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An analysis of vertical shear forces and bending moments during nodule loading for a standard bulk carrier in the Clarion-Clipperton Zone

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Abstract

This article presents an analysis of vertical shear forces and bending moments during nodule loading in the case of a standard bulk carrier around the Clarion–Clipperton Zone. An operational efficiency index was applied to an assessment of internal forces during loading which took into account wave heights and periods around this zone. The aim of this research was to investigate whether waves could have a negative effect on loading efficiency and to estimate the nodule mass that can safely be loaded onto a standard bulk carrier taking these waves into account. Moreover, a calculation was made to discover the acceptable vertical shear force percentage limit, while also taking into account wave activity during loading.

Introduction

The search for raw materials and their extraction from small and medium seabed depths has taken place for several decades. Since the 1970s, research has also been carried out on the possibility of extracting polymetallic nodules located on the seabed at depths of 4000–6000 m (Abramowski & Szelangiewicz, 2011). Currently, Poland has the right to explore seabed deposits containing polymetallic nodules in the Clarion-Clipperton zone. The Clarion-Clipperton zone is a geological submarine fracture zone of the Pacific Ocean spanning an area of 5000 km at depths of 4000 to 5500 meters. The seabed of the Clarion-Clipperton zone is rich in concrete nodules, which are very attractive sources of rare metals. Various mining systems have been designed to collect the polymetallic nodules in this zone. Abramowski and Szelangiewicz (Abramowski & Szelangiewicz, 2011) argued that these systems should perform the following functions:

1) collect nodules from the seabed,
2) mine them from the ocean surface (per mining unit),
3) perform preliminary cleaning,
4) periodically store nodules in the mining unit hold,
5) load nodules into bulk carrier holds on the ocean surface.

Current publications have only focused on nodule extraction methods, efficiency of the mining system, and organization of mining equipment work. There is only a relatively small amount of research addressing the problem of polymetallic nodule loading onto vessels at sea.

Research focusing on methods of nodule transfer (‘transhipment’) at sea, from mining vessels to transport vessels, was contracted by the American government in 1977 (Dames and Moore and EIC Corporation, 1977). A key finding of this research was that polymetallic nodules can be loaded in solid, semi-solid, and dry form. The following reloading systems can be used to transport nodules in these states:

- hydraulic transport systems,
- belt conveyor systems,
- pneumatic conveyor systems.

According to (US NOAA, 1981, pp. 232–235), polymetallic nodules crushed at the extraction stage can be transhipped in a water/nodule suspension. However, in this case, larger pieces of nodules would need to be reloaded onto the destination vessel by means of conveyor belts. The second method is crushing and grinding nodules on the mining ship and then pumping that material onto the transport ship. Another method is to crush, grind, and dry polymetallic nodules on the mining ship and reload this mass on the transport ship using a pneumatic transport system. Research presented in (US NOAA, 1982, p. 41) shows that hydraulic transport systems are the most forward-looking for nodule transport. These studies focused only on the problems of reloading systems. However, the problem of selecting a suitable transport ship-type has not been addressed.

Wakefield and Myers (Wakefield & Myers, 2018) propose a barge as transport unit, which would be towed to the nearest processing station. Deepak et al. (Deepak et al., 2001) propose crushing the nodules at the extraction stage to a thickness of 30 mm (or less) and then transporting them to the barge or bulk carrier by means of pumps. Brockett et al. (Brockett, Huizingh & McFarlane, 2008) propose moving the nodules in a dense suspension to the transport ship using pumps and flexible pipes. It was assumed in this research that nodules in a suspension would be loaded into ship tanks rather than holds. Brockett et al. (Brockett, Huizingh & McFarlane, 2008) also propose transporting concretions from mining vessels to transport vessels using flexible pipes floating on the sea surface. Additionally, recent research conducted by Blue Nodules consortium worked on the assumption that nodules will be de-watered and moved to the transport vessel using pumps and flexible pipes. It has been suggested that de-watering nodules would happen on the mining vessel – but this would take too much space. To solve this problem, the consortium is working on a more effective, mechanical drying method that would also take up much less space on the mining vessel (Lennartz, 2019). During reloading operations, the mining of the nodules by the mining vessel will have to be stopped if using this solution. The possibilities for simultaneous transhipment and mining operations in given environmental conditions still constitute the subject of this research. Meanwhile Vercruijsse and Kovács (Vercruijsse & Kovács, 2018) argues that research has to be carried out using hydrodynamic calculations and model tests.

