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Boon, A.D.; Wellens, P.R.

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HOW DRAFT AND FREEBOARD AFFECT GREEN WATER: A PROBABILISTIC ANALYSIS OF A LARGE EXPERIMENTAL DATASET

Anna D. Boon[1],*, Peter R. Wellens[1],*,

[1]Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Netherlands

ABSTRACT

Green water is a rare and complex wave impact event that can affect the safety of the ship and those aboard. During the design process, the risks that these events pose have to be mitigated, preferably by minimizing the probability of a high impact pressure. As green water events are rare and complex it is difficult to get a statistically representative dataset and thus previous work has mostly compared design variations through a limited number of events, instead of comparing the probabilities. The present study will use probabilities to compare design variations with different drafts and freeboards at the bow. A large set of green water events in irregular waves with forward velocity was experimentally obtained for six different bow designs. The dataset represents 57 hours of sailing per bow design and 3263 green water events. The data demonstrates that both freeboard and draft at the bow affect the probability of green water in a complex way. Increasing the draft at the bow increases the swell-up, reducing the effective freeboard and in turn, increasing the probability of green water. Increasing the freeboard results in a decrease in the probability of green water, as expected. However, the probability is not reduced equally for different green water impact pressures. The joint probability of green water occurrence and pressures shows that increasing the freeboard only decreases the probability of low-pressure events. Counter-intuitively, increasing the freeboard increases the probability of high-pressure events. These interesting results show the value of using statistically representative datasets when designing for green water.

Keywords: Green water, Draft, Freeboard, Probability, Big Data, Experiments

NOMENCLATURE

Roman capital letters

D Draft of model at bow [m]

P_{GW} Probability of green water, calculated by dividing total number of events by testing time [s^{-1}]

$P_{GW_{box}}$ Probability of green water reaching deck box [s^{-1}]

$P(p_{exc} \cap GW)$ Probability of green water and pressure exceedance [s^{-1}]

RWE Relative wave elevation [m]

R_{RWE} Variance of relative wave elevation [m^2]

U Forward velocity of ship [m/s]

Roman lowercase letters

fb Freeboard [m]

fb- Without increased freeboard

fb+ With increased freeboard

g Gravitational acceleration [m/s^2]

h Difference in freeboard height [m]

p_{exc} Pressure exceeded [Pa]

su Swell-up [m]

Greek symbols

α_E Half entrance angle of bow [rad]

ρ Water density [kg/m^3]

1. INTRODUCTION

Green water is defined as a wave impact on the deck or superstructure of a ship or offshore structure. These impacts can damage the ship and pose danger to those on board. Green water on the bow of a ship is an active field of study as these rare events can endanger the ship and those on it. Not only the events themselves have been researched but also how different ship designs influence green water. Previous studies have examined the influence of bow shape on green water, with contributions from Buchner who looked at different breakwaters, bow fullness, hull shapes and flare angles [1, 2]. Greco looked at the effect of wave length and steepness, trim angle, bow flare angle and length over breadth ratio's [3]. Others have researched the effect of bow overhang [4], bow flare [5, 6], bow rake angle [7], bow rake angle and angle of entrance [8], bow rake angle of a tumblehome bow [9] and rectangular breakwaters [10]. However, most of these studies have primarily compared bow designs by analyzing the differences for a limited number of green water events.

Existing research has revealed mechanisms of green water loading, but falls short in comparing the probabilities of green water as designs are compared based on a limited number of

*Corresponding author: a.d.boon@tudelft.nl, p.r.wellens@tudelft.nl

green water events. Because of the limited number of green water events, the bows can not be compared based on the tail of the probability distribution: the probability of the rarer but higher pressure impacts. The probability of high pressure impact is, however, a critical parameter as the probability of a high pressure green water impact should be minimized in the design process.

In the present study, we compare bow designs based on the probabilities of impacts and probability distributions of impact pressures, rather than focusing on the flow over the bow for a few events. The present study includes variations in draft at the bow and freeboard. The effect of the draft at the bow on green water is a relatively unexplored aspect in existing literature, even though literature has shown that increased draft at the bow results in larger swell-up [11]. The swell-up is the increase in water level at the bow due to the effect of the presence of the ship in the waves and the ship's forward velocity. An increase in draft will increase the relative wave elevation, which is known to correlate with green water occurrences and pressures [2, 12, 13]. Increasing the freeboard is known to reduce the probability of green water [3, 14–16]. However, it remains unclear whether this reduction affects all green water events uniformly or selectively eliminates some green water types while leaving the occurrence of other types unchanged.

The present study will evaluate the effect of draft and freeboard on green water by considering their probabilities and the distribution of impact pressures. First, the effect the probabilities and pressure are analyzed. Secondly, the shape of the probability distributions of impact pressures are analyzed. Lastly, the pressure distributions for different drafts and freeboards are compared while accounting for the difference in probability of green water. The draft and freeboard both change the probability of green water, but the freeboard also changes the pressures. The difference in pressures turns out to not only be caused by the reduced number of green water events.

