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DOI
10.5957/JOSR.07230022

Publication date
2024

Document Version
Final published version

Published in
Journal of Ship Research

Journal of Ship Research, Vol. 68, No. 2, June 2024, pp. 66–76
http://dx.doi.org/10.5957/JOSR.07230022

The Effect of Surge on Extreme Wave Impacts and an Insight into Clustering

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The original goal of the present research is to investigate the influence of surge on green water and slamming. Long-running experiments with forward velocity and irregular waves were repeated with and without surge. Surge is found to increase the probability of green water events, but the impact pressures on deck and the probability of a green water event reaching the deck box decreases when the ship is free to surge. Green water and slamming events turned out to not occur independently as both event types cluster for large probabilities of occurrence. Clusters are caused by large pitch motions. Larger pressures on deck are found for clustered events.

Keywords: green water; slamming; surge; clustering; probability

1. Introduction

Extreme wave impacts can be green water where water impacts the deck and superstructure of a ship, or slamming where the ship impacts the water. The forces that occur during these events can be dangerous for the ship and the people on it (Ersdal & Kvitrud 2000). For safety, the ship needs to be designed for these impacts.

To be able to design for extreme wave impacts the pressures they induce and how often they occur have to be known. Green water and slamming are complex and their occurrence and impacts depend on parameters like the ship's geometry, forward velocity, motions, and waves (Ochi & Motter 1973; Buchner 1995; Greco et al. 2004). As green water and slamming are complex problems, the probability and pressures of impacts are normally found by modeling a ship, either experimentally or with computational fluid dynamics simulations. In modeling the problem is simplified by limiting the parameters and reducing the degrees of freedom to save costs and make the modeling possible.

Most experimental extreme wave loading research reduces the degrees of freedom by restricting surge (Greco et al. 2004; Fonseca & Guedes Soares 2005; Pham & Varyani 2005; Soares & Pascoal 2005; Drummen et al. 2008; Greco et al. 2012; Lavroff et al. 2013; Ruggeri et al. 2015; Wang & Guedes Soares 2016; Babu et al. 2022). Exceptions are research with full-scale ships (Ersdal & Kvitrud 2000; Thomas et al. 2003) and free-running experiments (Ogawa et al. 2001; Hermundstad & Moan 2005; Kim et al. 2015). However, the role of surge in extreme wave loading events is not specifically investigated in these full-scale and free-running studies. Literature shows that both green water and slamming events occur when a large forward pitch motion occurs out of phase with a wave (Stansberg & Karlsen 2001; Fu et al. 2009). The phase difference between the pitch and waves will be influenced by the surge. Surge is thus expected to influence green water and slamming. The goal of the present research is to identify the influence of surge on green water and slamming events.

2. Methodology

To research extreme wave loading events, which do not occur often, long testing times are needed. Data for a sailing ship in head waves free to heave, pitch, and, for half the cases, the surge was collected for six different test conditions over a total of 42 hours of experimental data. The data can be downloaded through https://doi.org/10.4121/15f0d739-b84c-48f3-879a-68c08f068ab3 (Boon & Wellens 2024).

2.1. Experiments

The model experiments were carried out at the wave-current tank at the Delft University of Technology, a tank that allows for continuous testing with irregular waves and modeled forward

Manuscript received by SNAME headquarters 6 July 2023; accepted 18 April 2024; published online June 3, 2024.
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velocity (Boon & Wellens 2022). The tank is 7.4-m long and 2.35-m wide and the used water depth is 0.44 m. A 3D printed S175 model without forecastle at a Froude scaling of 1:130 was used for the experiments. The model was made smooth and watertight with multiple rounds of sanding and epoxy. The dimensions are given in Table 1. The vertical center of gravity and the radius of gyration were found with swing tests and the natural periods with free-decay tests. The ship model was placed 2.79 m from the wavemaker and 0.93 m from the side of the tank.

The suspension of the model allowed for free heave, pitch, and surge motion is shown in Fig. 1. The model was suspended through a hinge in the center of gravity. Two vertical linear guides, called the heave rods, were attached to this hinge, allowing for pitch and heave but limiting sway. The two vertical linear guides went through the surge carriage. This surge carriage was mounted to horizontal rails, allowing for the model to surge with limited resistance. In this setup, the mass of the pitching system (mass model) differs from the mass of the heaving system (mass model + mass heave rods), which again differs from the mass of the surging system (mass model + mass heave rods + mass surge carriage). The difference in mass for the surging and pitching systems is not representative of real-world scenarios. The sway motions were not perfectly restricted and some motion with a maximum of 0.5° was allowed. Soft springs with a spring stiffness of 3 N/m were attached to each side of the surge carriage to ensure in the free-to-surge cases the model would not move off the surge rail. The spring stiffness was chosen so that the natural surge period was at least 10 times the wave encounter frequency. To restrict surge motions, the surge carriage could be clamped so surge was restricted but the model was still free to heave and pitch.

2.2. Measuring equipment

Various measuring devices were placed in the setup through which data were acquired at 1000 Hz. Figure 2 shows the location of the measuring equipment on the bow. Three resistance-type relative wave elevation (RWE) probes were used. The distance between the probes is 0.06 m and their orientation is vertical at 0.01 m to the side of the deck. To measure the pressure, six GE druck PDCR 42 type sensors with a range of up to 350 kPa are used. Four were placed on the center line of the model on the deck with 0.04 m between them, and two were placed on the deck box at a height of 0.01 and 0.03 m. The signal from the third pressure sensor (0.14 m from the stem) was noisy and thus not used. The heave and pitch of the vessel were measured using Panasonic HG-C1400 laser distance sensors at the center of buoyancy and 0.645 m to the back of the vessel. Both sensors were attached to the surge carriage. The surge was measured with the Honeywell 940-R4Y-RD-ICO acoustic sensor measuring the horizontal location of the surge carriage. A load cell was placed between the hinge and the heave rod to measure the resistance. A wetness sensor was placed 0.005 m before the front pressure sensor to measure water on deck but during the experiments, water stayed around this sensor after impacts so the data were not used.

