). Based on wave distribution, the probability of significant wave height H_S and characteristic wave period T_0 occurrence is calculated and presented in Table 6.

Results

The following calculations were completed via the algorithm (as described in Figure 5). Calculations of the ship roll in irregular sea states were achieved by simulation using Seaway software. The latter is a frequency-domain ship motions program based on the linear strip theory (Journee & Adegeest, 2003).

Significant roll amplitudes of the selected bulk carriers for loading conditions are shown in Figures 2, 3, and 4. In this study, only the side waves are analyzed ($\beta = 90°$), for which it was assumed that the highest roll motion occurs on side waves.

Table 6. Probability of significant wave height and characteristic wave period occurrence throughout the one year around the Clarion-Clipperton Fracture Zone calculated on the basis of previous research (Lipton & Nimmo, 2016). Here, H_s is the significant height of the wave and T_0 is the characteristic period of a wave

H_s (m)	T_0 (s)										
	<4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	> 13
7 to 8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6 to 7	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.000
5 to 6	0.000	0.000	0.000	0.000	0.001	0.003	0.003	0.002	0.001	0.001	0.000
4 to 5	0.000	0.000	0.000	0.003	0.008	0.013	0.012	0.008	0.004	0.001	0.001
3 to 4	0.000	0.000	0.002	0.015	0.037	0.046	0.034	0.018	0.007	0.002	0.001
2 to 3	0.000	0.001	0.014	0.062	0.105	0.093	0.051	0.020	0.006	0.002	0.000
1 to 2	0.000	0.006	0.047	0.110	0.109	0.061	0.022	0.006	0.001	0.000	0.000
0 to 1	0.001	0.006	0.019	0.019	0.008	0.002	0.000	0.000	0.000	0.000	0.000

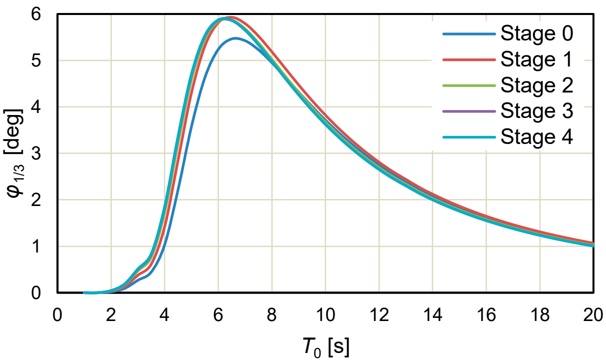

Figure 2. Significant roll amplitudes of bulk carrier A on an irregular side wave at each loading stage for selected bulk carriers, in which the wave direction β = 90° and the significant wave height H_S = 1 m

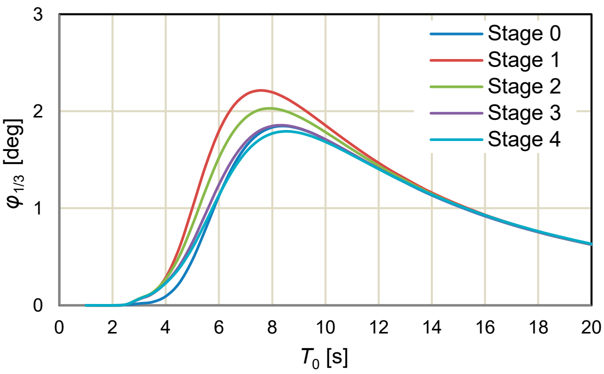

Figure 3. Significant roll amplitudes for bulk carrier B on an irregular side wave at each loading stage for selected bulk carriers, in which the wave direction β = 90° and the significant wave height H_S = 1 m

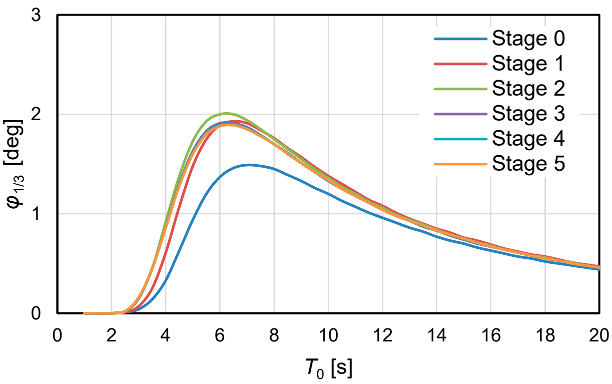

Figure 4. Significant roll amplitudes for bulk carrier C on an irregular side wave at each loading stage for selected bulk carriers, in which the wave direction β = 90° and the significant wave height H_S = 1 m

Because of the complexity of the calculations, the algorithm shown in Figure 5 will be explained on the basis of bulk carrier A for the fourth loading stage, in which Nordfosk limiting criteria will be applied to assess the effectiveness factor. Following this, the calculations have to be repeated for the range of limiting significant amplitudes of roll.

