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Research paper

Kinematics of green water in a large data set of events and a resulting prediction method of probability

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ABSTRACT

Green water is an extreme event that impacts ships and poses a risk to those on board. Conventional methods of screening assume a direct relation between exceedance and green water. This article demonstrates that the relation is not direct and identifies a difference between green water and exceedance that does not develop into a flow on deck. A proposed prediction method follows from the difference between green water and exceedance identified from analysing a big data set. The big data set is from experiments modelling 1945 full-scale hours and includes 409 green water events and 729 exceedance events which did not become green water. Pitch was identified as an important indicator for green water as green water events consistently occurred with large forward pitch motion, while exceedance also occurred with neutral pitch. A prediction method of probability is proposed that implements separate limits for the motions and wave elevation that occur simultaneously, thus including the phase difference between the motions and wave elevation. The result is a method for the prediction of the occurrence of green water on the deck of a ship with different forward velocities and in different sea states.

1. Introduction

Green water is an extreme wave impact event and has been defined as a continuous volume of water flowing on deck (Hernández-Fontes et al., 2021). Experimental research into green water has looked at the pressure and pressure development during events, finding impulsive and non-impulsive event types and a variety of flows and impacts (Hernández-Fontes et al., 2020; Song et al., 2015; Ariyarathne et al., 2012; Lee et al., 2012; Faltinsen et al., 2002; Mori and Cox, 2003). Parameters like freeboard, relative vertical motion, stem angle, surge motions and wave steepness are found to influence green water (Hamoudi and Varyani, 1998; Greco et al., 2012; Buchner, 1995; Boon and Wellens, 2024). Different types of green water events have been identified, like dambreak, plunging or the hammer-fist type for which no exceedance is measured (Greco et al., 2004, 2005, 2007). Analytical work on green water often uses the dam-break model (Buchner, 1995; Fonseca and Guedes Soares, 2004; Rajendran et al., 2015; Goda and Miyamoto, 1976; Chuang et al., 2023). However, not all green water impacts are dam-break type impacts (Hernández-Fontes et al., 2021). Even for the dam-break green water types, the dam-break model deviates from the green water impacts, as green water impacts are three-dimensional dynamic impact types where water flows over a moving deck (Kudupudi et al., 2023). Work on simulating green water impacts is also conducted (Temarel et al., 2016). However, the span of spatial and temporal scales needed to model green water means that numerical techniques are not yet capable of addressing the complexity and computational cost of screening for green water events from long time series of waves (Dias and Ghidaglia, 2018). The flow on deck caused by green water poses a risk as large pressures during impacts can damage the structure of the ship. The flow of water on the deck itself also poses a risk to people on deck.

Besides green water events, there are also exceedance events. Exceedance has been defined as a measured relative wave elevation exceeding the deck level, often measured by relative wave probes located at one or more locations at the bow (Buchner, 2002; Ogawa, 2003; Greco et al., 2004; Guedes Soares and Pascoal, 2005). Exceedance can occur together with spray events, which is when water comes on deck mostly in the form of a intermittent small volumes of water, not a continuous flow (Chuang et al., 2019; Benmansour et al., 2016). Exceedance can develop into green water, but it does not always have to Chuang et al. (2019) and Boon and Wellens (2022b). If exceedance does not develop into a flow on deck it does not pose a risk to the ship or those on board. Water exceeding the deck becomes a risk when it develops into green water.

Screening methods have been used for green water to identify the critical events to design for. Previous research has developed methods based on exceedance (Cox and Scott, 2001; Buchner, 2002; Ogawa,

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Nomenclature

D	Water depth [m]
d	Still water draft of model at bow [m]
EX	Exceedance that does not develop into green water
fb	Freeboard of ship at bow measured from waterline [m]
GW	Green water
GW_{EX}	Green water with measured exceedance
GW_{no}	Green water without measured exceedance
H_{m0}	Significant wave height [m]
h	Heave [m]
L_{pp}	Ship length between perpendiculars [m]
n	Number of impacts/events during test case [–]
n_w	Number of encountered waves [–]
$P_{GW_{EX} \cup EX}$	Probability of water exceeding deck level [s^{-1}]
P_{GW}	Probability of green water [s^{-1}]
RWE	Relative wave elevation [m]
RWE_m	Measured relative wave elevation [m]
su	Swell-up of water at bow of ship [m]
t_e	Time of maximum RWE_m during event [s]
T_p	Peak period [s]
t_{test}	Testing duration [hours]
T_{z_e}	Zero-crossing encounter period of wave spectrum [s]
V	Modelled forward velocity of ship [m/s]
x_{bow}	Distance from centre of gravity to bow [m]
η	Wave elevation [m]
θ	Pitch [rad]

2003; Price and Donohue Bishop, 1974; Hamoudi and Varyani, 1998; Guedes Soares and Pascoal, 2005). Nonlinearity in the waves and ship response and asymmetry in the relative wave elevation distribution causes deviations from the distribution (Cox and Scott, 2001; Watanabe et al., 1989; Buchner, 2002; Guedes Soares and Pascoal, 2005). Also, these cited prediction methods assume that all instances where water exceeds deck level lead to green water, but, as discussed, not all exceedance events become green water.

Previous research also proposed screening and prediction methods based on events that induce large pressures on deck (Stansberg, 2008; van Essen et al., 2021). These screening methods focus on large impact pressures. Low-pressure impact flows on deck are neglected, even though they can still be of risk to those on board. van.'t Veer and Boorsma (2016) specifically investigate green water. Their work focuses on the categorization of the green water events and the flow on deck, not the prediction of the probability of green water.

The present paper analyses the motions, waves and swell-up during a large number of green water events and exceedance events that did not develop into green water. From the analysis, differences between the motions during green water and exceedance events are found. Based on the difference, the present paper proposes a novel prediction method of probability predicts for green water events, excluding exceedance events that do not develop into green water. As part of the method limit values for heave, pitch and wave elevation are adopted, which will be discussed later in the article.