Table 1 Dimensions and parameters of the used model

Length between perpendiculars	1.346 m
Breadth molded	0.195 m
Draft	0.076 m
Freeboard (*fb*)	0.047 m
Mass model	8.76 kg
Mass heave rods	2.26 kg
Mass surge carriage	1.14 kg
Vertical center of gravity	0.067 m
Vertical center of buoyancy	0.040 m
Longitudinal center of buoyancy	0.653 m
The radius of gyration in pitch	0.359 m
Trim angle	0°
Natural heave period in water	0.767 second
Natural pitch period in water	0.625 second
Natural surge period in water	11 seconds
Dimensions deck box (L × W × H)	0.048 × 0.10 × 0.075 m
Distance to deck box from stem	0.22 m
Location RWE probe 1 from stem	0.025 m
Location pressure sensor 1 from stem	0.06 m

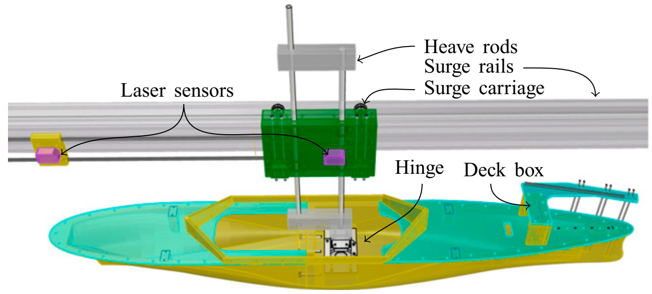


Fig. 1 Test setup

A resistance-type waveprobe was placed at 0.863 m from the side of the tank and 2.79 m from the wave maker. All data were filtered with a third-order low pass filter at 40 Hz to remove the noise from the electrical net.

Two webcams were used to acquire footage of all experiments, one placed to the side of the setup and one above the setup. All data, footage, 3D print files, and laser cut files are available at https://doi.org/10.4121/15f0d739-b84c-48f3-879a-68c08f068ab3 (Boon & Wellens 2024).

2.3. Test conditions

The tests were conducted in six different test conditions: with and without surge and with different spectral steepness (s_{op}) of 0.030, 0.037, and 0.042. The spectral steepness is calculated as $s_{op} = 2\pi \frac{H_{m0}}{g \cdot T_{m02}^2}$ where H_{m0} is the significant wave height, $T_{m_{02}}$ the

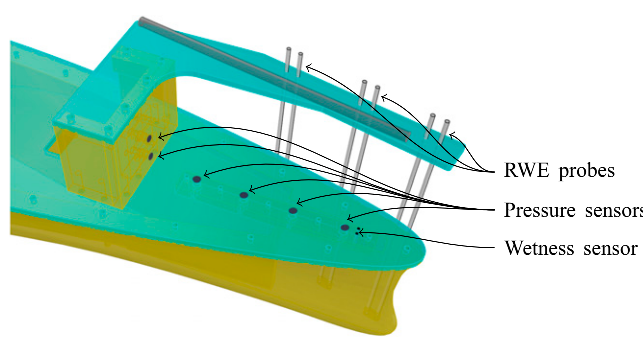


Fig. 2 Measuring equipment on the bow

mean wave period, and g is the gravitational acceleration. Most incidents with extreme wave impacts on ships occur for $s_{op} >$ 0.035 so the values around this spectral steepness were tested (Mendes & Oliveira 2021). Representations of the sea states were generated with the wavemaker following a 7-hour-long continuous wave file. The wave files were created by calculating the amplitudes of the wave components in the sea state, with a frequency resolution below 0.1 mHz to prevent repetition in the desired time span, and adding these wave components together with a random phase. Figure 3 shows the energy distribution of the wave spectra used and Table 2 gives the main parameters of the wave spectra.

For slamming bottom slamming events were considered, where the ship impacts the water. Slamming events were identified using the Ochi slamming kinematic criterion (Ochi & Motter 1973). The criterion consists of 1) the bow is out of the water (the measured RWE is lower than the draft) and 2) the relative velocity is above the limit value. The limit value is 0.33 m/s at the scale of the present work. A total of 83 slamming events were found. No slamming events were found for $s_{op} = 0.030$.

For green water, where water impacts the ship, a distinction between deck impacts and deck box impacts was made. During a green water event the water always impacts on deck, but for only some green water events did the water also flow far enough to impact the deck box.

Two criteria are used for green water identification. The first criterion is that a pressure larger than 50 Pa was measured on the most forward pressure sensor. The second criterion is that the impact coincided with a continuous flow of water on the deck. The second criterion was ensured by visually checking all the initially identified green water events. To identify the deck box impacts a lower limit value of 20 Pa on the bottom pressure sensor on the deck box was used. In total 4703 green water events are identified, of which 1543 events also impacted the deck box.

3. Results

With the experiments, a large data set of extreme wave loading events is obtained for a ship model with forward velocity in irregular waves, with and without surge. The effect of the surge on the probability of events and the pressures is analyzed. As the effect of the surge is of interest, the surge is quantified in Table 3 for context. This table shows the standard deviation of the surge throughout the experiments, as well as the average surge measured during green water and slamming events. The surge motions during green water and slamming events in Table 3 are between 3.6 and 1.9 times smaller than the extreme surge motions reported in Dhavalikar and Negi (2009) for the S175 ship in a similar sea state. Stills from video footage for green water and slamming impacts are shown in Fig. 4.

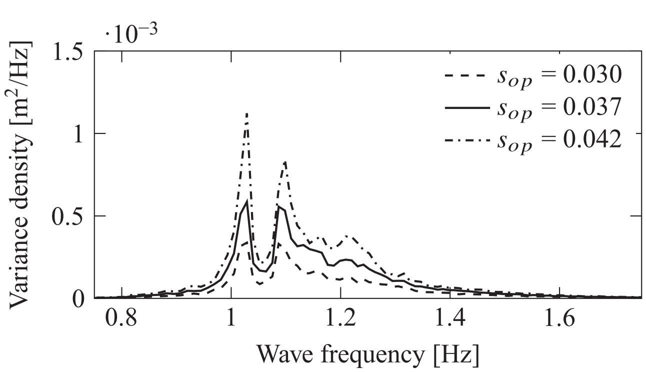


Fig. 3 Wave spectra with the different spectral steepnesses

Table 2 Wave spectra at model scale

T_p (s)	H_{m0} (m)	s_{op} (-)	V (m/s)	Froude number (-)	t_{test} (hours)
0.972	0.048	0.042	0.25	0.07	7
0.972	0.041	0.037	0.25	0.07	7
0.972	0.033	0.030	0.25	0.07	7

3.1. Probabilities and pressures

The probability of green water on deck is shown in Fig. 5A. In this figure, P is the probability of an event occurring and subscript $_{GW}$ indicates green water on deck, $_{GW\text{box}}$ is the green water that caused an impact on the deck box and $_{SL}$ is the slamming. The subscripts follow the definitions given in the section "Event identification".