2. METHODOLOGY

As in the present study the bow variations will be compared based on the probabilities and probability distributions of impact pressures, a large number of green water events has to be collected for each bow. A test setup that allowed for continuous testing with waves and modelled forward velocity is used, described in Boon and Wellens [17]. The bows were systematically varied to not only investigate how to compare different designs but also to find the effect of added draft and freeboard. To be able to systematically vary the bows a bow type with a straight stem was used: the axe-bow. The axe-bow was placed on the S175 container ship. To stay true to the axe-bow design the ship length was elongated by 25%.

2.1 Model design

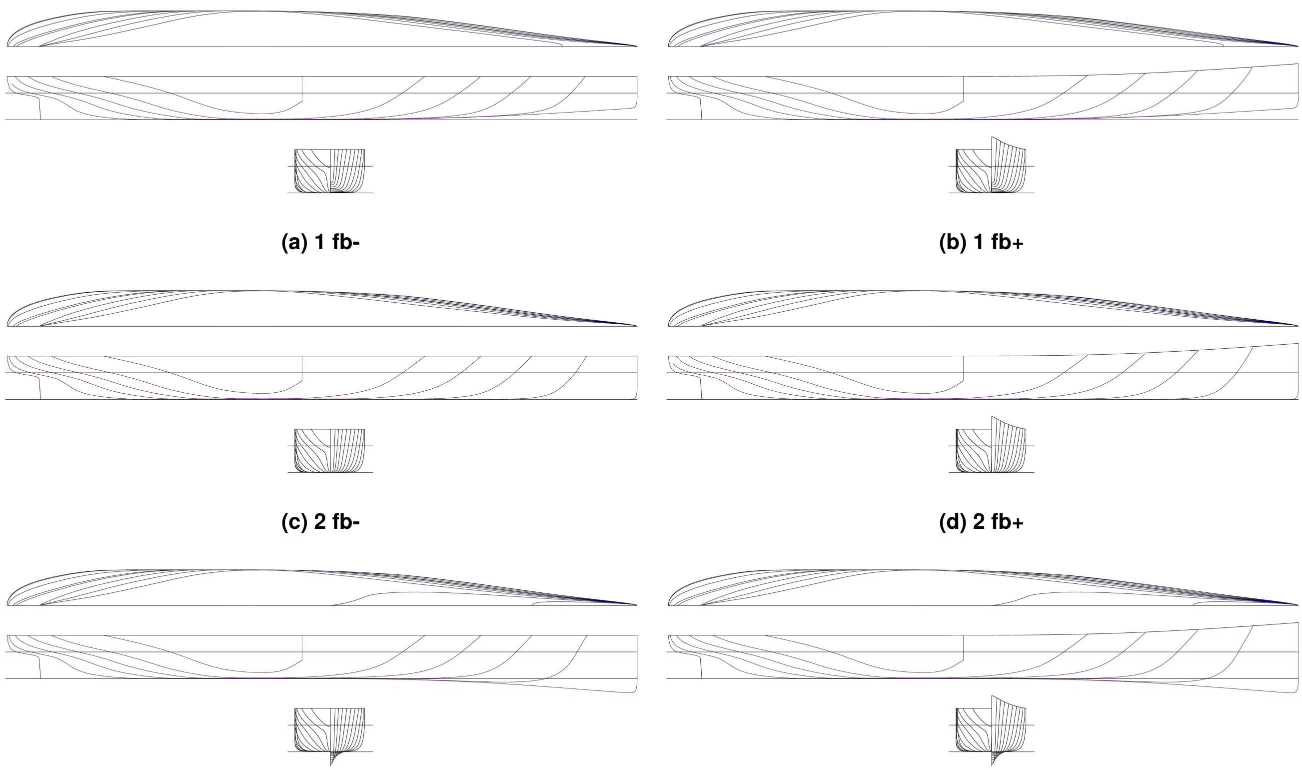
As a basis of the model design the S175 ship at a 1:130 scale is used. The draft of the bow is increased systematically. Three draft variations are implemented at the bow and all three were also tested with and without an increased freeboard.

The lines plans of the models are shown in figure 1. The models were 3D printed with separate freeboard pieces that could be removed. The parametric description of the models is given in table 1. When two numbers are given for a bow the left value is for a freeboard equal to the deck height (fb-) and the right for the extended freeboard (fb+). As the focus of the research is on the geometry of the bow, the radius of gyration, mass and the centre of gravity is kept close to constant for the various bow designs by utilizing ballast weights in the model. As the volume at the bow changes, the centre of bouyancy changes and thus the longitudinal centre of gravity also changes for the different models to keep the trim neutral. The radii of inertia were obtained with swing tests. To model a superstructure a deck box was placed at 0.34 m from the bow with a width and height of 0.06 and 0.12 m respectively.

2.2 Test setup

The model experiments are conducted in the wave-current tank that allows for continuous testing in irregular waves with modelled forward velocity [17]. The tank dimensions are 7.4 x 2.35 x 0.44 meters (length x width x depth). The testing condition is a 5 hour irregular wave spectrum with a significant wave height of 0.062 m and a peak period of 0.97 s. The modelled forward velocity is 0.25 m/s. The full scale equivalent is a 57 hour wave spectrum with a significant wave height of 8.1 m, a peak period of 11.1 s and a modelled forward velocity of 2.85 m/s. This sea state and forward velocity are chosen as they represent realistic sailing conditions within the working range of the test facility.