2. Methodology

Green water and exceedance events are identified by using the distance of continuous flow onto the deck as an identifier. If the flow on the deck is limited, but water is measured to exceed the deck level, the event is classified as exceedance. A continuous flow of water on the deck from the stem to at least 8% of the ship's length between perpendiculars (L_{pp}) is classified as green water. This limit was chosen based on the green water events described by Buchner (2002) and Pham and Varyani (2005) which all reached over 8% L_{pp}. Green water events for which no exceedance was measured were also identified. During these events water has flowed onto deck, so water exceedance has occurred. No measured exceedance means that the exceedance was local and the location differs from the exceedance measurement location. As the exceedance for GW_{no} events is local, the kinematics possibly differ from GW_{EX} type events. GW_{no} events could be the plunging or hammer-fist type events mentioned in the introduction. Fig. 1 shows schematics for the different event types.

Data from experiments modelling 1945 full-scale sailing hours at forward speed in irregular head waves is used, also used in Boon and Wellens (2022b). The data set is available on https://doi.org/10.4121/21031981 (Boon and Wellens, 2022a) and the experiments are described in Boon and Wellens (2022b). With the data set, a focused investigation is conducted of exceedance and green water events and their differences. Different data sets for exceedance events and green water events with and without measured exceedance are created. The set of green water events for which exceedance is measured is called GW_{EX}, and the set of exceedance events for which no green water occurred is EX. The green water events that do not belong to either group are GW_{no}.

The relations between sets are

$$GW_{EX} \cap GW_{no} = \emptyset, \quad GW_{EX} \cup GW_{no} = GW, \tag{1}$$

$$GW \cap EX = \emptyset, \quad GW_{EX} \cup EX = \{\text{events}|\text{RWE}_m > fb\} \tag{2}$$

In Eq. (2) fb is the still water freeboard.

2.1. Experiments

The experiments model a ship at forward speed, with heave and pitch as degrees of freedom, in irregular waves from different sea states. The data set includes the occurrence of green water, the relative wave elevation (RWE) at the bow, the motions and the wave elevation. Some aspects of the experiments relevant for the present work are discussed. The ship model is placed in the middle of the wave–current tank, shown in Fig. 2, with a distance of 2.35 m between the front of the wave maker and the stem of the model. The tests were conducted in relatively shallow water with a depth of 0.45 m, including all accompanying intermediate or shallow water effects. The ship was mounted using a cylindrical linear guide rail and a linear guide at the stern of the model limiting surge, roll, yaw and sway. The mounting of the ship model only leaves heave and pitch as free motions.

The ship is number 523 in the Delft Systematic Deadrise Series. The dimensions of the model are displayed in Table 1. A box was placed on the deck to represent a superstructure or equipment on deck. The dimensions are provided in Table 1. Swing tests were performed to determine the radius of gyration.

Wetness sensors were installed adjacent to the front four deck pressure sensors to detect when a green water event happened. The wetness sensors are made up of probes on deck that measure changes in electrical resistance and provide a binary "wet or dry" signal. The vessel's movements were monitored using Panasonic HG-C1400 laser distance sensors. One was positioned at the hinge in the centre of gravity to measure heave, and the second was placed at 0.682 m from the first to the rear of the vessel to measure pitch. The laser sensors have an accuracy of 0.3% of the measuring range of 0.4 m. The overall setup is shown in Fig. 2. A resistance-type wave probe was installed 0.64 m from the tank's side. The wave probe was at the same longitudinal position of the tank as the RWE probe on the ship model, 2.35 m from the wavemaker. The RWE probe was mounted to the model's port side bow, 0.05 m from the centre and 0.04 m behind the stem. Calibration of both the RWE and the wave probe revealed no errors above 2% of the utilized range of 0.1 m.

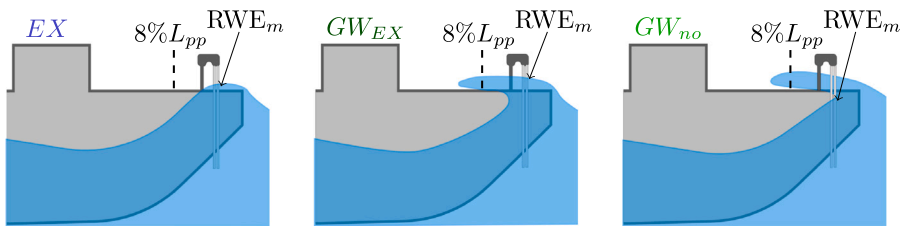


Fig. 1. Schematics of the different event types. From left to right exceedance without green water (EX), green water with exceedance (GW_{EX}) and green water without exceedance (GW_{no}).

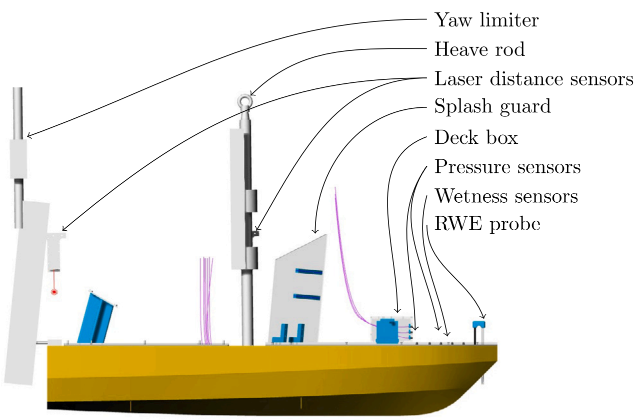


Fig. 2. Side view of test setup.

Table 1
Dimensions and parameters of the used model.