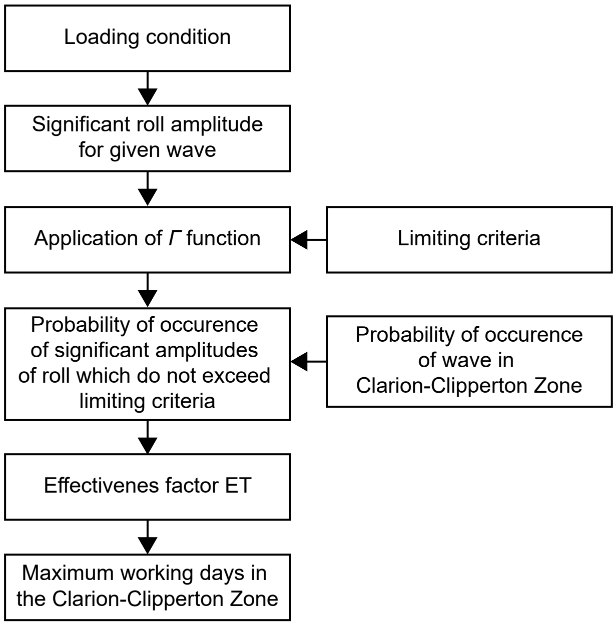

Figure 5. Key steps in evaluating the effectiveness factor E_T of the bulk carriers in view of significant roll amplitudes

Firstly, the significant roll amplitudes for the selected loading stage for all waves characterized by the significant wave height H_s and the characteristic period T_0 (as shown in Table 6) were calculated via the Seaway software. Significant roll amplitudes for the fourth loading stage for bulk carrier A, in wave parameters given in Table 6, are shown in Table 7.

By application of the Γ function given in Equations (8) and (9) and selected limiting criteria, for this example, the significant roll amplitude is limited up to 8° as stated in Nordfosk sea-keeping criteria. Next, the results in terms of the Γ function are shown in Table 8.

By application of the occurrence probability given in Table 6 and the Γ function in Table 8, we can determine the probability of occurrence of favorable waving conditions via the following formula:

$$p'(H_S, T_0) = p(H_S, T_0) \cdot \Gamma(H_S, T_0) \quad (11)$$

The results are shown in Table 9.

Then the effectiveness factor is a sum of the probability occurrence of favorable waving conditions where acceptable significant roll motions are not exceeding the limiting value, i.e.:

$$E_T = \sum_{H_S,T} p' = 0.09 \quad (12)$$

It should be noted that the value of the E_T index for the selected bulk carrier depends on the limiting criteria. To ascertain overall effectiveness, the assessment following calculations have to be completed for each loading stage, and the variable

Table 7. Significant roll amplitudes calculated for bulk carrier A, for the fourth loading condition and wave angle β = 90°, calculated for wave parameters given in statistical data Table 6

H_s (m)	T_0 (s)										
	< 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	> 13
7 to 8	14.86	37.67	46.98	45.24	39.84	34.09	28.98	24.73	21.22	18.42	16
6 to 7	13.01	32.96	41.11	39.59	34.86	29.83	25.36	21.64	18.57	16.12	14
5 to 6	11.15	28.25	35.24	33.93	29.88	25.57	21.74	18.55	15.92	13.82	12
4 to 5	9.29	23.55	29.37	28.28	24.9	21.31	18.12	15.46	13.27	11.51	10
3 to 4	7.432	18.84	23.49	22.62	19.92	17.04	14.49	12.36	10.61	9.21	8
2 to 3	5.574	14.13	17.62	16.97	14.94	12.78	10.87	9.273	7.959	6.908	6
1 to 2	3.716	9.418	11.75	11.31	9.96	8.522	7.246	6.182	5.306	4.605	4
0 to 1	1.858	4.709	5.873	5.655	4.98	4.261	3.623	3.091	2.653	2.303	2

Table 8. Values of the Γ function calculated for a bulk carrier A, for the fourth loading condition and wave angle β = 90°, calculated for significant roll amplitudes given in Table 7 and Nordfosk limiting criteria