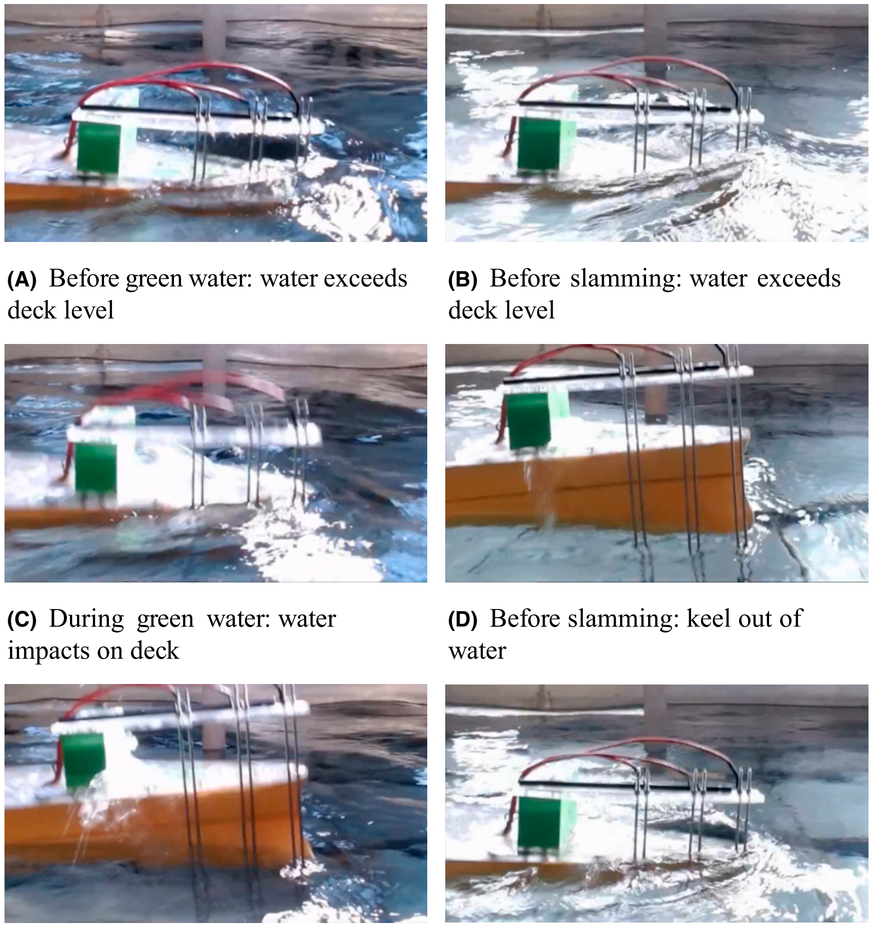
The probability of green water is higher for cases where the model can surge compared to no-surge cases. An effect of the surge on the probability of green water was expected as the surge will change the phase between pitch and wave. The phase shift introduced by the surge increases the number of green water events. No clear conclusions can be made for the influence of surge on the probability of slamming events, as shown in Fig. 5B. However, for the largest spectral steepness, the probability of slamming is also larger for surge cases compared to no-surge cases.

The reverse is true for deck box events: the probability of impacts on the deck box is larger if the model is restricted in the surge, as shown in Fig. 5C. The water has to travel over the bow to the deck box for green water to impact the deck box. The larger probability of deck box impacts for no-surge cases thus indicates that large events are more likely when the model is restricted in the surge. A possible reason is that part of the energy of the water at the bow is transferred to decrease the forward velocity of the ship through the surge, resulting in less energy in the impacting water and water not traveling as far over the bow when the model can surge.

If green water events are indeed larger for the no-surge cases because the surge motion absorbs energy, larger pressures should occur for the no-surge cases compared to surge cases. Figure 6A shows that restricting surge indeed leads on average to large impact pressures for deck impacts. The impacts are larger on deck for both the maximum pressure measured on deck during an impact ($p_{\max_{\text{deck}}}$) as for the median of the maximum pressures

Table 3 Surge motions

s_{op} (-)	Standard deviation (m)	Average during green water (m)	Average during slamming (m)
0.042	0.0036	0.020	—
0.037	0.0041	0.020	0.019
0.030	0.0048	0.021	0.023



(A) Before green water: water exceeds deck level

(B) Before slamming: water exceeds deck level

(C) During green water: water impacts on deck

(D) Before slamming: keel out of water

(E) During green water: water impacts on deck box

(F) After slamming: water exceeds deck level

Fig. 4 Stills from a green water event on the left side (A, C, and E) and slamming events on the right side (B, D, and F). Chronological order from top to bottom

measured by each pressure sensor on deck ($\overline{p}_{\max_{\text{deck}}}$) for the no-surge case.

However, Fig. 6B shows the reverse for the pressures on the deck box: the pressures on the deck box are larger when the model is free to surge. On average the peak impact pressure on the deck box occurred 0.32 seconds after the peak impact on the deck was measured. With the time difference, a theory was that 0.32 seconds after the initial impact the model starts surging forward on the wave, causing a large relative velocity to the water, increasing the pressure on the deck box. However, no-surge velocities were found large enough to cause the difference in impact pressures shown in Fig. 6B. Further research is required to explain the larger impact pressures on the deck box for surge cases compared to no-surge cases.

Figures 5 and 6 show that all the probabilities and pressures increase with an increase in spectral steepness, except for the deck box impact pressures. The increase in the probability of slamming and green water and pressures during these events is expected as a larger spectral steepness at a constant peak period, and spectral shape indicates more energy in the spectrum. The median deck box pressures are constant up to $s_{\text{op}} = 0.037$ and then decrease for $s_{\text{op}} = 0.042$. For $s_{\text{op}} = 0.042$ the probability of events occurring is large, meaning they follow each other up quickly. A possible cause for the decrease in deck box pressures is the interaction of events with water on the deck from the previous event.

To further check if the difference is created by surge, single events for surge and no-surge cases should be compared. However, the conducted experiments do not allow for such an analysis. As the tests were conducted in irregular waves, the encountered wave trace is dependent on location. When the model was free to surge, the position of the model was different from the no-surge cases, thus the motions and encountered waves were not directly comparable. Further research that allows for event-level comparison should be conducted to further investigate the difference between surge and no-surge green water and slamming impacts.

