ABSTRACT

CONTENTS

1 SETUP: GREENWATER TYPES

- S: Green water is a thing.
- C: There are still questions about green water, and it is difficult to predict, and thus design for. This is difficult because different types of events captured in one model. First, further insights into all events As stated, statistics needed.
- Q: Is there a way to improve prediction of green water by looking at the different types of impacts as separate phenomenon?

  What are the statistics for each of the green water events?

  What are the overall lifetime loadings of green water on a vessel?
- A: Going to do long running experiments With methods to identify the different event types

  ?????????????

Ships and offshore structures are out in the ocean to transport the many goods we send around the world, pump up oil, or place wind turbines. Waves impact these structures, causing large loads. Green water is one of these impact types. Green water is water that impacts on deck or superstructures. It can lead to huge impact pressures. As Buchner [7] stated, green water is a non-linear and strongly complex problem. Also as during green water events, free surface, air and water interact in a way that can lead to entrained and entrapped air [53]. It was found that with increased forward speed, the probability of green water increased [19, 22]. Most studies focused on head waves, but green water can also occur on the side of a vessel.

1.0.1 Green water event types

Green water events have been classified into four main categories: dam-break, plunging, plunging dam-break combination and hammer-fist events [18, 12, 56]. The impacts can be an isolated impact event, but multiple events can also follow each other up, influencing the loading [30]. For dam-break scenarios, a wall of water is created around the deck as a consequence of large relative vertical motions between the ship and the water [7]. As this water exceeds the freeboard, water flows onto deck. The subsequent fluid motion on the deck resembles a wet dam-break flow [14]. Researchers have developed a good understanding of the impact due to this type of event [1].

However, plunging and hammer-fist type events lead to the most severe impacts [18]. This is because they lead to impulsive pressures. Impulsive pressures have a high pressure rise time, in contrast to non-impulsive pressures which have a slow rise time [12]. The maximum instantaneous pressure is related to this pressure rise time [49].

In contrast to the dam-break event, the plunging wave is not the result of a ship interaction with steep waves causing run-up [12, 14]. Plunging green water events are thought to be caused by an (almost) breaking wave impacting on deck or superstructures [14]. As the wave breaks and overtops the structure, the flow becomes multi-phased and chaotic as an air pocket is formed [52]. This air pocket can lead to pressure oscillations and pressure peaks [35]. Trapped air introduces a randomness which leads to variations in impact pressure [1].

A hybrid event type called a plunging dam-break event has also been identified. This type of event is the result of the interaction of a steep wave with the bow resulting in a wave breaking on deck. Plunging dam-breaking is the most common type of green water [18, 19]. With this type, air is also being trapped.

Hammer-fist type of events are, together with the plunging events, the most severe as they lead to the largest impacts. A hammer-fist impact happens when either a wave is focused locally in front of the edge of the deck, or when a strong wave impacts the vertical wall of the structure, pushing wave run-up onto the deck while maintaining a positive free-board [12]. The hammer-fist impact is connected to steep, non-breaking wave. Hammer-fist impacts are blunt water-deck impacts. For these type of events there is no apparent air entrapment near the bow [18]

At this moment no clear quantification of the different events could be found in the literature. The found research made the classifications of the events based of of visuals [18, 12, 56]. Based on the discussed literature it is thought that for dam-break, a distributed non-impulsive impact is expected, for plunging a local impulsive impact, for dam-break plunging global pressure distribution with higher pressures at the edge and non-impulsive impact, and for the hammer-fist a global distributed, impulsive impact is expected. NOG GOED NADENKEN, DIT IDD ZO? ANDERE CLASSIFICATIE? BASEREN OP TIME TRACES VAN PRESSURES? MISS OOK IETS TOEVOEGEN OVER LUCHT INSLUITING EN OF DAT ALS CLASSIFICATIE KAN WORDEN GEBRUIKT. MISS JUIST WEL HOE HET WATER AAN BOORD KOMT GEBRUIKEN? IS DEZE MANIER VAN CLASSIFICEREN NIET MISS IETS WAT IK WIL DOEN DOOR MIDDEL VAN SVM OF DISCISION TREES? MAAR HOE GA IK ZE ANDERS ONDERSCHEIDEN? MISS JUIST WEL ONDERSCHEIDEN DOOR DE INKOMENDE GOLF EN DE BEWEGING VAN HET SCHIP DAT ER BIJ HOORT???