Length between perpendiculars	1.50 m
Breadth moulded	0.330 m
Depth moulded	0.207 m
Draft	0.117 m
Freeboard	0.091 m
Total mass	46.0 kg
Vertical centre of gravity	0.161 m
Longitudinal centre of gravity	0.703 m
The radius of gyration in pitch	0.366 m
Natural heave frequency in water	1.11 Hz
Natural pitch frequency in water	1.64 Hz
Deck box (L × W × H)	0.150 × 0.180 × 0.090 m
Distance to deck box from stem	0.300 m
Location RWE probe from stem	0.004 m

Table 2
Model scale parameters of test cases.

Case	T_p [s]	H_{m0} [m]	T_{z_e} [s]	V [m/s]	t_{test} [h]
1	0.95	0.0351	0.67	0.25	8
1a	0.97	0.0337	0.67	0.28	8
1b	0.93	0.0383	0.65	0.21	8
1c	0.97	0.0241	0.67	0.28	8
2	1.05	0.0322	0.68	0.25	40
3	1.05	0.0378	0.68	0.25	40
4	0.91	0.0397	0.61	0.25	40
4a	0.82	0.0417	0.62	0.21	2
5	0.95	0.0417	0.67	0.25	14

2.2. Test conditions

174 h of testing were conducted for various wave spectra and model forward speeds. The properties of the tests that were run are displayed in Table 2. The peak period is T_p, the significant wave height is H_{m0}, and the zero-crossing encounter period of the spectra is T_{z_e}, which depends on the modelled forward velocity V. The experiments had different testing durations t_{test}. Froude scaling with a factor of 125 was used, making the equivalent full-scale sailing velocity between 4.6 and 6.1 knots, equivalent peak periods between 9.2 and 11.7 s and equivalent significant wave heights between 3 and 5.3 m.

Table 3
Number of events included in each data set and the probability per event type.

	n_{EX}	P_{EX}	$n_{GW_{EX}}$	$n_{GW_{no}}$	n_{GW}	P_{GW}
Case 1	16	0.00037	8	1	9	0.00021
Case 1a	9	0.00021	6	1	7	0.00016
Case 1b	37	0.00083	15	5	20	0.00045
Case 3	35	0.00017	29	5	34	0.00016
Case 4	221	0.00094	160	39	199	0.00084
Case 4a	20	0.00189	9	0	9	0.00083
Case 5	91	0.00119	81	10	91	0.00181

2.3. Event type identification

Wetness sensors are used to initially detect the occurrence of green water events. Visual identification from video footage was used to check for false positives and negatives. The wetness or pressure sensor 0.012 m behind the stem of the bow (distance bow-sensor representing 8% of the length of the ship), must be reached for an event to be considered a green water event. According to the visual inspection, this criterion excludes spray-like deck wetness events. Exceedance events are defined as RWE being at least 0.01 s above deck level. Fig. 3 shows events for different tested cases from both GW and EX. Time traces during a green water and exceedance event are given in Fig. 4. In this figure, h is the heave, θ the pitch and η the wave height.

For all event types, the maximum measured relative wave elevation (RWE_m) measured during the event was used as the time the event took place, t_e.

3. Results

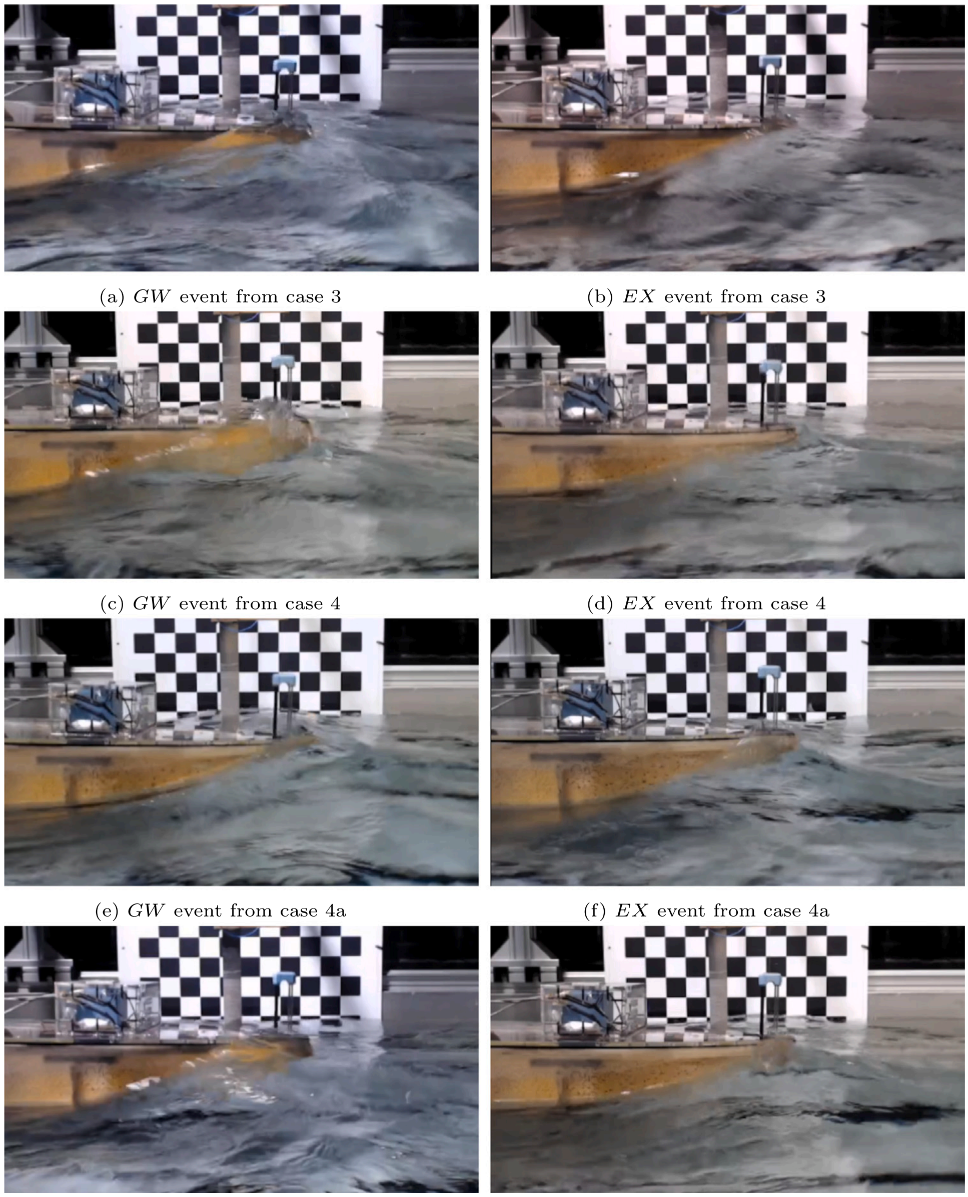
The difference between the events, as defined in paragraph 2.3, is analysed. Test cases 1c and 2 were excluded from further analysis as not all event types occurred for these test cases.