The Royal IHC Consortium which conducts research on the transhipment of nodules in a wet state, has a different approach. Knight (Knight, 2017) proposes that before transhipment, the concretion will have to be cleared of sediment on the mining vessel and then transhipped in a wet state to a bulk carrier equipped (additionally) with a drainage system.

Taking into account the above solutions, the following types of ship could be used for polymetallic nodule transport:

- a tanker adapted to transport nodules in a wet state in cargo tanks,
- a bulk carrier adapted to transport nodules in a wet state in a hold equipped with a bilge-drainage system,
- a standard bulk carrier for transporting nodules in a dry state.

Either one type of ship alone or several types simultaneously could be used for nodule transport. In any case, the equipment of a mining vessel would have to be optimized with regard to the types of transport ships used. Using multiple types of transport vessels simultaneously would offer the following advantages:

- a portion of the nodules could be transported in a dry state using a standard bulk carrier,
- the remaining nodules, in a wet state, could be transported using an adapted tanker or bulk carrier.

This study presents an analysis for using a standard bulk carrier to transport nodules in a dry state. The study was performed on a **B-517 series** bulk carrier with the following characteristics:

- length between perpendiculars: LBP = 185 m,
- breadth moulded: $B = 24.4$ m,
- design draught: $T = 11$ m,

The B-517 series bulk carriers, characterised by 32,000 DWT, were designed and built in the 1980s at the Szczecin Shipyard and used to transport coal, ore, phosphorites, and grain cargo. Figure 1 shows the section lines of the B-517 series ship.

Polymetallic nodules are characterized by high density, from 2 to 3 t/m^3. While loading a ship with such substantial cargo, large vertical shear forces and bending moments can occur.

Standard bulk carriers carrying heavy cargo are designed with the assumption that loading takes place in port. Typical loading/unloading sequences are developed to ensure safe loading in port. Guidelines have yet to be created to develop a sequence for heavy cargo loading at sea.

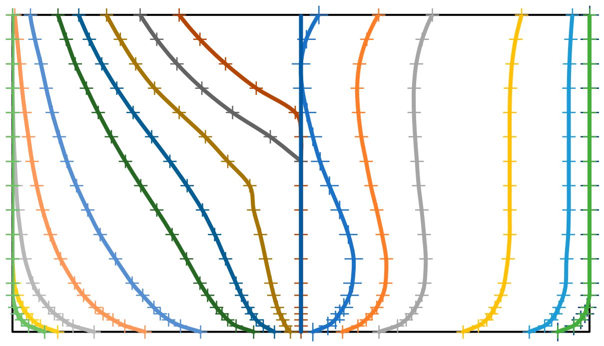

Figure 1. Bulk carrier B517 Body Lines Plan

During ship loading operations at sea, high waves may occur increasing internal forces on the vessel to their limits. The aim of this research was to analyse these internal forces during nodule loading operations and investigate whether these waves could have negative effect on loading efficiency. An additional aim was to estimate the nodule mass that can be safely loaded onto a standard bulk carrier taking waves around the Clarion-Clipperton Zone over a one year period.

Research method

An operational effectiveness index was applied to assess vertical shear forces and bending moments at loading. This index enables quantitative assessment of the sea-keeping performance of a given ship for a particular operation. The index was introduced by Karppinen (Karppinen, 1987) to estimate how long various ship operations would take under given wave conditions. Szelangiewicz (Szelangiewicz, 2000) applied this index to estimate the design characteristics required for a ship. Cepowski, (Cepowski, 2007) applied this index to the assessment of sea-keeping performance for a ballast-loaded bulk carrier.

In this study, the operational effectiveness index E_T expresses the probability P of an event where the internal forces of a ship do not exceed a certain limited level under given wave parameters, such as significant wave height H_S and characteristic period T. This E_T index is calculated as follows (Szelangiewicz, 2000):

$$E_T = \Sigma_{Hs,T} P(G = 1) \qquad (1)$$

where:

E_T – operational effectiveness index,

H_S – significant wave height,

T – characteristic wave period,

P – probability that ship internal forces do not exceed limited level,

G – a bivalent function that has only two values for given wave conditions:
- "0" when ship internal forces exceed the acceptable level or
- "1" when ship internal forces do not exceed the acceptable level.