Data was acquired at 1000 Hz. Three resistance type relative wave elevation (RWE) probes are placed 0.06 meters apart with the most forward RWE probe at the stem. The RWE probes are oriented vertically and are attached to the model via the deck box with a plexiglass plate reinforced with carbon fiber. Six GE Druck PDCR 42 type sensors with a range of up to 350 kPa are used to measure the pressure. Two were positioned on the deck box at a height of 0.01 and 0.03 m, and four were positioned on the model's center line on the deck with 0.04 m between them. The third pressure sensor's (0.14 m from the stem) signal was noisy, so the measurements from this sensor were not used. The model was free to heave, pitch and surge as two vertical linear guides, also called heave rods, attached the model to the surge carriage (dark green in figure 2). The surge carriage was attached to the tank via a vertical rail. Two soft springs (5 N/m) restricted the model from moving off the rail. At the center of buoyancy and 0.645 meters behind the centre of bouyancy, Panasonic HG-C1400 laser distance sensors were used to measure the vessel's heave and pitch. Both laser sensors were attached to the surge carriage. The Honeywell 940-R4Y-RD-ICO acoustic sensor, which measures the horizontal location of the surge carriage, was used to measure surge. In order to gauge the resistance, a load-cell was positioned in between the hinge and the heave rod. To measure water on deck, a wetness sensor was positioned 0.005 m in front of the forward most pressure sensor. However, during the experiments, water remained around the sensor after impacts, so the data was not used. At 0.86 meters from the tank's side and 2.79 meters from the wave maker, a resistance-type waveprobe was placed. To remove noise originating from the electrical power grid from all data, a 3rd order low pass filter set to 40 Hz was used. All experiments were recorded using two webcams, one positioned above the setup and the other to the



(a) 1 fb-

(b) 1 fb+

(c) 2 fb-

(d) 2 fb+

(e) 3 fb-

(f) 3 fb+

FIGURE 1: LINES PLANS OF THE VARIATIONS TESTED

TABLE 1: PARAMETERS OF THE VARIATIONS ON TEST SCALE

	Bow 1		Bow 2		Bow 3	
	fb-	fb+	fb-	fb+	fb-	fb+
Length perpendiculars [m]	1.683		1.683		1.683	
Max. width on waterline [m]	0.195		0.195		0.195	
Depth at midship [m]	0.123		0.123		0.123	
Draft at stem [m]	0.041		0.073		0.105	
Freeboard at stem [m]	0.050	0.085	0.050	0.085	0.050	0.085
Underwater volume [l]	12.9		13.3		13.7	
Mass model+heave rod [kg]	12.9		13.3		13.7	
Mass heave rod [kg]	2.26		2.26		2.26	
Mass surge carriage [kg]	1.14		1.14		1.14	
Centre of bouyancy [m]	0.734		0.759		0.777	
Centre of gravity [m]	0.734		0.759		0.777	
Vertical centre of bouyancy [m]	0.041		0.040		0.038	
Vertical centre of gravity [m]	0.065	0.064	0.066	0.065	0.066	0.066
Water plane area [m^2]	0.220		0.221		0.221	
Centre of floatation [m]	0.718		0.721		0.722	
Pitch radius of gyration [m]	0.438	0.436	0.439	0.437	0.433	0.433