The number of events of each type per case is shown in Table 3. Here n is the number of events, with the subscript indicating the data set it belongs to. P is the probability of an event occurring per encountered wave with again the subscript indicating what data set it refers to. P is calculated with

$$P = \frac{n}{n_w}. \tag{3}$$

The number of encountered waves (n_w) is calculated as $n_w = \frac{t_{test}}{T_{z_e}}$.

All the data sets are of different size, but the relative number of occurrences of the different event types is somewhat constant. The average relative number of occurrences is $n_{GW} = 0.45 \cdot (n_{EX} + n_{GW_{EX}})$ and $n_{GW_{no}} = 0.17 \cdot n_{GW}$. These results indicate, that for over 80% of green water events, water was measured to exceed deck level before the event. Also, over half of all measured exceedance events did not develop into green water. The exceedance was measured at one location, likely increasing the number of GW_{no} event types compared to



(a) GW event from case 3 (b) EX event from case 3

(c) GW event from case 4 (d) EX event from case 4

(e) GW event from case 4a (f) EX event from case 4a

(g) GW event from case 5 (h) EX event from case 5

Fig. 3. Stills from footage of GW and EX events for different cases.

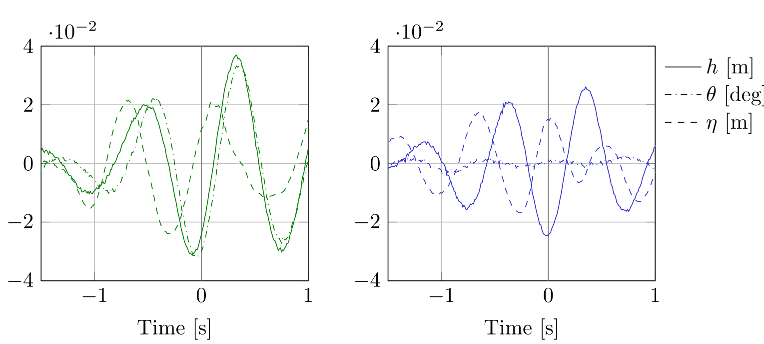


Fig. 4. Time traces of the measured heave, pitch and wave height during a green water event (left) and exceedance event (right) both from case 3. Note that the wave height is measured at forward speed of the ship model.

experiments with more RWE probes. The values in Table 3 show that less than half of all exceedance events ($GW_{EX} \cup EX$) are the problematic green water events, while at least a tenth of all green water events are not included when only measured exceedance is considered, as the exceedance for these events took place away from the measurement location (see Fig. 5).

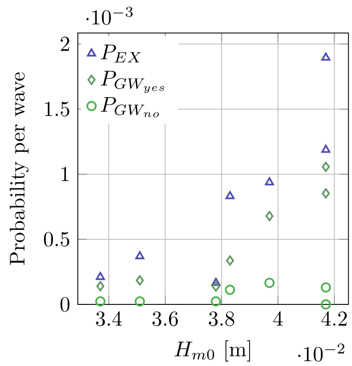


Fig. 5. Increase of probability of occurrence of EX and GW_{EX} per case, increasing with H_{m0}. GW_{no} remains fairly constant.

3.1. Relative wave elevation

Fig. 6 shows the maximum measured relative wave elevation during events $\mathrm{RWE}_m(t_e)/fb$ as a function of H_{m0} for the different event types. Guedes Soares and Pascoal (2005) identified an increase in $\mathrm{RWE}_m(t_e)/fb$ as a function of H_{m0} for a data set containing all exceedance events ($GW_{EX} \cup EX$ in the present study). The present study found a similar increase in $\mathrm{RWE}_m(t_e)$ for $GW_{EX} \cup EX$ as was found by Guedes Soares and Pascoal (2005). The increase in $\mathrm{RWE}_m(t_e)$ for $GW_{EX} \cup EX$ is mostly caused by an increase in $\mathrm{RWE}_m(t_e)$ for GW_{EX}, as GW_{EX} increases from 107% of the freeboard to 122%, while EX $\mathrm{RWE}_m(t_e)$ only slightly increases from 103% to 106%. Overall, the average $\mathrm{RWE}_m(t_e)$ for EX is consistently lower than the average $\mathrm{RWE}_m(t_e)$ for GW_{EX}. This difference is notable as the difference in the definition for GW_{EX} and EX events is water flowing on deck, not the relative wave elevation. Apparently, there is a difference between the kinematics of GW_{EX} and EX, resulting in different relations between $\mathrm{RWE}_m(t_e)$ and H_{m0}. To investigate where the differences come from, the different contributions to $\mathrm{RWE}_m(t_e)$ are analysed.