3.2. Statistical distributions

After looking at the median of the pressures and probabilities per case in the previous paragraph the overall statistical distributions are looked at. Previous literature shows that for green water impacts the pressures are Fréchet distributed (Boon & Wellens

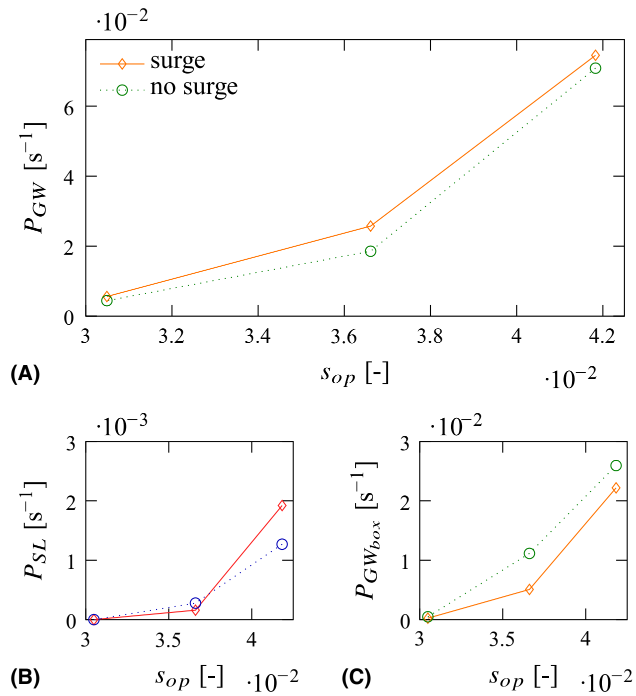


Fig. 5 Effect of surge on the probability of green water and slamming (A) Surge increases the probability of green water impacts (P_{GW}). (B) The influence of surge on the probability of slamming (P_{SL}) is not consistent for different spectral steepnesses (s_{op}). (C) Surge reduces the probability of impact on the deck box (P_{GWbox})

2022). For slamming and green water the time between events (λ) is exponentially distributed (Ochi & Motter 1973; Mansour & Lozow 1982; Ferro & Mansour 1985; Boon & Wellens 2022).

The applicability of the distributions from the literature on the new data is checked. To be able to check, first, the Fréchet and exponential distributions are fitted to the data of the different tests using least squares to find the optimal parameters. The quality of fit for the

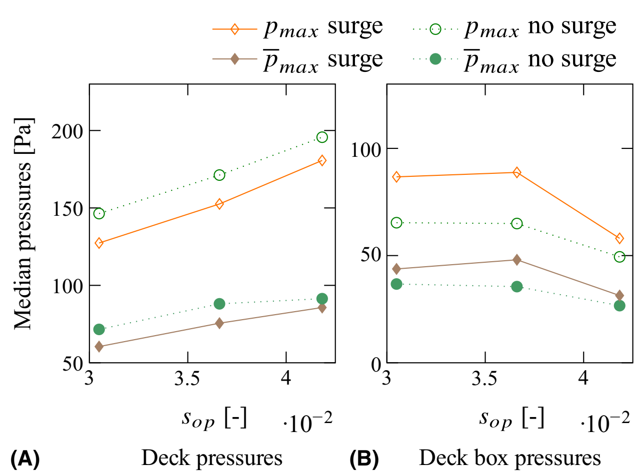


Fig. 6 Larger maximum (p_{max}) and median ($\overline{p}_{max}$) impact pressures on deck were measured for restricted surge compared to cases where the model was free to surge. Similar impact pressures on the deck box were found with and without surge

fitted distribution is then checked using the Kolmogorov–Smirnov test. If the *p*-value of the Kolmogorov–Smirnov test is above a limit value, the statistical distribution can describe the data. The limit of .05 is chosen, but the less strict limit of .01 is also commonly used. The results are shown in Table 4. The Fréchet distribution fits the distribution of the pressures for the deck and deck box impacts. The exponential distribution does not fit the new data. For none of the cases does the exponential distribution fit the distribution of time between green water deck events, and the exponential distribution does not fit the times between green water deck box impacts and slamming events for the large probability cases. Boon and Wellens (2022) show that the times between green water events follow the exponential distribution and thus conclude that events occur randomly and independently. So is our previous publication wrong or is there a problem with the new experimental data? To visually inspect why the events do not follow the exponential distribution, the distributions of the time between events are plotted in Fig. 7 for green water deck and slamming events.

The figures show an excess of the minimum value for all the cases for which the exponential distribution does not fit. Data sets that are expected to be independent and random but have an excess of the minimum value are zero-inflated (Lachin 2009). Zero-inflated data can be a result of combining two distributions, like an exponential distribution and a distribution that generates the minimum value. The minimum value, in our case the shortest time between events, is captured in the location parameter shown in Table 4. Zero inflation occurs mostly for a time between events of 0.48 to 0.7 seconds. This range matches the natural period of the pitch.

In slamming literature a possible physical phenomenon that can generate the minimum value is found: clustering (Hansen 1994; Jiao 1996; Dessi & Ciappi 2013). For clustering grouping of events causes multiple events to occur after one another, resulting in a mechanism in the system that causes the assumption of events occurring independently to be invalid. To test if clustering is the cause of the zero inflation for green water and slamming, the events that follow an event are removed from the data. Removing the clusters should remove the distribution that generates the minimum value from the set and leave us with the originally expected exponential distribution.

3.3. Clusters

Clusters are removed from the data set by ignoring events that occur within the minimum time (t_{min}), visualized in Fig. 9. t_{min} is set to be larger than the natural pitch period (0.625 seconds), as zero inflation was found to occur around this period. t_{min} is also chosen larger than the peak wave encounter period (0.81 seconds) as for slamming and green water literature shows that events occur when a large forward pitch motion occurs out of phase with a wave (Stansberg & Karlsen 2001; Fu et al. 2009). t_{min} is set at 1 second.