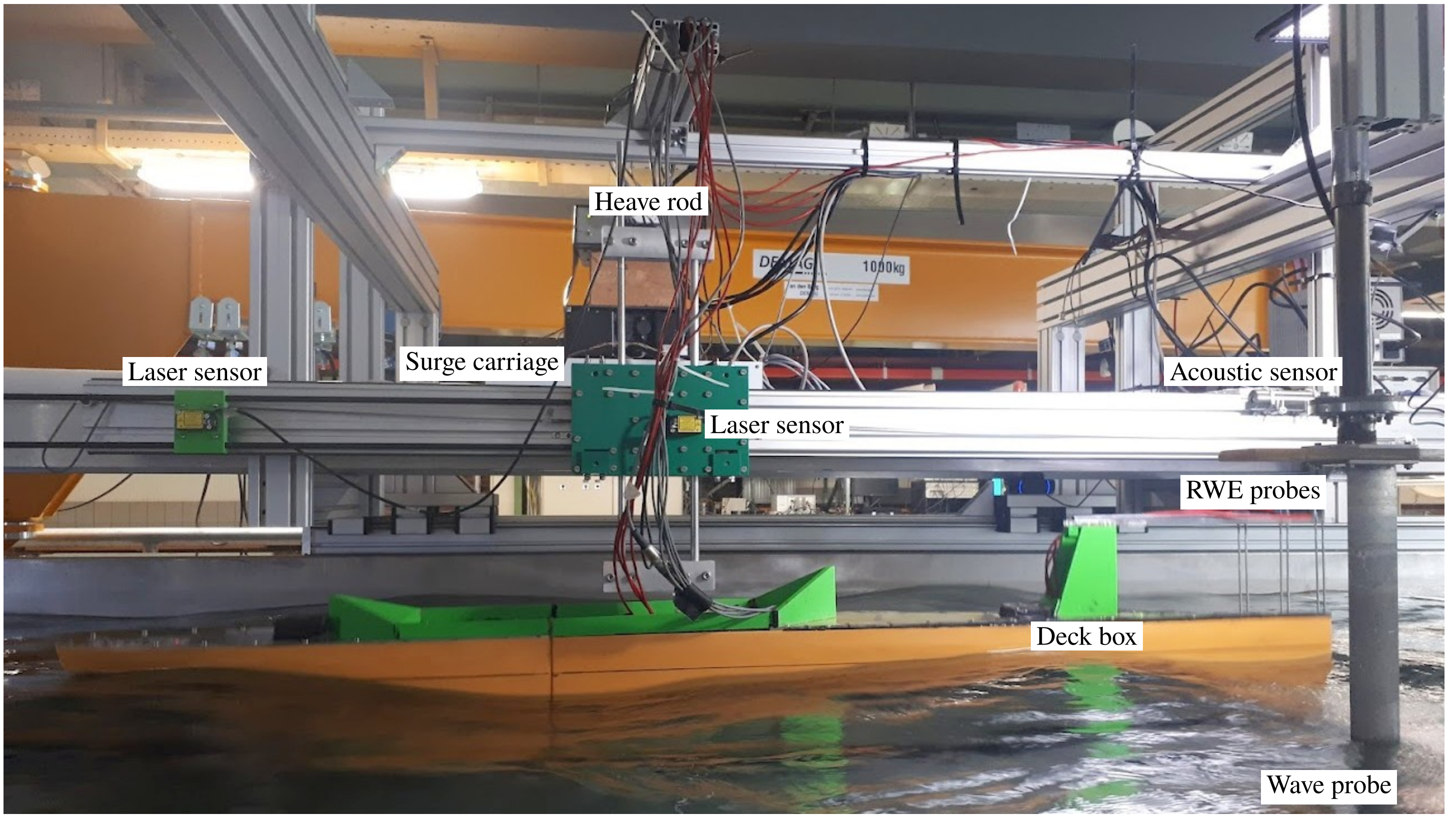


FIGURE 2: PICTURE OF THE TEST SETUP

side of it. All information is available on https://doi.org/10.4121/15f0d739-b84c-48f3-879a-68c08f068ab3 [18], including data, video, 3D print and laser cut files.

2.3 Event identification

For the initial identification of events, the most forward pressure sensor was used. If a pressure higher than 10 Pa is measured on a sensor the event is marked. Some pressure peaks were caused by noise or previous water on the deck flowing off. To eliminate these events from the dataset the camera footage was used and each identified pressure peak was visually checked. Only the events where water flowed over the bow onto deck towards the deck box, causing the pressure peak were kept. In total 3263 green water events were identified. Deck box impacts were identified creating a subset of green water events for which a deck box impact pressure of 50 Pa was measured. 472 green water events that impacted the deck box were found.

3. RESULTS

The experimental data for the 6 different variations are analyzed to gain insight into the effect of draft and freeboard on the statistics of green water.

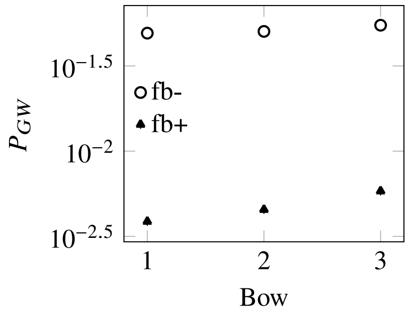
3.1 Freeboard's effect on probabilities

The first step of analyzing the green water events is to compare the probability of a green water event (P_{GW}) for the tested variations. The probabilities of green water events are found by dividing the total number of events by the testing time for each event. Figure 3 shows the results.

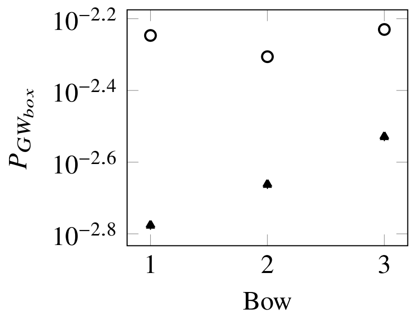
TABLE 2: DECREASE IN P_{GW} CAUSED BY INCREASING FREEBOARD FROM EXPERIMENTS COMPARED TO CALCULATION METHODS FROM LITERATURE. DECREASE DUE TO ADDED FREEBOARD IS GIVEN IN PERCENTAGES

	fb- P_{GW}	fb+ P_{GW}	Decrease [%]
Experiments Bow 1	0.049	0.0038	1289
Experiments Bow 2	0.050	0.0045	1111
Experiments Bow 3	0.055	0.0058	948
$e^{\frac{fb^2}{R_{\mathrm{RWE}}}}$ [15]	0.039	$5.34\ e^{-5}$	73034
$e^{-1.19\left(\frac{fb}{H_{m0}}\right)^2}$ [17]	0.456	0.091	501