$\mathrm{RWE}_m(t_e)$ can be calculated as

$$RWE_m(t_e) = h(t_e) + tan(\theta(t_e)) \cdot x + \eta(t_e) + su(t_e). \tag{4}$$

The heave ($h(t_e)$), pitch times the distance from the centre of gravity to the RWE probe ($\tan(\theta(t_e)) \cdot x$) and the undisturbed wave elevation ($\eta(t_e)$) are the maximum value during 0.1 s before and after an event. The swell-up ($su(t_e)$) has been determined by subtracting the heave, pitch and wave height from $\mathrm{RWE}_m(t_e)$. Swell-up consists of radiated and reflected wave components and dynamic swell-up, further discussed in Section 3.1.1. Fig. 7 shows for each event type the average of heave, pitch, wave height and swell-up over H_{m0}. The figure shows that on average a negative heave and pitch occur together with a positive wave height at the bow, indicating that the phases between the motions and wave are consistently out of phase for all events.

The contribution of heave, pitch, wave height and swell-up differ for the different event types. The average percentages show that the contribution of motions is larger for GW_{EX} compared to EX, while it is close to the same for GW_{no} and GW_{EX}. Buchner (2002) has found similar values for exceedance events similar to ($GW_{EX} \cup EX$), shown in Fig. 7, but in his case obtained for a moored FPSO.

The previously identified increase in $\mathrm{RWE}_m(t_e)$ for larger H_{m0} is not the same for EX and GW_{EX}, implying a difference in the kinematics leading up to $\mathrm{RWE}_m(t_e)$. Fig. 7 shows that for EX the increase in $\mathrm{RWE}_m(t_e)$ is caused in equal parts by an increase in wave height and the swell-up, while the contribution of pitch decreases. For GW_{EX} the increase in $\mathrm{RWE}_m(t_e)$ is caused by the increase in the swell-up, while the wave height stays about constant above $H_{m0} = 0.034$ m. The heave and the pitch actually decrease for larger H_{m0} for GW_{EX}. This decrease means that the swell-up causes the increase in $\mathrm{RWE}_m(t_e)$ for GW_{EX}.

A decrease in the contribution of the ship motions to $\mathrm{RWE}_m(t_e)$, shown in Fig. 7, is not in line with the standard deviation of the motions found throughout the experiments shown in Fig. 8. The smaller motions during GW_{EX} events for larger H_{m0} should thus be explained on the basis of what happens during the events. With the decrease in heave and pitch, also an increase in the standard deviation of the heave and pitch is found for GW_{EX}, as the shaded area becomes wider. This increase in the standard deviation, combined with the larger GW_{EX} data set sizes for larger H_{m0} makes it likely that for larger H_{m0} large swell-ups occur. Larger swell-ups make additional green water events more likely at lower heave and pitch. The GW_{EX} data set is thus extended with events with lower heave and pitch for larger H_{m0}, lowering the average and increasing the data set size and the standard deviation.

The increase in wave height and swell-up leading to a decrease in the average heave and pitch contribution is not found for EX events. The contribution of the wave height does increase, similar to GW_{EX}, but this increase does not lead to the large increase in swell-up found for GW_{EX}. The increase in swell-up is similar to the decrease of the average pitch, but no increase in the standard deviation is found related to the decrease. The pitch is thus smaller overall for EX for larger H_{m0}, instead of the data set being extended by events with lower pitch as was the case for GW_{EX}.

In summary, the contribution and relations of the heave, pitch, wave elevation and swell-up differ per event type. To further understand the differences between EX, GW_{EX} and GW_{no} the swell-up is analysed.

3.1.1. Swell-up

The large values found for the swell-up and the differences in swell-up for the different types of events are motivations for further investigation. The swell-up consists of wave reflection from the bow, wave radiation from the ship's motions, and dynamic swell-up from the forward speed (Journée and van 't Veer, 1995; Buchner, 2002; Tasaki, 1960). No existing estimation method based on the combination of these effects was found, but a study by Blok and Huisman (1983) gives values for separate empirical swell-up coefficients for the heave, pitch and wave elevation, all at forward speed. Tasaki (1960) gives the swell-up coefficient for the combination of heave, pitch and wave elevation but does not include forward speed. Noblesse et al. (2008) propose a partially empirical equation for the swell-up at forward speed, and Journée and van 't Veer (1995) give a theoretical equation for the swell-up of a radiated wave resulting from the motion of a ship at forward speed, but do not themselves include the swell-up due to the forward speed.

The combination of the two methods above is used to predict the swell-up during events identified in our data set. The predicted swell-up by Noblesse et al. (2008) is added to the swell-up predictions by Journée and van 't Veer (1995) and Tasaki (1960) to account for the swell-up caused by forward speed. The predictions resulting from the different estimation methods are compared to the swell-ups found during the different events in Fig. 9. For the calculations, the heave, pitch, wave elevation and forward speed were inputs, as well as draft, Froude number and waterline entrance angle. As the heave, pitch and wave elevation are irregular the choice was made to use the motion and wave elevation during an event: $h(t_e)$, $\tan(\theta(t_e)) \cdot x$ and $\eta(t_e)$.

The measured swell-up is reasonably well predicted by Journée and van 't Veer (1995) and Noblesse et al. (2008) for GW_{EX}. A discrepancy is shown between the predicted and measured swell-up for EX. Buchner (2002) identified a similar discrepancy and concluded that the discontinuity at the freeboard level is the cause. Even though the same discontinuity at the freeboard level happens for GW_{EX} as for EX, the same underestimations are not found. The difference between GW_{EX} and EX for the prediction accuracy suggests that the underestimation for the swell-up for EX is due to a different driver for the swell-up during these impacts, not to the discontinuity at the freeboard level. A hypothesis for the different driver is given at the end of the next section.