MOGELIJKE METHODE: EERST VISUEEL ALLES CLASSIFICEREN. DAARNA NAGAAN WELKE MANIER HET OOK KAN (PRESSURE TRACES, SPEED OF WATERFRONT (from camera footage), ETC.)

1.0.2 Prediction methods

Tools to help predict loading due to green water have been developed. They can be categorized into three groups: approximations, numerical and experimental [27].

Numerical methods are more accurate than these approximation methods. The problem with numerical simulations is that they take excessive computational time [48].

Experiments for green water events are still being carried out today, as it is an affordable and relatively accurate method.

Approximations are empirical and analytical methods. They are simple and fast but less accurate. They consist mostly of predicting freeboard exceedance, as most greenwater events occur when the freeboard is exceeded. Prediction of exceedence of the freeboard is complex due to the many dependencies [35]. These are for instance wave steepness or structure motions [15, 7]. These parameters also introduce nonlinearities [14]. Researchers have made probability distributions of the freeboard exceedance based on empirical parameters. Examples are Buchner [7], Cox and Scott [13] and Guedes Soares and Pascoal [20].

DIFFERENT EVENTS AND MORE UNDERSTANDING NEEDED, NEEDED THROUGH STATISTICS

As stated by [8, 4, 5, 44**?**], variability within 'constant' conditions, statistics needed

1.0.3 Experiments in literature

Experiments are still the most reliable way to find green water loading. A database with experimental results was developed for validation of the simulations [36]. Almost exclusively FPSO type vessels or container ships, or simplified structures (step structures and cubic shapes) have been researched [12]. The focus on FPSO's is because of the equipment on deck, but it is found that green water loadings are significant and should also be considered while designing other ship types [33].

Experimental work has been conducted by Buchner [7] and Greco [15] leading to insight into green water loading, both focussed on FPSO type vessels. From the 2D study by Greco [15], it is found that various aspects of the ship are of importance. From most to least influence on the loading: Freeboard, wave steepness, relative vertical motion, coupled flow between deck and outside, local flow at the bow, 3D effects, local design of deckhouse, stem angle, trim angle, hydro-elasticity during impact. Experiments are conducted, focussing on the influence of the bow overhang for a multipurpose cargo ship. This too is a factor in the resulting amount of green waters [3]. Also, an increase in green water was found with an increase of forward velocity [19]. Experiments using bubble image velocimetry techniques found the full green water velocities. A correlation between velocity and impact pressure was identified [49].

The most common form of water overtopping onto the deck is the dam-break scenario. This can be modelled with the Saint Venant shallow water equation implemented by Ritter [45]. Experiments show that this dam-break model captures the green water events reasonably well [46, 11]. The relationship between the initial water depth of the dam-break and the freeboard exceedance remains unclear [12]. In addition to dam-break solutions, shallow water equations are also directly applied to simulate green water flows [19, 37]. Green water can occur because of a negative freeboard as discussed in paragraph **??**. However, hammer-fist events can occur when there is a positive freeboard [15]. Still, research is conducted into finding the relative wave elevation to help predict the occurrence of green water [6, 20, 42, 13]. This has not resulted in a generalized method due to the complexity of wave-structure interactions and the non-linear sea states and dynamic structure responses [12].

Air entrapment

ADD A SUMMARY/INFORMATION FROM KIGER 2011 TO THIS TEXT (ALSO ABOUT NONDIMENSIONAL NUMBERS) "As a final closing comment to this discussion, we acknowledge that a mechanistic approach from direct observation also has its limitations, particularly when there is the potential for the nonlinear interactions of multiple dynamic processes."

When experiments are conducted, the problem is scaled down to fit inside test facilities. For green water experiments, scaling laws are violated for the effect of air entrapment. Air entrapment in scaled experiments can for instance lead to surface tension influencing the green water [17]. A high level of aeration can increase both the force and impulse on a structure [1].