Increasing the freeboard decreases the probability of green water events occurring. The decrease in probability due to the freeboard increase is expected. To further investigate if the probabilities found from the experiments correspond to the expectations based on literature, the probabilities are quantitatively compared. To quantify the expected change of P_{GW} due to the freeboard increase the probability estimation for deck wetness by Price and Bishop [16] and Hamoudi and Varyani [15] is used. This probability estimation is based on the assumption of Rayleigh



(a) Deck



(b) Deck box

FIGURE 3: PROBABILITY OF A GREEN WATER EVENT CAUSING AN IMPACT ON THE DECK OR DECK BOX

distributed extremes:

$$P_{GW} = e^{\frac{fb^2}{R_{\text{RWE}}}} . \tag{1}$$

In this equation R_{RWE} is the variance of the relative wave elevation for which the average over all relative wave variations is used. With equation 1 the probability of green water is calculated, shown in table 2. As the probabilities deviate from the actually found probabilities, an empirical equation from Boon and Wellens [17] is also used to calculate the expected probabilities of occurrence for fb- and fb+. Comparing the results shows that all predictions vary greatly from one another. The prediction from Hamoudi and Varyani [15] overestimates the decrease in probability by increasing the freeboard with a factor 50. The prediction from Boon and Wellens [17] underestimates the decrease in probability by a factor 2 and overestimates P_{GW} for both cases.

3.2 Draft's effect on probabilities

Looking back at figure 3 we see that the draft at the bow also influences P_{GW}. Especially for bows with an increased freeboard a larger draft correlates with a larger probability of green water. This correlation fits with the hypothesis that for an increased draft the probability of green water increases. The theory is that increased draft increases the swell-up, resulting in a larger relative wave elevation, and thus results in a larger probability of green water occurrences.

To test the hypothesis the expected difference in probability of green water is calculated. The calculated change in probability following this hypothesis is compared to the actually measured difference in probability. To calculate the hypothesized difference in P_{GW} due to draft various assumptions are made. The motion response of the vessel to the waves is assumed constant over all bow variations. This assumption was checked for heave and pitch by comparing the standard deviations and the distribution of crest amplitudes. Only in the tail of the crest amplitude distributions some differences were identified. The second assumption is that the probability of green water can be calculated with equation 1. The last assumption made is that the swell-up (su) at the bow is constant over time, which is only true for the bow wave created by the forward velocity, not the swell-up created by wave radiation and reflection. As the swell-up is assumed constant over time the change will not be captured in R_{RWE}. A constant increase of swell-up can also be seen as a decrease in effective freeboard, so the swell-up is taken into account with $fb - su$. The swell-up is calculated using the equation proposed by Noblesse et al. [11]:

$$su = \frac{2.2 * U^2/g}{1 + \frac{U}{\sqrt{g*D}}} * \frac{\tan(\alpha_E)}{\cos(\alpha_E)} . \tag{2}$$

In this equation, U is the forward velocity, g the gravitational acceleration, D the draft at the bow and α_E the entrance angle of the bow. As the motion response is assumed to be constant over all bow variations R_{RWE} should be the same for all bows. As R_{RWE} is assumed constant and we are only interested in the expected change in P_{GW} we can use

$$R_{\text{RWE}} = -\frac{(fb - su)^2}{\ln(P_{GW})} \tag{3}$$

to find R_{RWE}. Because the difference in P_{GW} between fb- and fb+ can not be quantified with equation 1 as shown in table 2, R_{RWE} is calculated for fb- and fb+ separately. Bow 2 fb- and bow 2 fb+ are used to find R_{RWE}. Next the expected change in P_{GW} for different draft variations can be calculated with

$$P_{GW} = e^{-\frac{(fb-su)^2}{R_{\text{RWE}}}} \tag{4}$$

where the only varying parameters over the design variations are fb and su. Table 3 shows the results. As bow 2 is used to find R_{RWE} only the results of bow 1 and 3 are shown.

Table 3 shows that for the fb- cases the difference in probability for the different bows is explained well by the increase in swell-up. For the fb+ cases the actual increase in P_{GW} for larger drafts is larger than is expected under the above assumptions. As following the hypothesis with all its assumptions only leads to a maximum error of 20% the increase in swell-up due to the increase in draft is deemed to be the reason for the increase in probability of green water.

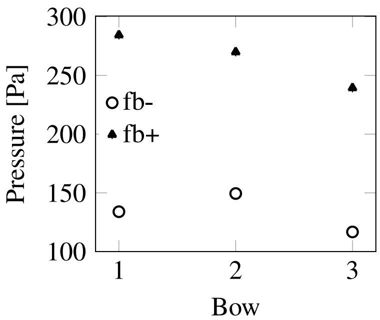
3.3 Pressures

For design purposes it is not only interesting to know what the probability of green water is, but also what pressures to expect. The average pressures on the deck and deck box for the different designs are compared in figure 4.