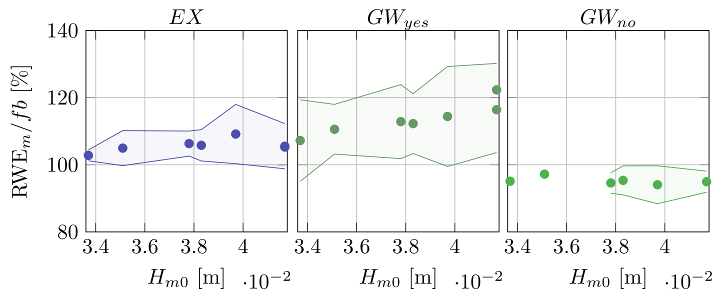


Fig. 6. Difference in average RWE_m during events per case for EX, GW_{EX} and GW_{no} shown from left to right. The shaded area indicates the standard deviation of RWE_m. For $H_{m0} < 0.038$ m the GW_{no} set has one event per case, so no standard deviation is shown.

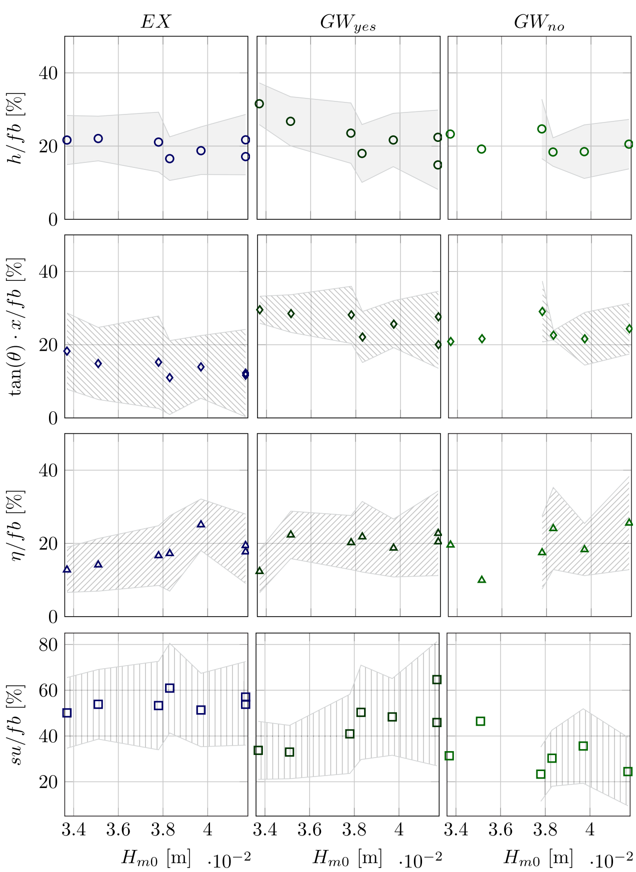


Fig. 7. Contribution of the heave, pitch, wave elevation and swell-up to RWE_m on average per case for EX, GW_{EX} and GW_{no} from left to right. The shaded area indicates the standard deviation. For $H_{m0} < 0.038$ m the GW_{no} set has one event per case, so no standard deviation is shown.

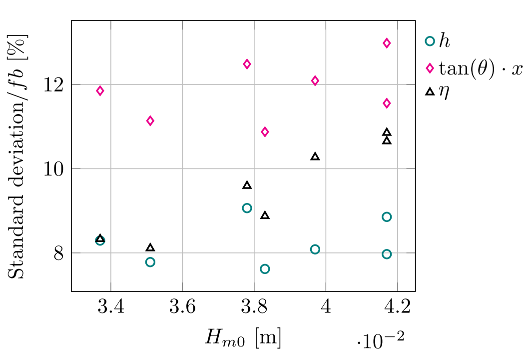


Fig. 8. The heave, pitch and wave height's standard deviations from the overall experiments instead of only during an event.

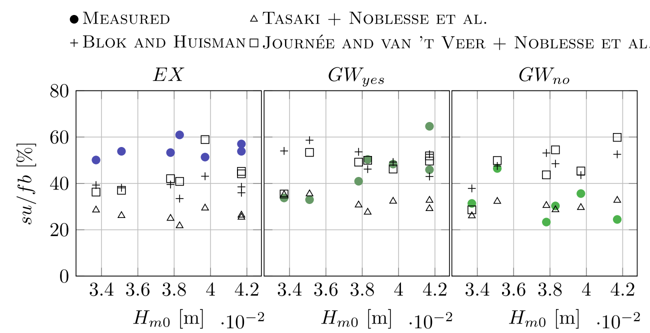


Fig. 9. Difference between measured swell-up for EX, GW_{EX} and GW_{no} and estimations for the swell-up based on literature (Tasaki, 1960; Noblesse et al., 2008; Blok and Huisman, 1983; Journée and van 't Veer, 1995).

For GW_{no} similar swell-ups as for GW_{EX} are predicted from theory. The measured swell-ups are lower, but as the predictions are similar for GW_{EX} and GW_{no} there is no apparent reason for the swell-up for GW_{EX} and GW_{no} to be different. Section 3.1 also concludes that GW_{EX} and GW_{no} are similar for everything except the swell-up. The only difference between GW_{EX} and GW_{no} events is if the swell-up was measured by the RWE probe. In the following analysis GW_{EX} and GW_{no} are combined into GW.

3.2. Motion and wave elevation

After analysing the swell-up, the differences between GW and EX for the motions and wave contribution to $\mathrm{RWE}_m(t_e)$ are examined. Histograms of the heave, pitch, wave height and $\mathrm{RWE}_m(t_e)$ are shown in Fig. 10. The histograms are density histograms, averaged proportionally over all cases.