H_s (m)	T_0 (s)										
	< 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	> 13
7 to 8	0	0	0	0	0	0	0	0	0	0	0
6 to 7	0	0	0	0	0	0	0	0	0	0	0
5 to 6	0	0	0	0	0	0	0	0	0	0	0
4 to 5	0	0	0	0	0	0	0	0	0	0	0
3 to 4	1	0	0	0	0	0	0	0	0	0	1
2 to 3	1	0	0	0	0	0	0	0	1	1	1
1 to 2	1	0	0	0	0	0	1	1	1	1	1
0 to 1	1	1	1	1	1	1	1	1	1	1	1

Table 9. Table of the probability of occurrence of favorable waving conditions where a limit value is not exceeded

H_s (m)	T_0 (s)										
	< 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	> 13
7 to 8	0	0	0	0	0	0	0	0	0	0	0
6 to 7	0	0	0	0	0	0	0	0	0	0	0
5 to 6	0	0	0	0	0	0	0	0	0	0	0
4 to 5	0	0	0	0	0	0	0	0	0	0	0
3 to 4	0	0	0	0	0	0	0	0	0	0	0.001
2 to 3	0	0	0	0	0	0	0	0	0.006	0.002	0.000
1 to 2	0	0	0	0	0	0	0.022	0.006	0.001	0.000	0.000
0 to 1	0.001	0.006	0.019	0.019	0.008	0.002	0.000	0.000	0.000	0.000	0.000

limiting criteria start from 1 to 10. The results of the overall effectiveness calculations are shown in Figures 6, 7, and 8.

Each loading state of the selected bulk carrier may be expressed by the efficiency factor E_T. Figures 6 to 8 show an effectiveness factor for each loading stage in all the range of the limiting significant amplitudes of roll, $E_T(\varphi_{1/3})$. It should be noted that, for general assessment, the lowest value of effectiveness should be taken into consideration because this parameter reduces the overall effectiveness of the loading of the selected bulk carrier.

The highest values of effectiveness are reached for every bulker only for the very first stage – i.e., the ballast condition. The most effective loading stages are listed below:

- bulk carrier A – stages no. 1 and 2,
- bulk carrier B – stage no. 1,
- bulk carrier C – stage no. 4.

Table 10 shows the minimum effectiveness factors that occur during the loading of nodules for selected bulk carriers when limiting criteria (Karppinen, 1987; Elzinga, Iribarren & Jensen, 1992) were used. Maximum operable days, in which favorable waving

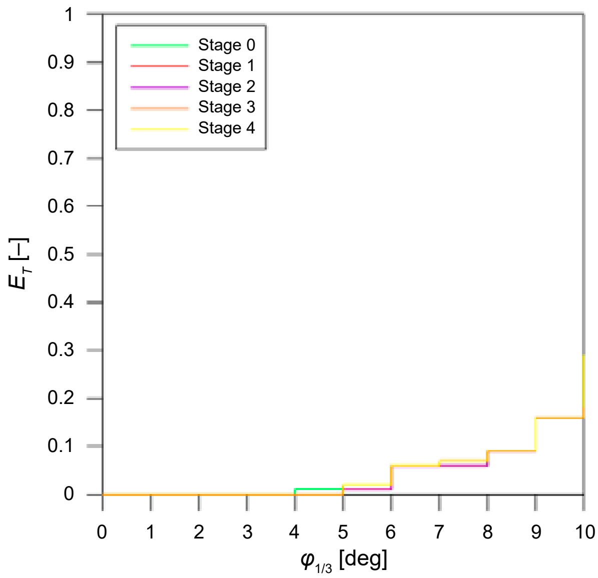

Figure 6. Effectiveness factors throughout all the loading stages and a set of limiting significant roll amplitudes for bulk carrier A

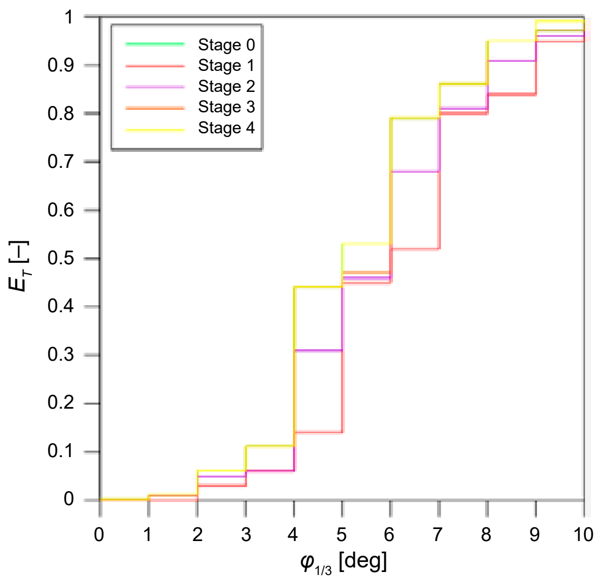

Figure 7. Effectiveness factors throughout all the loading stages and a set of limiting significant roll amplitudes for bulk carrier B

conditions exist in the Clarion-Clipperton Zone, can be calculated via Equation (10). Results of the application of Equation (10) are shown in Table 10, which shows the maximum number of operable days where