The index E_T is the sum of the probabilities of wave conditions for which ship internal forces will not exceed the acceptable level. Hence, the index E_T takes values between 0 and 1. Higher index values mean the ship has better sea-keeping properties. The following procedure was used to calculate E_T :

1) collecting statistical data on wave occurrence probability for a given area and time period,
2) calculating vertical shear forces and bending moments during ship loading for given wave conditions,
3) comparing the shear force and bending moment values with their assigned limits,
4) calculating the G function values,
5) calculating E_T as the sum of the H_S and T probabilities for which $G = 1$, using formula (1).

Statistical data

In this study the wave parameters around the Clarion-Clipperton Zone for one year were taken as givens. Table 1 shows wave distributions around this zone throughout the year based on 1,000,000 waves. On the basis of this distribution, the probability of wave height and period occurrence was calculated by dividing the number of waves occurring under given weather conditions by the total number of all observed waves. The results are presented in Table 2. Calculations have shown that the probability of waves over 8 m high is close to zero, so these conditions were not included in this study.

Numerical method

Cross-sectional loading can be calculated using the following general methods (Phelps, 1997):

- for still-water loading – when a ship is floating at rest in still water – the total net forces and moments on the ship should be zero for equilibrium;
- the static-balance or quasi-static method, in which the ship is momentarily balanced upon a design wave, so that net forces and moments on the ship are zero. This method provides a yardstick by which to assess the adequacy of existing or proposed designs, but does not provide a realistic assessment of loads imposed on a ship by particular seaways;

Table 1. Distribution of significant wave height (H_S) and characteristic period (T) in the Clarion-Clipperton Zone (Nimmo, 2012)

H_S [m]	T [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
> 14							1	1	2	2	1
13 to 14							1	1	1	1	1
12 to 13						1	2	2	2	2	1
11 to 12						1	3	4	4	3	2
10 to 11					1	3	6	8	7	5	3
9 to 10					2	7	13	15	13	8	5
8 to 9				1	7	21	36	39	30	18	9
7 to 8				6	35	94	140	137	97	54	25
6 to 7			3	44	220	503	659	571	363	182	76
5 to 6			29	342	1405	2721	3060	2307	1290	576	216
4 to 5		6	270	2482	8126	12851	12036	7684	3690	1432	473
3 to 4		77	2248	14994	36987	45414	33875	17593	7002	2289	646
2 to 3	5	811	14312	62200	105325	92690	51355	20410	6381	1675	387
1 to 2	89	5696	47330	109935	109092	60473	22327	6190	1399	273	48
0 to 1	475	6365	19086	18471	8166	2131	391	57	7	1	

Table 2. The significant wave height (H_S) and characteristic period (T) occurrence probabilities for one year in the Clarion-Clipperton Zone

H_S [m]	T [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				0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
6 to 7			0.0000	0.0000	0.0002	0.0005	0.0007	0.0006	0.0004	0.0002	0.0001
5 to 6			0.0000	0.0003	0.0014	0.0027	0.0031	0.0023	0.0013	0.0006	0.0002
4 to 5		0.0000	0.0003	0.0025	0.0081	0.0129	0.0120	0.0077	0.0037	0.0014	0.0005
3 to 4		0.0001	0.0022	0.0150	0.0370	0.0455	0.0339	0.0176	0.0070	0.0023	0.0006
2 to 3	0.0000	0.0008	0.0143	0.0623	0.1054	0.0928	0.0514	0.0204	0.0064	0.0017	0.0004
1 to 2	0.0001	0.0057	0.0474	0.1100	0.1092	0.0605	0.0223	0.0062	0.0014	0.0003	0.0000
0 to 1	0.0005	0.0064	0.0191	0.0185	0.0082	0.0021	0.0004	0.0001	0.0000	0.0000	

- the linear strip theory method, based on two-dimensional potential flow theory, where the solution is simulated only for the domain of wave frequency;
- a non-linear method based on three-dimensional potential flow theory, where the solution is most often simulated for the time domain.

Of the above methods only the linear strip theory and non-linear methods take into account wave impacts. The linear strip method is less accurate than the nonlinear method, but much simpler to apply. Non-linear methods are more accurate, but more complex and difficult to use. These methods require model test verification.