Fig. 10 shows that the pitch motions during EX are not the same as the pitch motions during GW. The difference in pitch motion causes a difference in $\mathrm{RWE}_m(t_e)$. The pitch for GW is normally distributed and larger than the pitch for EX, which is not normally distributed. The latter has one peak around 0 and a smaller peak near 35%. The spread in data is explained in part by the trend over H_{m0} shown in Fig. 7. Another part of the explanation is that a strict definition for green water is used, causing EX to include events similar to green water events, explaining the large number of EX events with pitch similar to GW events. The separate peak around a neutral to somewhat forward pitch would then be most representative for EX. The main difference between GW and EX impacts is thus identified to be the pitch motion during the event.

Comparing the values from the histograms to the standard deviation of the motions and wave height found throughout the experiments, Fig. 8 shows that the motions and wave elevations found during GW events are large. These large motions of forward pitch and downward heave occur while the wave elevation at the bow is positive. The

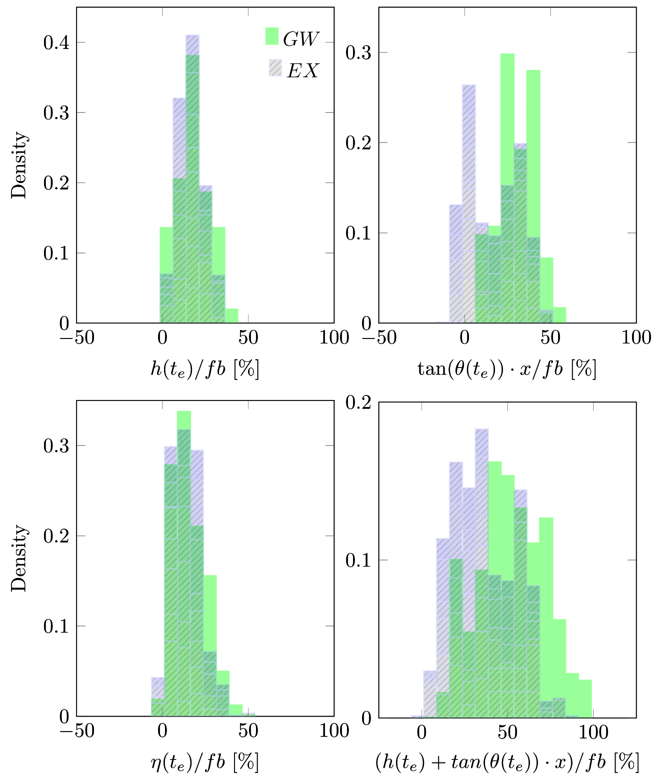


Fig. 10. Visualizing the differences and similarities between EX and GW with $h(t_e)$, $\eta(t_e)$, $\tan(\theta(t_e)) \cdot x$ and $\eta(t_e)$ as a percentage of freeboard in density histograms proportionally averaged over the cases 1, 1a, 1b, 3, 4, 4a, 5.

combination of a large downward heave and forward pitch with a positive wave elevation at the bow is unlikely, possibly as unlikely as green water events are to occur.

From the above, it is hypothesized that if a low heave and large wave height coincide but the pitch is neutral, an event will be an EX event, and thus will pose a limited risk to the ship or people on the ship. When this situation coincides with a large forward pitch, a GW event occurs. The reason for this difference is not clear from the present data and further research is needed. A possible explanation is that the swell-up combined with a neutral or somewhat forward pitch results in a large swell-up with mostly vertical velocities, causing exceedance but no flow on deck. A large forward pitch motion coinciding with a wave leads to a scooping effect, causing a continuous flow on deck. This explanation is also in line with the difference in prediction accuracy of swell-up for EX and GW_{EX} events discussed in Section 3.1.1. The driver for the swell-up to be different is the pitch motion.

3.3. Predicting the occurrence of green water

Differences between GW and EX events have been identified above. From the difference, a prediction or screening method can be proposed specifically for GW impacts and excluding EX events. The result is a method that focuses on the impacts that pose a risk. The prediction method uses the heave, pitch and wave height and is based on the histograms in Fig. 10.

Limit values based on the values found during impacts are used to quantify for which heave, pitch and wave height GW impacts occur. Fig. 10 shows that green water impacts mostly occur for certain values of heave, pitch and wave height. The combined data of all impacts is used to find the limit values, as otherwise no representative limit value could be determined for cases with few impacts. The limit values should be chosen such that they adhere to the requirement

$$su_{lim} \geq fb - h_{lim} - \tan(\theta_{lim}) \cdot x - \eta_{lim}. \tag{5}$$

Table 4
Limit values above or below which GW events occur based on the values found during events and the percentages of the events included by these limit values.

	Limit as ratio to fb	% of GW events above limit
h_{lim}	0.13	85%
$\tan(\theta_{lim}) \cdot x$	0.25	85%
η_{lim}	0.095	90%
su_{lim}	0.58	75%

In Eq. (5), the subscripts lim indicate limit values. The equation ensures that an upper limit for the expected swell-up is included through the used limit values, as the swell-up depends on wave elevation and motion on the ship, as discussed in paragraph 3.1.1. To ensure a realistic upper limit for the swell-up, su_{lim} is conservatively chosen so that 25% of GW events were measured to have a larger swell-up than su_{lim}. For the wave crest elevation, a limit is chosen for which 90% of the wave elevations found during GW events are larger than η_{lim}. The limit values for the heave and pitch are chosen such that they fulfil the condition in Eq. (5). The condition is fulfilled for limits for the heave and pitch where 80% of events occurred with larger heave and pitch. The resulting limit values are shown in Table 4. The swell-up is accounted for through the limit values of heave, pitch and wave elevation, as they adhere to the requirement in Eq. (5). The swell-up is also implicitly included because the swell-up is caused by the heave, pitch and wave elevation.