Air entrapment is also relevant for coastal engineering [9], sloshing [40], and slamming events [21]. The literature from these research areas involving air entrapment is used to look into air entrapment. Through experimental research on waves impacting a vertical wall, it is found that small amounts of entrapped air lead to a significant increase in impact pressure. A large amount of entrapped air has a damping effect on the pressures [23]. With computational simulations, slamming events where air and water mix are also researched. Pockets of bubbles can cushion the pressures, while for small bubbles in the water the pressure oscillations are more intense [51]. Particle image velocimetry (PIV) combined with pressure sensors showed oscillating behaviour for air entrapment during sloshing [40]. The cushioning effect of air entrapment on the loading for a cylinder entering water is investigated numerically and experimentally [21]. Air entrapped for ocean waves impacting on sea walls is experimentally researched. It shows that air can be compressed to a pressure of several atmospheres and pressure shock-waves can lead to pressures comparable with those of the initial impact [5]. Research to improve numerical simulations of air entrapment has also been conducted in recent years [51?].

1.0.4 Theories of Interest

Waves on wall (sloshing), slamming (ship on wave) and green water (wave on ship), some similar physics, so when looking at one, look if you can use theories and research from the others. Mostly useful for air entrapment and scaling.

- Piston model of Bagnold 1939 (ELP3). Can partially correct for the compressibility bias (Lafeber 2012)
- Wagner 1932 (wedge entering water) (ELP2)
- Rankine-Hugoniot 1870, 1887, 1889 (ELP1)
- Braeunig et al.'s (2009) "Phenomenological study of liquid impacts through 2D compressible two-fluid numerical simulations"
- L. Brosset & J.M. Ghidaglia 2013
- Oumeraci, H. 1993, does what I want to do (classifying impact types on forces instead of visuals), but than for a wall
-

1.0.5 Simulations

Despite difficulties with the numerical simulations of green water, work continued. Work on the numerical simulation has been focussed on reducing the costs of calculations and increasing the quality. This research is also mostly conducted for FPSO type vessels or container ships, or simplified structures. Even though several numerical models have been developed to predict impact pressure, most of them are based on simplified assumptions such as inviscid and incompressible fluid, and single-phase flows [1].

One of the simulation methods is numerical time-domain simulations based on an incompressible flow solver operating on unstructured grids. It shows good agreement with experimental results [39]. An SPH method was used to simulate an extreme plunging wave impinging on the deck [48] and to predict the fluid behaviour for green water [34]. A hybrid CFD method involving linear seakeeping and nonlinear CFD analysis, both using 3D modelling of the hull, was introduced [32]. Also, a three-step method (CFD-BEM-FEM) has been introduced to evaluate the loads due to green water on a container ship [33]. The Natural Element Method (NEM) employs a CIP-based method and a particle method to simulate strongly nonlinear wave-body interaction problems and is promising to be a valid alternative for green water simulations [26]. A CFD method with VOF-multiphase and SST-turbulence gives access to high spatial resolution free surface position, water velocities and load distribution, phenomena usually not available from experiments [28]. Simulations with a multiphase-flow software based on a free-surface capturing method is used to evaluate green water for a Wigley hull. To reduce numerical diffusion at the free surface a solid-liquid-gas flow coupling model is developed by adopting Blend Reconstruction Interface Capturing Scheme (BRICS) [24].

From research into simulating green water loading with dam-break simulations it is found using a turbulence model, in this case k-ϵ turbulence closure, gives the most accurate simulation results [31]. By comparing vertical loadings found with experiments to simple potential theory-based simulations and commercial CFD code it was found that potential code is adequate to find vertical loadings due to isolated impact events [30]. A potential theory-based engineering tool called KINEMA3 is developed to predict wave-induced impact loads on FPSOs in steep irregular waves, and for use in design load analysis [47]. A combination of the KINEMA3 and a CFD tool using the finite volume VoF (STARCCM+) is introduced. KINEMA3 is used to generate inlet conditions and STARCCM+ to model detailed flow on the deck [43]. Another way of combining a potential and CFD tool is by using a potential solver which finds the motions of a vessel and then using a CFD solver to find the green water loading [57]. A numerical approach using potential theory in the frequency domain to predict the relative wave elevation response for an FPSO can also be used [54].