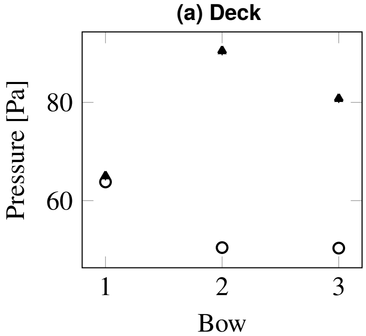
The figures show that additional freeboard increases the average pressures on the deck and deck box. The average pressures increase with an increase in freeboard, indicating that not all

TABLE 3: CALCULATED INCREASE IN P_{GW} FOLLOWING THE PROPOSED HYPOTHESIS FOR INCREASED DRAFT LEADING TO INCREASED P_{GW} COMPARED TO ACTUAL INCREASE IN P_{GW}

	Experiments P_{GW}	Calculated P_{GW}	Difference [%]
Bow 1 fb-	0.0493	0.048	-1.8
Bow 3 fb-	0.0548	0.052	-6.0
Bow 1 fb+	0.0038	0.0043	13
Bow 3 fb+	0.0058	0.0046	-20



(a) Deck

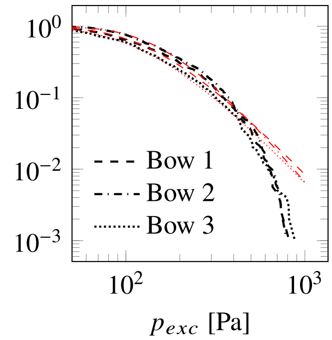


(b) Deck box

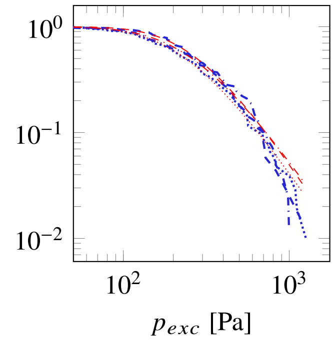
FIGURE 4: AVERAGE OF THE MAXIMUM MEASURED PRESSURES PER EVENT ON THE DECK OR DECK BOX

events are reduced equally when the freeboard is increased. Increasing the freeboard causes the probability distribution of the pressures to be different, resulting in different average pressures. The difference indicates that the distribution of the pressures has to be further analyzed, as to find what design minimizes the probability of high pressure impacts.

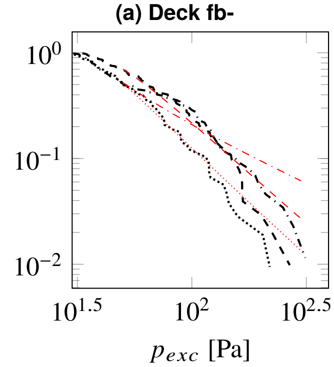
As figure 4 indicates that the probability distribution of the pressures might be different for fb- and fb+ cases these probability distributions are further analyzed. The probability distributions are analyzed by means of the probability of exceedance. The probability of exceedance is commonly used in green water research, most often for the (relative) wave elevation [12, 19–21]. The probability of exceedance for the pressures is shown in figure 5 with the fitted Fréchet distributions. Based on literature the probability distribution of the pressures is expected to be Fréchet distributed [17]. The fitted Fréchet distributions are tested with the Kolmogornov-Smirnov test and all fit with a p-value above 0.05, meaning that the pressure can indeed be Fréchet distributed.