Not only swell-up but also the effect of forward speed is implicitly included through the heave, pitch and wave elevation as the motion is influenced by the forward speed. In previous paragraphs, no need for including the differences in forward speed explicitly in the analysis was found. The influence of the forward speed on the occurrence of green water is thus thought to be indirect as the influence of forward speed influences the motion and swell-up, which in turn influences the probability of green water.

To test the hypothesis that events occur when the limit values of heave, pitch and wave height are exceeded, the probability of an event occurring is calculated with

$$P = P(\eta > \eta_{lim}) \cdot P(h > h_{lim}|\eta > \eta_{lim}) \cdot P(\theta > \theta_{lim}|\eta > \eta_{lim}). \tag{6}$$

The equation is based on prediction methods for exceedance events which use the standard deviation of the total relative wave elevation (Guedes Soares and Pascoal, 2005; Ogawa, 2003; Buchner, 2002; Cox and Scott, 2001).

To find the probability of a limit value being exceeded, needed for Eq. (6), the probability density functions of the wave height, heave and pitch are used. Following linear theory, heave and pitch are assumed to be independent from each other, but to both depend on the wave elevation. The dependent distributions of both the heave and pitch are found for each case by identifying all heave and pitch values coinciding with $\eta > \eta_{lim}$. The probability density functions of η, $h|\eta > \eta_{lim}$ and $\theta|\eta > \eta_{lim}$ were assumed to be normal distributions. This assumption was shown to be correct with the D'Agostino–Pearson test yielding a p-value limit of 0.05 (D'Agistino et al., 1990).

Fig. 11 shows the resulting prediction of the method in Eq. (6) with the results closely following the experiments. The diamonds in the figure show the sensitivity of the prediction to changes in used limit values as the diamonds indicate the difference in predictions for P_{GW} if h_{lim} and θ_{lim} are chosen so that they include 5% more or fewer events. The prediction method in Eq. (6) is sensitive to the limit values used. There could be arguments made for choosing the limit values differently, which would lead to somewhat different results.

Cox and Scott (2001) propose a method based on the relative motion of the bow exceeding the freeboard to calculate the probability of exceedance ($P_{GW_{EX} \cup EX}$). This estimation is compared to P_{GW} from the experiments and P_{GW} estimated with Eq. (6). As expected, the method of Cox and Scott (2001) for $P_{GW_{EX} \cup EX}$ results in a large overprediction of P_{GW} as it uses exceedance as an analogy for green water.

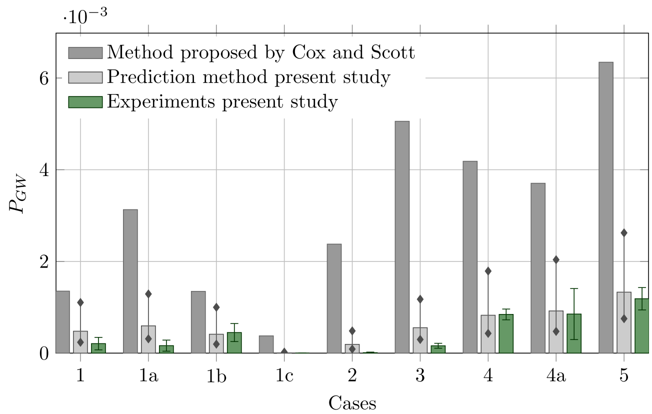


Fig. 11. The probabilities estimated with the proposed prediction method compared to the probabilities found from the experiments and literature. The lines indicate a 95% confidence interval and the diamonds a 5% in- and decrease in the percentage used to determine the limits.

Using exceedance is in line with most existing literature on predicting green water events (Cox and Scott, 2001; Price and Donohue Bishop, 1974; Hamoudi and Varyani, 1998; Buchner, 2002; Guedes Soares and Pascoal, 2005). As a consequence, no data from previous work could be adopted for further comparison.

Fig. 11 shows the proposed method gives better predictions than the method proposed by Cox and Scott (2001). The method is based on the same data set it is tested on, resulting in the most optimal results. Still, Eq. (6) being able to predict the number of green water events shows promise, likely because of these improvements:

(1) Eq. (6) explicitly sets limit values for heave, pitch and wave height, instead of using RWE, thus becoming a prediction method for specifically green water as exceedance is not required anymore and events with neutral pitch are excluded.

(2) Because of the use of dependent limit values the phase between the heave and wave and pitch and wave is included

(3) The swell-up is implicitly included through the limit values set, because the swell-up depends on heave, pitch and wave elevation

Comparing outcomes of the prediction method to the data gives confidence in the hypothesis that if a certain heave, pitch and wave elevation occur it will lead to a green water event. Future research is to be conducted to include the effect of different ship designs, surge, sea states and forward velocities to improve the choice of limit values.

4. Conclusion

A large data set from experiments was used to find the difference between heave, pitch and wave elevation for which exceedance events occur and when they develop into the continuous flow on deck associated with green water. Based on the results, a prediction method of probability is proposed that focuses on the high-risk green water events.

The difference between green water events and exceedance events that do not develop into green water is explained by the pitch of the ship. Green water events consistently occurred with large forward pitch motions, while exceedance also occurred when the pitch was neutral. Also, differences in the relative wave elevation during green water and exceedance events were identified. For green water events, the wave elevation above deck increases by 15% for an increase of the significant wave height of 24%. The increased wave elevation is caused by an increase in swell-up. For exceedance events, only a limited increase in relative wave elevation above deck was found, caused by an increase in heave and wave elevation.

Previous work uses exceedance to predict green water. With the newly identified differences between green water and exceedance events, a method is proposed that focusses on green water events with risk. By using the values of heave, pitch and wave height found during green water events and calculating the probability of these limit values all being exceeded at the same time, an improved estimate of the probability of green water can be obtained.

CRediT authorship contribution statement

A.D. Boon: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **P.R. Wellens:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: P. R. Wellens reports financial support was provided by Dutch Research Council. Corresponding author employed by Deltares If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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