Jensen and Petersen (1981) noted that the effects of wave nonlinearity induced bending moments and shearing forces for a sailing VLCC carrier were small under moderate conditions at sea. For vessels with high block coefficient value, such as bulk carriers and tankers, linear models are sufficiently accurate and effective. This study was conducted for bulk carriers characterised by high block coefficient values. Therefore, the linear strip method was used in this study to calculate internal forces on ships from waves.

A solution under the strip method comprises a set of vertical shear forces and bending moment transfer functions. Statistics for internal forces can then be calculated on the basis of these transfer functions and the wave energy spectrum. The energy spectrum for sailing ship motions in irregular waves is calculated by multiplying squared motion transfer functions and wave energy spectra. A common ITTC spectrum (ITTC, 1978) based on the Bretschneider wave energy spectrum, was used here.

Vertical shear forces and bending moment values in still water were calculated using the author's own software. Whereas internal force values for waves

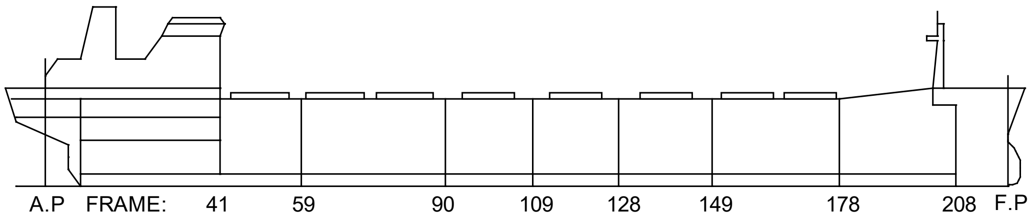

Figure 2. Bulk carrier section number map

were calculated using SEAWAY software. SEAWAY is a frequency-domain ship-motion computer program, based on linear strip theory, to calculate wave-induced loads, motions, added resistances, and internal loads for six degrees of freedom of displacement among ships sailing over regular and irregular waves (Journée, 2001).

Limit values

In this study, the values of shear forces and bending moments were compared with their permissible values in order to calculate the E_T index. The seagoing limit-values presented in the loading manual (Szczecin Shipyard, 1986) were used as acceptable values of vertical shear force (SF) and bending moment (BM). Table 3 presents these limit-values. Figure 2 shows forces per bulk carrier section, by section number.

Table 3. Acceptable values of vertical shear force (SF) and bending moment (BM) (Szczecin Shipyard, 1986)

	Section							
	41	59	90	109	128	149	178	208
SF [kN]	28822	32530	36434	38337	38210	31784	43929	55004
BM	934795 kNm							

Results and discussion

Initially, we checked typical loading sequences from the loading manual for ship B-517. Shear forces and bending moments were compared with acceptable values for still water. It was noted that shear forces exceeded the limit values during loading in still water during the third loading stage according to a typical loading sequence. Therefore, a new loading sequence was developed in which internal forces would not exceed the limit values under seagoing conditions. This new loading sequence consisted of nine loading stages.

Internal force results during the loading simulation for calm water showed that shear forces rather than bending moments are limiting loading process. Therefore, only shear forces have been taken into account in further analysis. In particular, the highest shear forces value was 34,600 kN at stage 7 in section 90 (Figure 2). Next, we analysed sectional forces at stage 7, section 90, taking into account shear force and the influence of waves. Figure 3 shows the wave direction coordinate system used in this study.

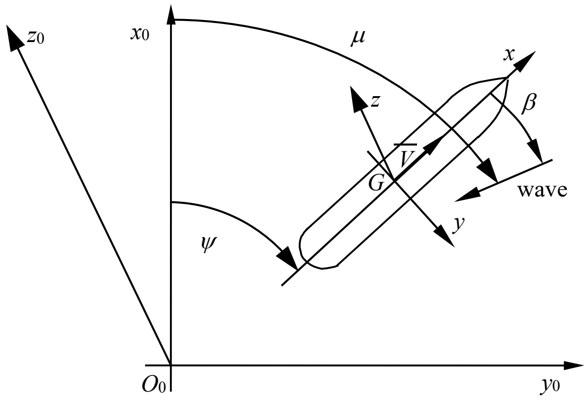

Figure 3. Coordinate system Rigid body, O_0, x_0, y_0, z_0 – global, G, x, y, z – local of the ship

Figure 4 shows the influence of wave angle on shear forces at stage 7, section 90, assuming constant significant wave height (H_S = 1 m) and peak wave period (T = 7 s). This figure confirmed that the maximum forces occur at a 180 degree wave angle.