With the clusters removed from the data, the exponential distribution is now found to fit the data. The fit of the data with the clusters removed is shown in Table 5 and visualized in Fig. 8. The exception is the steepest spectral steepness as the *p*-value is below .05. The probability of events occurring is large in these cases ($P_{GW} > 0.06\ s^{-1}$), thus eliminating events that follow each other also eliminates events that are independent and occur close together. Figure 8 indeed shows a decrease in the data at the lowest value, showing that the low *p*-value is caused by eliminating

Table 4 The fitted Fréchet and exponential distribution are quantified with the shape, scale, and location parameters. The quality of fit of the distributions to the data is tested, with *p*-value > .05 as the limit value. The *p*-values show that the Fréchet distribution fits the pressures, but the exponential distribution does not fit the time between events

			Surge			No-surge		
		s_{op}	0.030	0.037	0.042	0.030	0.037	0.042
Green water Deck	p_{max}	***p*-Value**	**.53**	**.33**	**.48**	**.95**	**.34**	**.11**
		Shape	9.04	2.10	3.76	3.65	1.38	3.83
		Scale	435	150	289	211	129	285
		Location	−328	−25.8	−134	−88.4	10.6	−115
	$\overline{p}_{max}$	***p*-Value**	**.60**	**.81**	**.78**	**.81**	**.09**	**.26**
		Shape	5.99	1.80	3.25	2.59	1.27	3.39
		Scale	131	67.6	123	67.0	61.8	125
		Location	−82.7	−67.9	−50.5	−96.5	8.13	−46.9
	λ	***p*-Value**	**.01**	**9e^{-30}**	**4e^{-137}**	**.02**	**3e^{-23}**	**2e^{-174}**
		Location	0.57	0.60	0.58	0.31	0.48	0.55
		Scale	177	38.1	15.0	207	55.0	13.6
Green water Box	p_{max}	***p*-Value**	**.98**	**.57**	**.69**	**.85**	**.35**	**.57**
		Shape	1.18	1.46	1.39	1.10	0.90	1.57
		Scale	57.6	70.2	37.1	47.3	31.0	30.1
		Location	0.49	−3.33	8.20	5.35	15.0	9.64
	$\overline{p}_{max}$	***p*-Value**	**.98**	**.79**	**.74**	**.89**	**.50**	**.36**
		Shape	1.02	1.42	1.34	1.11	1.07	1.51
		Scale	22.5	36.5	19.1	24.1	21.9	15.6
		Location	6.21	−0.97	5.74	4.49	5.71	6.48
	λ	***p*-Value**	**.78**	**2e^{-6}**	**3e^{-25}**	**.32**	**1e^{-5}**	**1e^{-41}**
		Location	2387	0.64	0.62	575	0.61	0.58
		Scale	4179	224	51.1	2546	153	37.9
Slamming	λ	***p*-Value**	**—**	**.80**	**.02**	**—**	**.61**	**.19**
		Location	—	3980	0.70	—	270	0.67
		Scale	—	1433	510	—	2480	745

events that independently follow each other. For slamming with and without surge no clustering occurred for $s_{op} = 0.037$, thus slamming events only start clustering for $P_{SL} > 1.6e^{-4}$ s^{-1}. Even above $P_{SL} > 1.6e^{-4}$ s^{-1} the clustering for slamming events is limited, as the *p*-value is .02.

In the new data green water events are found to cluster, but Boon and Wellens (2022) did not find a clustering of green water events. For slamming not all cases are found to cluster, while most slamming literature did find clustering (Hansen 1994; Jiao 1996; Dessi & Ciappi 2013). In our data slamming events only cluster above a certain probability of occurrence, so possibly green water events also only start clustering above a certain probability of occurrence. Figure 10 compares the present work to the literature. Note that all the work in Fig. 10 was for different ships in different sea states and different forward velocities, thus the exact values of when clustering starts can vary. The scaling of probability is accounted for. In the figure, the grey tones indicate the areas in which clustering occurs based on the quality of fit before clusters are removed from the data, quantified by the *p*-values in Table 4. The used *p*-value limit of .05 is strict, as a *p*-value above .01 is also often considered acceptable, and as such cases with a *p*-value between .01 and .05 are placed in a transition region.

Figure 10 shows that even though the previous and present work do not agree on whether events cluster, neither is wrong, they just investigate different ranges. For the low range of probability of occurrence tested in Boon and Wellens (2022) indeed, no clustering is expected, while for the high probability of occurrence in Dessi and Ciappi (2013) clustering is expected.

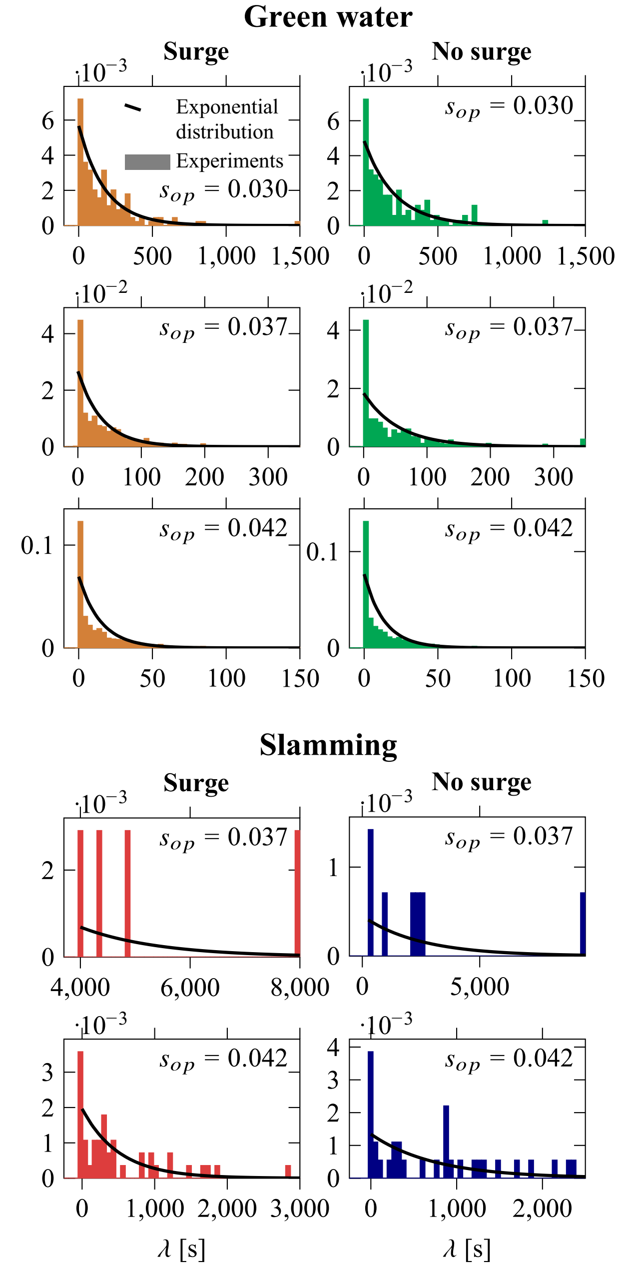


Fig. 7 Density histograms of time between events (λ) show zero inflation caused by clustering. The fitted exponential distribution does not fit the data due to the zero inflation

Exceptions are Ochi and Motter (1973) and Ferro and Mansour (1985) which do not mention clustering. The distributions shown in their work do show zero inflation, as is expected from Fig. 10. For Ochi and Motter (1973) no spectral steepness is known but was estimated based on the Beaufort 9 condition.