2 SETUP: NEW WAY OF INVESTIGATING NONLINEAR WAVE EVENTS

S:
Nonlinear wave events, like green water and slamming can lead to problems.
These event types are also very complex.
Main methods of investigating: experiments, some simulations
C:
Simulations still very expensive
Experiments done in towing tank or wave flume
Either limited testing times or no forward velocities
Can be overcome by knitting, but very expensive
Back in the day no problem, because limit on data we can handle
Not anymore, now the testing facilities and expenses are limiting
Large data sets needed for (name for what Sanne is doing)
This limited size of data sets possibly also prevents experimental data to be used for machine learning
Need for cheap method of generating large data sets for nonlinear wave impacts
Continues experiments would be perfect but not yet a facility for them
Q:
Experimental method needed that can cheaply generate data for loads of different nonlinear wave events
A:
Wave-current tank good option. Adapting flumetank by placing a wavemaker and beach on it
Does have limits (wave reflections, scale), but can give great insight into the stochastic of events like green water and slamming

Such a wave-current tank created
Green water experiments conducted to see if it works
Validated with green water experiments in towing tank (same model)

First insights from big data (to show value of such a test facility)

3 CONTINUOUS TESTING FACILITY

Because of these reasons this experimental facility will be created.
Existing flumetank is used
ALL INFO ABOUT EXISTING FLUMETANK

3.1 WAVEMAKER

Wavemaker: some design conditions
1: has to operate in flow (no obstruction but still good waves)
2: has to be operable within the dimensions of the tank
3: has to be able to make regular and irregular waves
Plunging wedge type wavemaker, based in theory developed over the years by Madsen [41], Wu [55], Lowell and Irani [38]
Designed for waves of a length between 0.05 meter and 3 meter with a maximum wave height over length of 1/50. These values are chosen because at maximum water depth the waves will be deep water to intermediate gravity waves in this range.
To move and control the wavemaker a servo motor (EMMT-AS-80-M-HS-RSB), servo motor controller (CMMT-AS-C3-11A-P3-EP-S1) and electric cylinder (ESBF-BS-50-300-10P-S1-R3) are used.

3.1.1 Waves wavemaker

HIER METINGEN VAN DE GOLVEN DIE GEMAAKT WORDEN (CONSTANT/SPREIDING, MAX, MIN, ONREGELMATIG)

3.2 BEACH

To minimize reflections which will interfere with the created waves, the waves should be dissipated as much as possible once they have moved passed the model
For this a beach is used.
Shape based on [25]. Parabola most effective, exact dimensions from this paper. Perforations are also found to be effective to reduce wave reflections, exact size based on Chegini [10].
Longest waves the largest reflection coefficients are found in previous research [50]. They also contain more energy compared to shorter waves on average, move faster thus could actually be able to move towards the model even if there is current, and they have the highest chance of influencing the results. Because of all these reasons the focus during the designing of the beach has been on damping these largest waves.

3.2.1 Effectiveness beach

HIER METINGEN VAN DE DEMPING VAN GOLVEN (VERSCHILLENDE REGELMATIGE GOLVEN, ONREGELMATIGE GOLVEN, VERSCHILLENDE STROOM SNELHEDEN)

3.3 VALIDATION FACILITY

HIER DE VERGELIJKING TUSSEN DE SLEEPTANK EN DE CONTINUOUS TESTING TANK

3.4 DATA HANDLING

Goal of test facility is to create large amounts of data, but we need to also save, store and work with this data
The data is obtained with the discussed equipment, and acquired with the NI USB 6009.
The data is saved in new files every X minutes using Labview, software from National Instruments.
Video footage is obtained and saved using the open source software Open Broadcaster Software (OBS).

3.4.1 Data analysis

To find the events the wetness sensors are used
EXPLAIN HOW I HANDLED ALL THE DATA

4 OBJECTIVE

The research proposed in this document should fulfill the project requirements set in the research proposal for workpackage B. The research should consider nonlinear extreme wave loadings. Also, the resulting data should be high fidelity and possibly lead to a reduced-order model. Lastly, it should give realistic results for expected lifetime loadings [29].

From the overview of literature shown in chapter **??**, research gaps are identified. Firstly, there is a need to investigate the statistical characteristics of green water in random waves [42, 11]. For complex phenomena, the use of full long-term analysis is advised for this [2]. Secondly, the effect of air entrapment on the green water loading is not cohesively researched, while it is known to affect experimental results [12, 17]. Also, loadings due to plunging and hammer-fist type events are not well-understood, while they are known to cause the largest loadings [1]. Lastly, it was found that almost all green water research has been conducted for FPSO vessels or simple geometries [12]. This means that it is difficult to predict green water loading for other types of vessels.