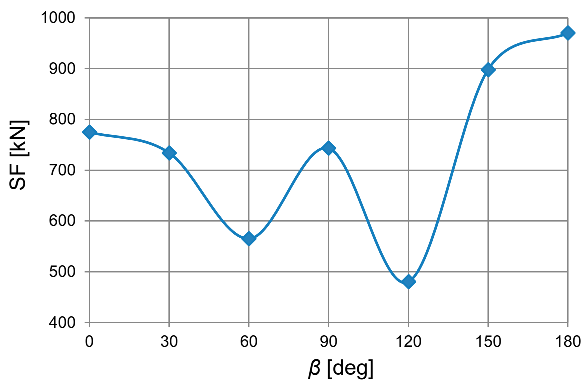

Figure 4. The influence of wave angle on shear forces at stage 7, section 90, significant wave height H_S = 1 m, characteristic wave period T = 7 s

Table 4. Shear forces on irregular waves at stage 7, section 90, wave angle β = 180°

H_S [m]	T [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	3200	4400	6400	7600	7680	7600	7360	6560	6000	5440	4800
6 to 7	2800	3850	5600	6650	6720	6650	6440	5740	5250	4760	4200
5 to 6	2400	3300	4800	5700	5760	5700	5520	4920	4500	4080	3600
4 to 5	2000	2750	4000	4750	4800	4750	4600	4100	3750	3400	3000
3 to 4	1600	2200	3200	3800	3840	3800	3680	3280	3000	2720	2400
2 to 3	1200	1650	2400	2850	2880	2850	2760	2460	2250	2040	1800
1 to 2	800	1100	1600	1900	1920	1900	1840	1640	1500	1360	1200
0 to 1	400	550	800	950	960	950	920	820	750	680	600

Table 5. Total shear forces in steel water and irregular waves at stage 7, section 90, wave angle β = 180°

H_S [m]	T [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	37800	39000	41000	42200	42280	42200	41960	41160	40600	40040	39400
6 to 7	37400	38450	40200	41250	41320	41250	41040	40340	39850	39360	38800
5 to 6	37000	37900	39400	40300	40360	40300	40120	39520	39100	38680	38200
4 to 5	36600	37350	38600	39350	39400	39350	39200	38700	38350	38000	37600
3 to 4	**36200**	36800	37800	38400	38440	38400	38280	37880	37600	37320	37000
2 to 3	**35800**	**36250**	37000	37450	37480	37450	37360	37060	36850	36640	**36400**
1 to 2	**35400**	**35700**	**36200**	36500	36520	36500	36440	**36240**	**36100**	**35960**	**35800**
0 to 1	**35000**	**35150**	**35400**	**35550**	**35560**	**35550**	**35520**	**35420**	**35350**	**35280**	**35200**

The E_T index value for this loading stage was calculated as follows; Firstly, the shear force values for irregular waves at stage 7, on section 90, were calculated for all waves presented in Table 2 using SEAWAY software. Table 4 shows the results of these calculations. Then, these shear forces were increased by the value of shear force in calm water, 34,600 kN. Table 5 shows total shear forces calculated for still water and for irregular waves.

Next, the shear force values from Table 5 were compared with the limit-value from Table 3. In cases when the shear force value did not exceed the limit-value, the value of $G = 1$ was assumed. Otherwise, $G = 0$ was assumed. Shear force values within the allowable range are shown in bold in Table 4. Table 6 shows the G function values.

Table 6 presents dangerous wave-activity ranges in detail, taking into account shear forces at stage 7. This table shows that loading can be safely carried out in waves up to:

- 1 metre in height and for any wave period,
- 2 metres in height for a wave period of less than 6 s and greater than 10 s.

To calculate the E_T operational effectiveness index according to equation (1), the probabilities p' for which $G = 1$ need to be calculated. The probabilities p' were calculated as follows:

$$p'(H_S, T) = p\ (H_S, T)\cdot G\ (H_S, T) \qquad (2)$$

Table 6. Values of the function G calculated by the use of shear forces at stage 7, section 90

H_S [m]	T [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	0
2 to 3	1	1	0	0	0	0	0	0	0	0	1
1 to 2	1	1	1	0	0	0	0	1	1	1	1
0 to 1	1	1	1	1	1	1	1	1	1	1	1

Table 7. Probability values p' for which $G = 1$, sum of p' values equals 0.117

H_S [m]	T [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
2 to 3	0	0.0008	0	0	0	0	0	0	0	0	0.0004
1 to 2	0.0001	0.0057	0.0474	0	0	0	0	0.0062	0.0014	0.0003	0
0 to 1	0.0005	0.0064	0.0191	0.0185	0.0082	0.0021	0.0004	0.0001	0	0	0

where:

p' – probability for which $G = 1$,

p – wave occurrence probability values from Table 2,

G – G function values from Table 6.