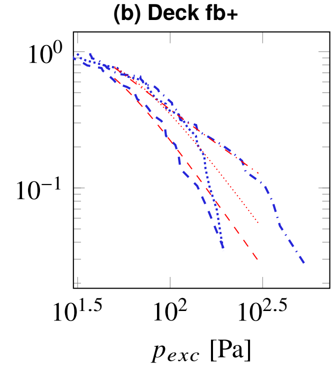
(a) Deck fb-



(b) Deck fb+



(c) Deck box fb-



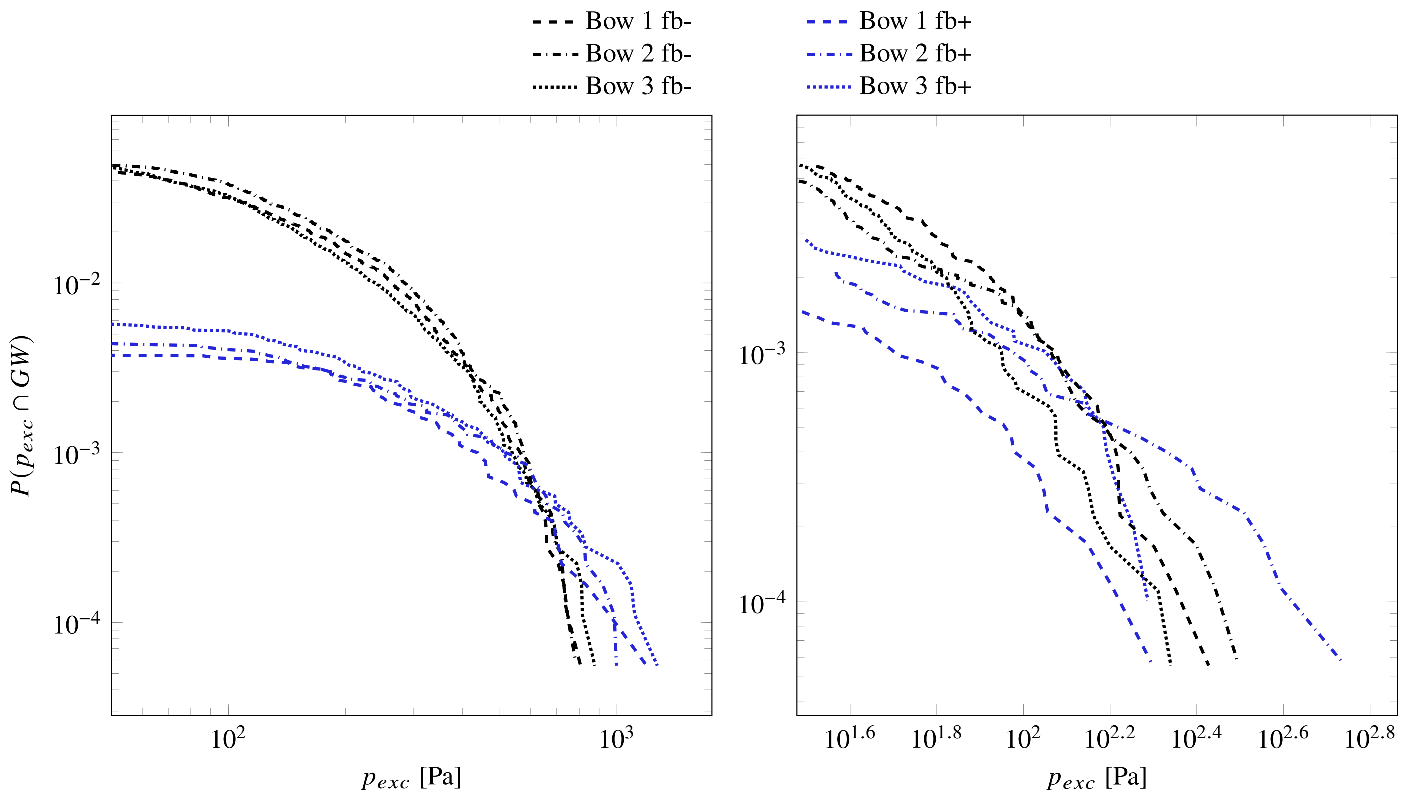
(d) Deck box fb+

FIGURE 5: PROBABILITY OF EXCEEDANCE PLOT FOR THE PRESSURES WITH THE FITTED FRÉCHET DISTRIBUTION SHOWN IN RED

Figures 5a, 5b, 5c and 5d show both the experimental and fitted Fréchet distribution. Deck box impacts are rarer than deck impacts so less data has been collected on these impacts. As there is less data the distributions of experimental data in figures 5c and 5d fluctuate and thus no conclusions are made based on these figures. Figures 5a and 5b are visually analyzed. The figures show that for the fb- variations the tail of the distribution does not fit with the fitted Fréchet distribution. The tail in the distribution from the actual data is lower than that of the expected distribution for the fb- cases. In other words, the low-probability high-pressure impacts for the fb- cases are somehow different than higher-probability lower-pressure impacts as the larger, rarer events do not cause the pressure impacts expected based on the Fréchet distribution. Figure 5b does not show this difference between the experimental data and the Fréchet distribution. It is thus concluded that a difference in high and low pressure events only occurs for the fb- cases. The analysis in the following section concludes in a possible reason for the difference between fb+ and fb-.

3.4 Joint probability of events and pressures

When comparing the design variations using the probability of exceedance for pressures, as is done in figure 5, the difference in the probability of an event occurring in the first place is ignored. Ignoring P_{GW} will result in a skewed comparison. To exemplify this statement we give an example: there are two designs and during testing a similar number of high pressure impacts occurred. But for the first design only high pressure impacts



(a) Deck pressures

(b) Deck box pressures

FIGURE 6: THE JOINT PROBABILITY OF EXCEEDANCE FOR PRESSURES SHOWING THAT THE ADDITIONAL FREEBOARD REDUCES THE PROBABILITY OF LOW IMPACT EVENTS, BUT INCREASES THE PROBABILITY OF HIGH PRESSURE IMPACTS

occur while for the second design also a similar number of low pressure impacts occur. The second design will seem preferable when comparing the probability of pressures because for the first design 100% of the events caused high pressures, while for the second design only 50% of the events caused high pressures. The conclusion of which design minimizes high pressure impacts is wrong because P_{GW} is not included.

To prevent unequal comparison P_{GW} has to be included. To combine the probability of pressure exceedance and P_{GW} the probabilities are joined:

$$P(p_{exc} \cap GW) = P(p_{exc}|GW) \cdot P(GW)\ . \tag{5}$$

In this equation, p_{exc} is the pressure exceeded, and $P(p_{exc} \cap GW)$ is the probability of a green water event and the impact pressure exceeding p_{exc}. $P(p_{exc} \cap GW)$ is visualized in figure 6 for the design variations. The left side of the figures shows that for the minimum p_{exc} the increased freeboard decreases the probability and the increased draft slightly increases the probability, as was also shown in figure 3. As every green water impact exceeds the minimum p_{exc} indeed figure 3 and the left hand side of figure 6 show the same.