From the overlap of these gaps in previous research and the project objective, green water loadings on deck at the bow are chosen. The chosen subject should be relevant to society and there should not yet exist a way of anticipating the extreme wave loading. Green water fits this bill. Research into both the statistics and hydrodynamics of this problem will be conducted to work towards the end goal of developing a reduced-order model.

4.1 RESEARCH

The main methodology of the research will be experiments, as this is the only research tool that will give reliable data and statistics while staying affordable.

Firstly, long running experiments will be conducted to obtain long-term data. The long-term data set will allow for identification of extreme loading events, giving more insight into the hydrodynamics of the green water problem. The data from these experiments will also be used as input for a probabilistic model, the research subject of WP C (Sanne van Essen). To do these long running experiments, the existing flume tank will be adapted. The flumetank has an inlet and outlet on each end to create a constant current. Adaptations will be made as a wedge shaped plunging wavemaker and parabolic perforated beach will be added. The flume tank including these adaptations is shown in figure 4.1. This test facility will allow for continues experiments with waves and current to be conducted. It will become a fairly unique facility with many possibilities for future research.

Scaling effects will also be researched as lack of knowledge leads to inaccurate results for green water when scaled experiments are used in research. This is problematic because scaled experiments are the main methodology of researching green water. The scaling laws are broken for air entrapment during these experiments. If we know what the influence of scaling is and how that manifests in scaled experiments, a correction can be introduced. This correction will improve the quality of experimental results, thus improving any model based on the results. To find the scaling effects, parts of the long-running experiments will be repeated at larger scales in the two towing tanks of different sizes. Because of the statistical nature of

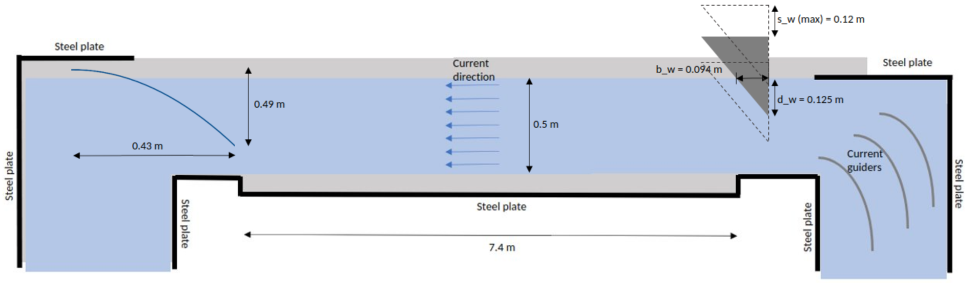

Figure 4.1: Sideview flumetank when wavemaker and beach are installed

the problem, it would be beneficial to not only look at irregular waves but to also test with wave trains. This is also a good idea because of long-running experiments are not possible in the towing tanks.

With the experimental research, data is obtained. By repeating the experiments at different scales, an indication of the fidelity of the data and what is not reliable about the data will become known. In combination with the results from the other two parts of the project, a multi-fidelity design tool will be created. The exact form this will take is dependent on the final form different parts of the project take.

4.1.1 Additional research topics

Possible additional research topics are found within the methodology. To find the lifetime loadings, long-running experiments with waves will be conducted. To achieve this the flume tank will be equipped with a wavemaker and a beach. It is an option to research the stability of the waves, the abilities of the wavemaker, or the effectiveness of the beach.

Also, data obtained from the experiments will have to be analyzed. Here, machine learning tools could be applied. From the literature study in section **??**, it is found that they show great promise, but their use within research focused on maritime applications has been limited.

The type of green water impact (dam-break, hammer-fist or plunging) is of importance to the loading found on deck. There are also different levels of understanding for each event. From small scale experiments without forward velocities and a stationary block, the type of event that occurs is found to depend on the relative wave height at the deck and the wave steepness [16]. Further improving the knowledge of when which events are expected will lead to an improvement of estimation methods for green water loading.

Almost all previous research has been conducted for FPSOs or simplified shapes. By experimentally investigating the lifetime loadings for structures not previously investigated, the understanding of the green water problem can be broadened. The applicability of previous estimation methods, possibly one from this research, on complex structures can be tested and possible improvements on the methods can be proposed.

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