3.3.1. Difference between clusters and single events. After identifying clustering and when events cluster, the next step is to look into what the influence of clustering is and why events cluster. First, the pressures on deck found for the clusters and single events are compared in Fig. 11. For all tested cases the median

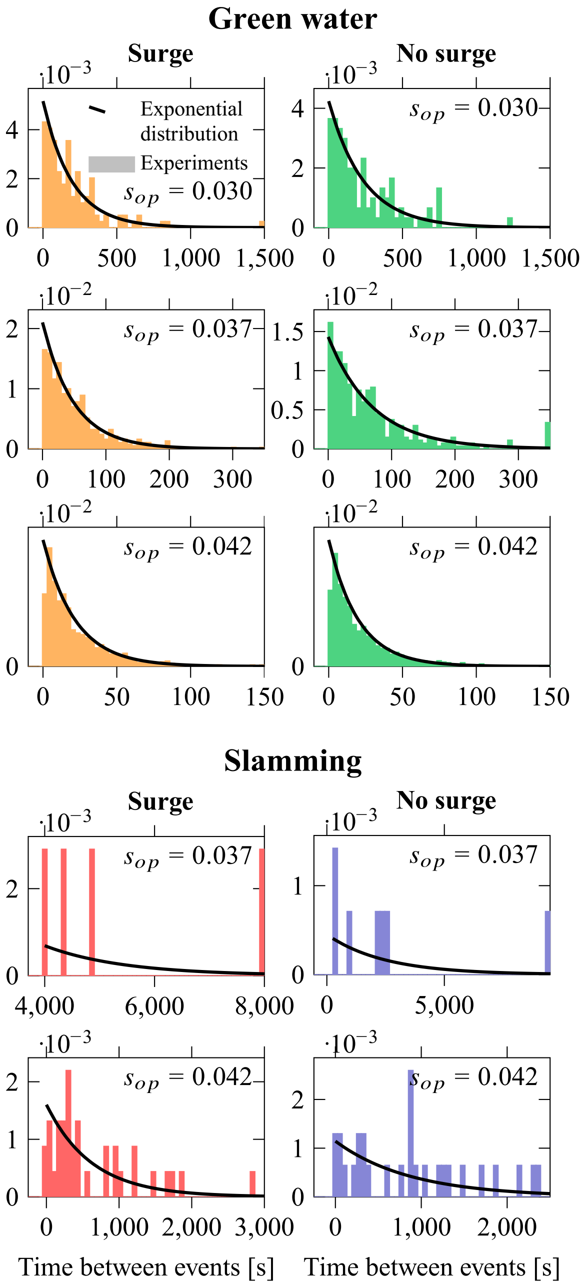


Fig. 8 Identification of clusters by using the minimum time between events (t_{min}), based on the natural pitch period

pressures found during clusters are larger than the median pressures found during single events. For surge cases, pressures caused by events that occurred during clusters induced on average 61% higher pressures compared to the single events. For no-surge cases, events in clusters induced 33% higher pressures on average. The overall pressures found for no-surge cases are larger, but the pressures caused by clusters are actually larger for surge cases. The complexity of events interacting in clusters combined with surge motion is a possible reason for the larger difference between pressures in clusters and single events for surge cases. More research is needed to be able to explain the differences.

Table 5 After removing clusters from data evaluate the quality of fit of the fitted exponential distribution. The exponential distribution is quantified with the location and scale parameter

			Surge			No-surge		
		s_{op}	0.030	0.037	0.042	0.030	0.037	0.042
Green water Deck	λ	***p*-Value**	**.89**	**.83**	**.01**	**.96**	**.09**	**4e^{-4}**
		Location	1.50	1.35	1.37	1.08	1.04	1.36
		Scale	195	48.9	21.7	237	70.9	20.1
Green water Box	λ	***p*-Value**	**.78**	**.50**	**.20**	**.32**	**.05**	**.08**
		Location	2387	2.27	1.36	575	1.47	1.37
		Scale	4179	277	66.5	2546	178	51.1
Slamming	λ	***p*-Value**	**—**	**.80**	**.65**	**—**	**.61**	**.42**
		Location	—	3980	1.59	—	270	2.33
		Scale	—	1433	626	—	2480	877

Within clusters, events occur at intervals around the natural pitch period, as is discussed in the previous section. From looking at footage of clusters during the experiments the hypothesis is developed that clusters are caused by large pitch motions. A pitch motion out of phase with the waves causes an event, and the theory is that in the built-up to a large pitch or as the large pitch motion damps out, there is a high probability of another event occurring as the pitch amplitude is still large.

Clustering and the probability of events correlate in Fig. 10 because if a sea state causes limited pitch motions, the probability of an event is small, and the probability of a large enough pitch motion to cause multiple events is also small. For a sea state that causes large pitch motions, the probability of an event is high, and the probability of a pitch motion large enough to cause a cluster is high, resulting in zero inflation.

If large pitch motions indeed cause the clustering of events we also expect the pitch in a cluster to be on average larger than the pitches during single events. The pitches for single events are compared to the largest pitch in a cluster in Fig. 12. A large pitch is far forward for green water, thus negative, and a large pitch is far backward for slamming, thus positive.

The mean pitch motions in clusters are for both green water and slamming larger than the mean pitch motions during single events. The pitch motions in clusters are on average larger, but the spread overlaps. A large pitch motion makes it likely for an event to occur in the periods before or after the large motion, but for an event to occur not only the pitch has to be large, but the wave also has to be out of phase with the pitch. In an irregular sea, the waves can shift phases, causing a pitch motion initially out of phase with the wave to be in phase with the wave, resulting in large pitch motions that could have caused multiple events to become single events. Events can also independently occur together, resulting in clusters without large pitch motions. Overlap of pitch motions for clustered and single events is thus expected.

The results in Fig. 12 are in line with the theory that clusters are caused by large pitch motions building up or damping out. To further check the theory, the number of events in clusters is analyzed. If clusters indeed occur because of the pitch motions building up or damping out the average size of a cluster is expected to be small, as the amplitude of the pitch will quickly become too small to cause green water or slamming events.