Moving to higher p_{exc} for deck impacts, further to the right in figure 6a, shows us the probability of higher pressure impacts. The probabilities for the fb- and fb+ move closer together for higher impact pressures exceeded, until a pressure of 600 Pa. For impact pressures above 600 Pa the probability of occurrence is actually larger for the designs with increased freeboard. For bows with additional freeboard green water events with a probability of below 10^{-4} go from a maximum impact pressure of 800 Pa for bows without an extended freeboard to an impact pressure above 1000 Pa for bows with an extended freeboard.

Figure 6a clearly shows that increasing the freeboard increased the probability of green water with an impact pressure above 600 Pa. For impacts that reached the deck box, in figure 6b, first increasing the freeboard reduces the probability of an event. As p_{exc} increases, the difference between the designs with and without increased freeboard decreases, similar to figure 6a. Due to the more limited dataset size for deck box impacts the probability curve is shorter and shows more variation, as was already shown in figures 5c and 5d. The figure does show that the reduction of probability of deck box events by increasing the freeboard only occurs for the low impact events.

The deck box data shows that a limited number of events limits our ability to compare the probability of a higher impact occurring. In figure 6a the lower the probabilities (lower on y-axis), the larger the uncertainty interval will become as the line is based on less data points, as less events occurred, thus making conclusions less certain at the lower probabilities. However, as for all three fb+ cases the highest pressure events are higher than their fb- counterparts and the same trend is found for deck and deck box events it is concluded that increasing the freeboard only decreases the probability of low impact events. The probability

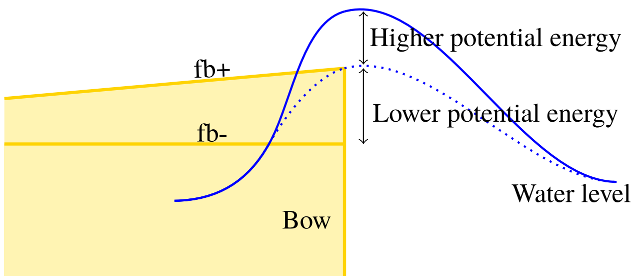


FIGURE 7: SCHEMATIC OF INCREASED FREEBOARD (FB+) RESTRICTING WATER WITH LOWER POTENTIAL ENERGY FROM FLOWING ON DECK

of a high pressure impact on deck actually increases when the freeboard is increased.

How freeboard decreases the probability of green water has been discussed in section 3.1, but how increasing the freeboard could cause an increase in high pressure impacts is not discussed. No explanation is found in literature either as no literature is found to discuss the increase of impact pressures due to an increased freeboard.

As no explanation is found a potential cause is hypothesized. As all the bows were tested in the same sea states and their mass and inertia is kept close to constant the probability of a certain wave and motion response are the same for fb+ and fb-. The probability of certain motions and waves that will lead to high pressure impacts is thus also the same. The probabilities staying the same means that the difference in figure 6a can only be explained by the same combination of motions and waves leading to higher pressures when the freeboard is increased.

The increased freeboard restricts water flowing onto deck at deck level. For low impacts this restricts the flow entirely. For large relative wave elevations only the water near deck level is restricted, the water that exceeds the extended freeboard will impact on deck. The difference in impact pressures follows from the difference in the height from where the water flows onto deck. As the deck levels are kept constant for all designs, increasing the freeboard leads to a larger height difference between the deck and water as the water can not flow onto deck at deck level. Only when the water is high enough to overtop the freeboard can it flow onto deck. Even then the water with lower potential energy, closer to deck level, is restricted from flowing onto deck. The added freeboard effectively only allows the part of the water with the largest potential energy to impact. Figure 7 shows schematically how the extended freeboard limits the flow of the water with lower potential energy.

If the freeboard restricting low potential energy water from flowing onto deck is indeed the reason for the increase in high pressure impacts, the difference in pressure for fb- and fb+ for low probability impacts should be close to the difference in potential energy between the deck and freeboard level: $\rho \cdot g \cdot h = 343$ Pa. ρ is the water density and h the difference in freeboard height between fb- and fb+. Looking at figure 6a the increase in the highest pressures on deck due to increasing the freeboard is about 250 Pa. This theory is also in line with the results found in figure 5, where we found that the impact pressures in the tail of the distribution are lower than the theoretical distribution for only the fb- cases. The combination of potential energy calculation as well as the difference in the fit to the theoretical distribution for fb- and fb+ cases both agree with the hypothesis. It is thus concluded that increasing the freeboard restricts water with low potential energy from entering the deck, eliminating low impact events but increasing the pressures of high pressure impact events.

4. CONCLUSION

The present study analyzed green water events for different bow designs with varying drafts and freeboards. Probabilities of the events and pressures were used to compare design variations. A large set of green water events in irregular waves with forward velocity was obtained experimentally using a continuous testing facility.

The results show that, especially for bow designs with increased freeboards, a larger draft correlates with a higher likelihood of green water events. The result supports the hypothesis that a greater draft leads to a larger swell-up, resulting in a reduced effective freeboard and, consequently, an increased probability of green water events.

The joint probability of green water occurring and the probability of pressure exceedance was also used to compare the bow designs. The joint probability shows that increasing the freeboard decreases the probability of low impact events, as expected. But increasing the freeboard increases the probability of high pressure impact events. The surprising result shows the importance of using statistically representative datasets when designing for green water impacts

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