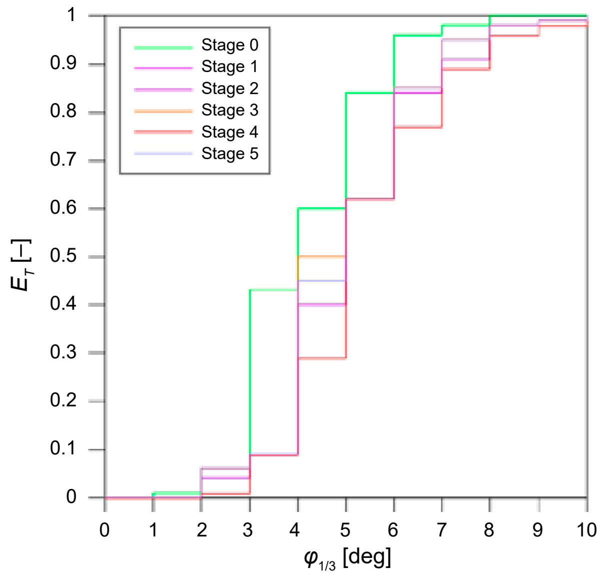

Figure 8. Effectiveness factors throughout all the loading stages and a set of limiting significant roll amplitudes for bulk carrier C

cargo handling operations can be completed safely and efficiently.

Reduction of acceptable significant roll amplitudes from 8° to 5° generates a reduction of operable days in the amounts of:

- bulk carrier A – reduction by 87.9%,
- bulk carrier B – reduction by 46.6%,
- bulk carrier C – reduction by 35.4%.

For the case when the required operability in the stage of the bulk carrier selection is set up to the minimum (i.e., E_T = 0.50), which means that the ship should be fully operable for 183 days during the year, then by the analysis of Figures 6, 7, and 8 we can determine that:

- bulk carrier A should be rejected from consideration since it is below the operability value,
- bulk carrier B with allowable significant amplitudes of roll should be no less than 6 degrees,
- bulk carrier C with allowable significant amplitudes of roll should be no less than 5 degrees.

For the factor of limiting criteria only:

- bulk carrier B fulfills criteria given in previous work (Karppinen, 1987),
- bulk carrier C fulfills criteria given in previous work (Karppinen, 1987; Elzinga, Iribarren & Jensen, 1992).

Table 10. Maximum operating days for selected bulk carriers in the Clarion-Clipperton Zone

Criteria	Bulk carrier A		Bulk carrier B		Bulk carrier C	
	E_T	D	E_T	D	E_T	D
$\varphi_{1/3}$ = 8° (Karppinen, 1987)	0.09	33	0.84	307	0.96	350
$\varphi_{1/3}$ = 5° (Elzinga, Iribarren & Jensen, 1992)	0.01	4	0.45	164	0.62	226

Conclusions

In this research, the roll motion during the loading simulation of three bulk carriers at sea was analyzed. This investigation showed that, depending on applied limiting criteria, the ability to perform loading at sea is reduced. The highest operational effectiveness is reached for the ballast condition for every investigated bulk carrier – during loading, the effectiveness drops – in which we can determine the loading stage that affects the loading process.

Based on the analysis, and applied limiting criteria, only bulk carriers B and C are characterized by the lowest significant amplitudes of roll and the highest efficiency factors throughout the loading process. Bulk carrier A, due to its very low effectiveness factor in relation to bulk carriers B and C, should be avoided for performing loading of nodules at sea. In view of the significant roll amplitudes in this analysis, bulk carrier C is the most suitable ship to perform loading at sea in view of significant roll amplitudes, which is due to its highest efficiency index values with the lowest significant amplitudes of roll.

One degree difference in significant amplitudes of roll between bulk carriers B and C has no difference with respect to operation efficiency, which is due to the fact that both ships are described by the same value of efficiency index. However, the third aspect during loading is that, despite the applied limiting criteria, the lowest amplitudes of roll are decisive parameters in view of loading safety.

Presentation of the effectiveness factor during the function of significant roll amplitudes during loading simulation can be a useful tool for the prediction of maximum working days of the ship in the Clarion-Clipperton Zone, and a method of assessment of the selected bulk carrier suitability to perform loading operations in the Clarion-Clipperton Zone in the view of significant roll amplitudes.

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