Figure 13 shows that clusters indeed tend to be small. Only two green water clusters within the 4703 green water events are

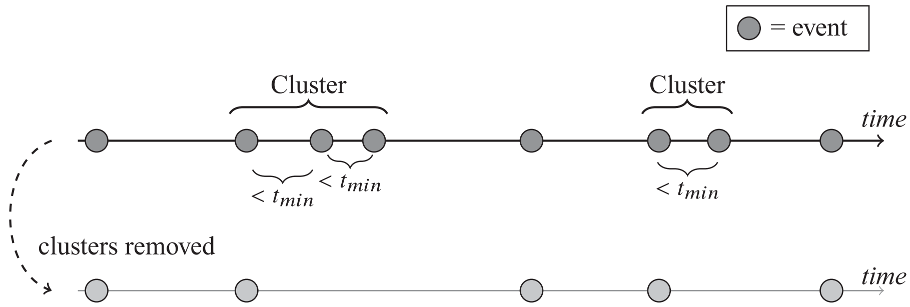


Fig. 9 Density histograms of time between events (λ) with clustering removed do fit the exponential distribution

six events long. The longest cluster for slamming is only three events.

The steepness of the sea state influences the length of the clusters and the number of clusters, as for $s_{op} = 0.042$ about 40% of green water events and 20% of slamming events are part of a cluster, while for $s_{op} = 0.037$ about 25% of green water events and none of the slamming events are part of a cluster. A larger spectral steepness leads to larger pitch motions, which take longer to build up or damp, and thus also lead to larger clusters.

Surge also influences the number of clusters. No-surge cases lead to slightly more and longer clusters for green water compared to surge cases. Previously smaller events were found for surge cases as energy from the water is transferred to reduce the forward velocity of the ship. Following the same reasoning no-surge cases are expected to lead to larger pitch motions and thus lead to larger clusters, as was indeed found to be the case. It can be concluded that both green water and slamming clustering of events are caused by large pitch motions.

3.4. Comparing green water and slamming

All conclusions hold for both green water and slamming: surge has a similar influence on probabilities of green water and slamming and clustering start to occur at certain probabilities. The only difference between green water and slamming is quantitative. The used ship model can be the cause of the quantitative difference, as the freeboard is important for green water, and the draft for slamming. Also, damping of the large pitch motions can happen quicker for green water compared to slamming, as the waves break over the deck, leading to a higher threshold for clustering.

Qualitatively, the underlying physics for the occurrence of events seems to be the same for green water and slamming. To test this theory the coincidence of green water and slamming is looked at. Slamming always occurs together with green water. For every slamming event green water occurred within 0.36 seconds of a slamming event, half of the natural period of pitch. For every occurrence of slamming a green water event occurred before or after. This coincidence suggests that these two event

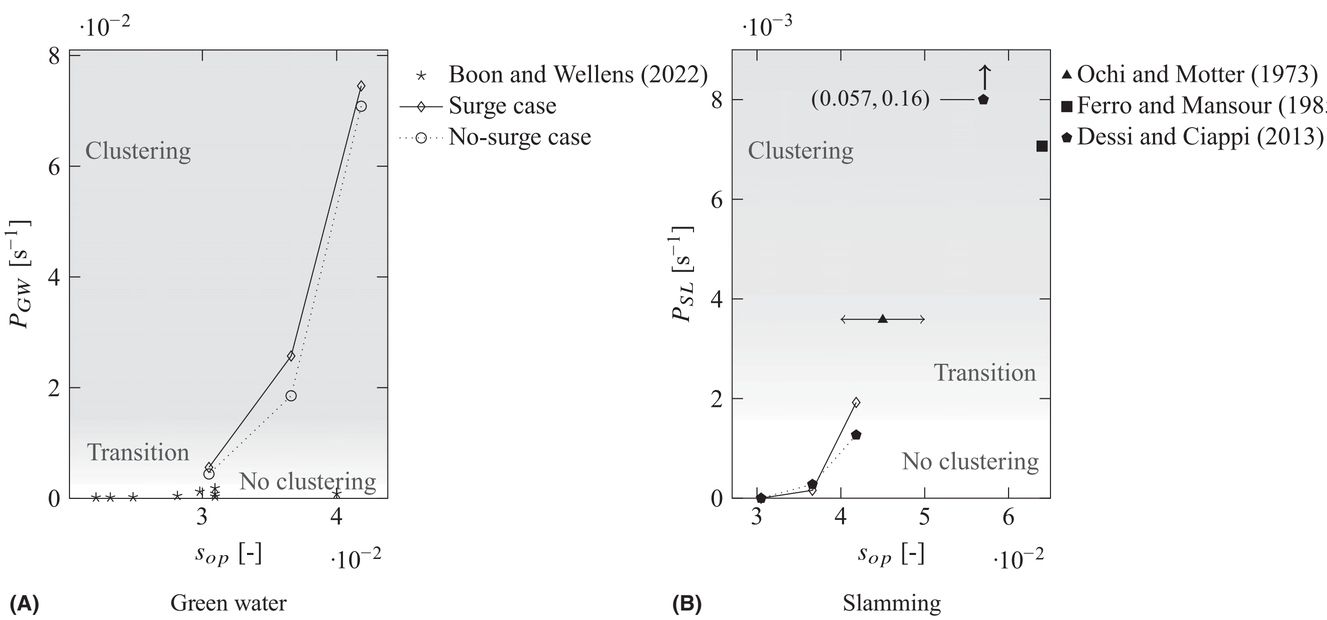


Fig. 10 The probability of green water and slamming from both the present experiments as well as literature set out. Gray background visualizes the range where zero inflation occurs and thus when clustering occurs

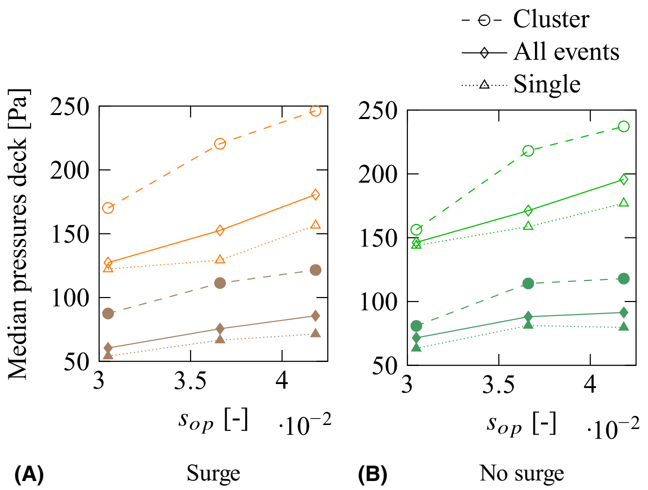


Fig. 11 On average the pressures on the deck for green water events in a cluster are larger than the pressures due to single events. The solid markers indicate the median pressures ($\bar{p}_{max}$) and the open markers the maximum (p_{max})