Table 7 shows probability values p'.

Finally, the E_T index value was calculated as the sum of probability values p' given in Table 7:

$$E_T = \Sigma_{Hs,T}\, p' = 0.117 \quad (3)$$

The E_T index value can be interpreted as the percentage of the time during which a ship can be safely loaded due to internal forces. In this way, the number of hours during a year when the ship can be safely loaded could be estimated, as follows:

$$h = 0.117 \cdot 365 \cdot 24 = 1025 \quad (4)$$

where:

h – hour number.

Assuming that approximately 3000 tons of cargo can be loaded within 1 hour, the maximum mass of polymetallic nodules loaded in one year is around:

$$Q = h \cdot 3000 = 3\ 074\ 760 \text{ t} \quad (5)$$

where:

Q – mass of polymetallic nodules loaded in one year.

It follows that this type of bulk carrier can safely load about 3 million tons of polymetallic nodules in the Clarion-Clipperton Zone in one year.

Table 4 shows shear force values here for irregular waves. On the basis of these values, the percentage limit of the acceptable vertical shear force for these waves can be calculated as follows:

$$\%SF_{w\text{limit}} = 100\frac{SF_{\text{limit}} - SF_w}{SF_{\text{limit}}} \quad (6)$$

where:

$\%SF_{w\text{limit}}$ – the percentage limit of the acceptable vertical shear force for waves,

SF_{limit} – acceptable vertical shear force taken from Table 3,

SF_w – shear force for irregular waves taken from Table 4.

Table 8 shows values calculated using Equation (6). Column "MIN", last in this table, showing the most limiting values for a given wave height range.

On the basis of Table 8, the range of permissible shear forces can be limited by assuming the wave-activity parameters for the loading period. For example, acceptable shear force can be reduced to 92% when the ship is loaded on a wave of up to 3 metres in height.

Table 8. Percentage limit of acceptable vertical shear force for calm water and irregular waves

H_S [m]	T [s]											MIN
	< 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	91%	88%	82%	79%	79%	79%	80%	82%	84%	85%	87%	79%
6 to 7	92%	89%	85%	82%	82%	82%	82%	84%	86%	87%	88%	82%
5 to 6	93%	91%	87%	84%	84%	84%	85%	86%	88%	89%	90%	84%
4 to 5	95%	92%	89%	87%	87%	87%	87%	89%	90%	91%	92%	87%
3 to 4	96%	94%	91%	90%	89%	90%	90%	91%	92%	93%	93%	89%
2 to 3	97%	95%	93%	92%	92%	92%	92%	93%	94%	94%	95%	92%
1 to 2	98%	97%	96%	95%	95%	95%	95%	95%	96%	96%	97%	95%
0 to 1	99%	98%	98%	97%	97%	97%	97%	98%	98%	98%	98%	97%

Conclusions

In this research, internal forces during nodule loading onto a standard bulk carrier at sea were analysed. This study has shown that standard loading sequences available in the loading manual cannot be used for loading polymetallic nodules at sea. Therefore, a new alternative sequence has been developed, taking into account wave conditions at sea, as well as shear forces and bending moments. Studies have also shown that shear forces rather than bending moments are limiting the loading process.

This study clearly shows that a B-517 bulk carrier can be safely loaded while enduring internal forces caused by waves of up to:

- 1 metre in height for any wave period,
- 2 metres in height for a wave period of less than 6 s and greater than 10 s.

This study also shows that:

- a B-517 bulk carrier can be safely loaded while enduring internal forces for 1025 hours,
- while loading a maximum of 3 million tons of polymetallic nodules,

within one year in the Clarion-Clipperton Zone.

To increase this range, the range of permissible shear forces can be limited using the values shown in Table 3. This study shows that, to safely load a B-517 bulk carrier on a wave of up to 3 m in height, the acceptable shear force should be reduced to 92%.

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