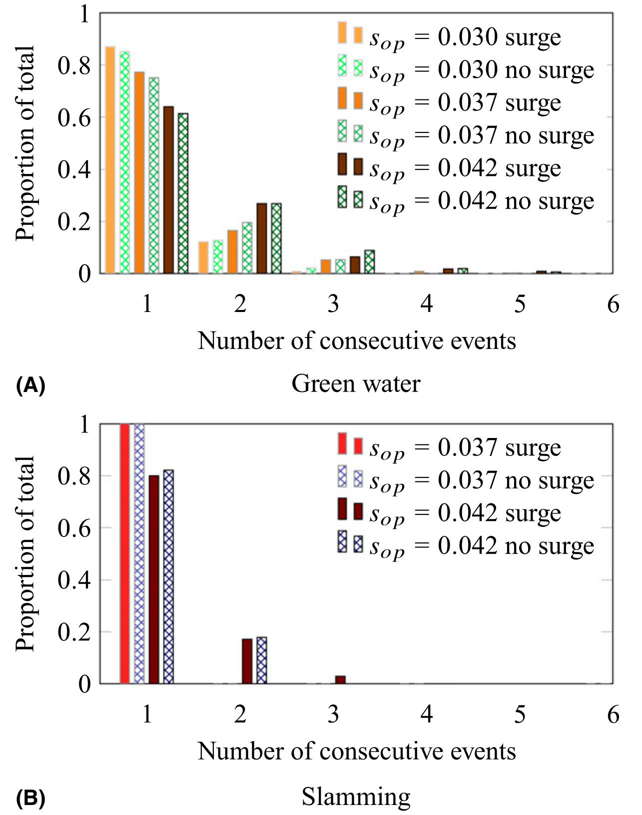


Fig. 13 Comparing the number of consecutive events for different spectral steepnesses. The average number of events per cluster is lower for a lower spectral steepness, with somewhat larger cluster sizes for test cases where the surge was restricted

types, often considered separately, are actually the outcomes of similar wave and ship motions. In the present work slamming has been identified with the Ochi criterion, and no pressures have been measured for slamming. The argument could be made that the slamming events discussed in the present work are not actual slamming events but just large backward-pitch motions followed by a large relative velocity. To investigate the theory that slamming and green water are similar we use the Ochi criterion to identify green water. The median pressures on the deck of green water events that occur before and after a slam are compared to the median pressures for all green water events, shown in Fig. 14. This comparison tests if the Ochi slamming criterion identifies green water that induces large pressures.

The Ochi criterion, developed for slamming, finds green water events with larger median pressures on deck than the average green water event. The events identified with the Ochi criterion were no larger than the average deck box impacts. Still, a tool designed to identify slamming finds large green water events, indicating that green water and slamming are closely related. Future work can look at how to use the similarity between green water and slamming to apply results from slamming research, which might be considered more developed than green water research, on green water.

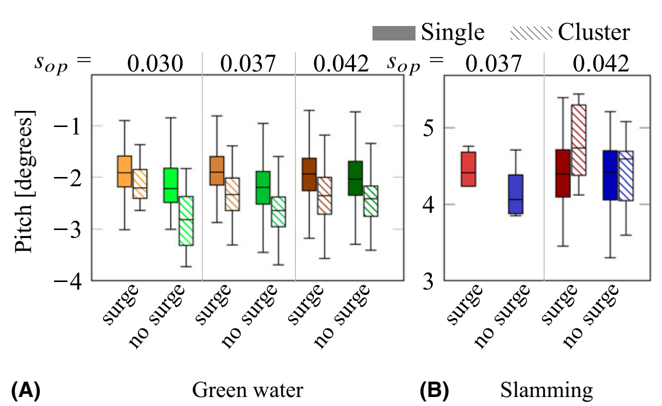


Fig. 12 The maximum pitch motion during clustered and single events are compared, showing on average larger pitch motions for clustered events than single events

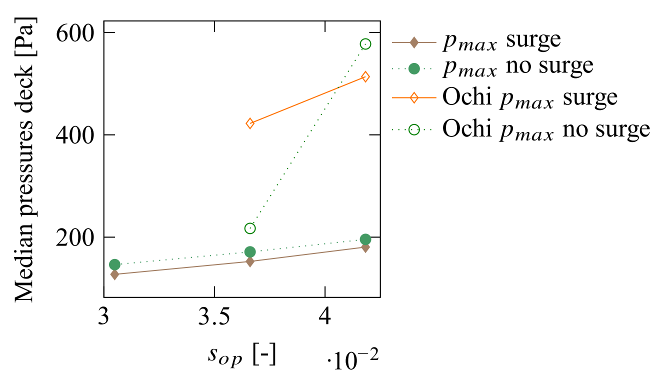


Fig. 14 Comparing the average impact pressures of green water events to the impact pressures of green water events identified with the Ochi slamming criterion. The Ochi slamming criterion identifies green water that induces large pressures

4. Conclusions

The original goal of this research is to find the influence of surge on green water and slamming events. Long-running experiments for a ship with forward velocity in head waves free to heave and pitch in irregular waves were repeated with and without surge.

The experimental results show that surge increases the probability of green water events on the deck, but reduces the pressures on the deck and the probability of green water events impacting the deck box. While checking the distribution of green water and slamming a larger-than-expected probability of events following each other closely was found: clustering.

Clustering of green water and slamming events only happens above a certain probability of occurrence. Events are found to cluster because of large pitch motions. A large pitch motion out of phase with the waves causes an event, and as this large pitch motion builds up or damps out additional events are likely to occur, creating a cluster of events.

The pressures on the deck during green water clusters are larger than during nonclustering events. For no-surge cases, the pressures during clustered events were 33% higher than nonclustering events, whereas for surge cases the pressures were 61% higher. Restricting surge also slightly increases the number of green water clusters. The number of clusters and events per cluster increases for larger spectral steepness.

Acknowledgments

Special thanks to C. P. Poot, F. J. Sterk, J. G. den Ouden, P. Taudin Chabot, and S. Schreier for all the help with the test facility and the support throughout the experiments. This publication is part of the project "Multi-fidelity Probabilistic Design Framework for Complex Marine Structures" (project number TWM.BL.019.007) of the research program "Topsector Water and Maritime: the Blue route", which is (partly) financed by the Dutch Research Council (NWO) and Stichting Bijlboegfonds.

Author contributions

A. D. Boon: conceptualization, methodology, formal analysis, investigation, visualization, writing – original draft. P. R. Wellens: conceptualization, writing – review and editing, supervision.

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