Master Thesis
Laboratory experiments on the stability of concrete cubes; a comparison of testing methodologies
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Summary

A commonly used breakwater type is the rubble mound breakwater with double layer cubes. The armour layer of this breakwater structure is designed with the stability formula of Van der Meer (1988) and after such a design is completed, the stability (or other characteristics) of the breakwater structures is physically tested on scale in a laboratory. These physical laboratory tests should confirm that the breakwater structure is well designed.

A classical method to test the stability of breakwaters with physical tests is subjecting the structure to 4 wave series with the first wave series starting at 60% of the design conditions until 120% of the design conditions. The design conditions are a significant wave height calculated from a return period or required lifetime and a wave period which is assigned based on wave steepness. This method is not based on the shape of a storm and one could think that testing breakwaters with a more realistic storm shape would lead to more realistic damage results.

Martín-Hidalgo, Martín-Soldevilla, Negro, Aberturas, & López-Gutiérrez (2014) worked on theoretical storm models that produce theoretical storms that have similar damage evolution as what a real storm would have. This thesis continues on one of these theoretical storm models, if this is a correct model and if it can be used to replace or improve the classical testing method. Since there is no literature on how well this classical method performs, the quality of this method and the necessity of improving this method are also questioned.

UPC has a researcher working on this subject who is almost continuously assisted by students. Where a student of the UPC itself left of with the calculations and choices towards the structure and the wave loads, a TU delft student (author) continued with the preparations for the tests and conducting the tests.

In the phase before the tests, a study has been executed towards the wave climate from which the storm profile has been chosen (chosen by the UPC student). In this study was found that the chosen storm profile was one of the biggest storms that happened in the past >20 years as well in the significant wave height of the peak and the duration of the storm. Also was found that the wave steepness for the storms of this wave climate generally is constant towards the peak and decreasing after the peak, in contrary to the chosen storm profile which has more or less constant wave steepness.

While this study was done, the elements for the armour layer needed to be gathered. Due to the small scale, no elements for the armour layer were available and these needed to be constructed. On this small scale the use of concrete for the elements did not fulfill the demands, therefore was switched to a rather different material, resin with a piece of lead (to ensure the correct weight). After a few modifications the constructed cubes fulfilled the requirements and the breakwater structure could be constructed for the tests.

The cross section of the physical model consisted of a foreshore of 1:30 and the breakwater itself had a slope of 1:1.5. The armour layer consisted out of 2 layers of randomly placed cubes with a nominal diameter of 1.45 cm with an average porosity of 45%. The filter layer consisted of stones with a grading of stone diameter 7-10 mm and the core consisted of stones with diameters <7 mm. The water level in the flume was 30 cm and in front of the breakwater this was 13.3 cm. The crest of the breakwater was designed such that it should be a non-overtopped breakwater.

Towards the damage assessment various methods have been researched and it has been decided to do the standard visual counting method, in which pictures are taken before and after tests and the cubes that moved are counted. Next to the visual counting method a new method has been tried, where multiple pictures were taken of the breakwater structure and then transformed to a 3D model, this method is not used in this thesis to assess the damage but only for the purpose of calculating the porosity and the orientation of the filter layer.

First an orientation test was conducted to see when and how much damage occurs. The orientation test consisted out of steps of 500 waves with an increasing significant wave height of 0.5 cm every step. From this test was concluded that the threshold for the storm profile could be placed higher such that the duration of the storm decreased what was beneficial for the duration of the tests, further was decided not to change the severity of the storm since the damage that occurred was not categorized as too much.

The chosen storm was measured at a depth of 65m, and due to the water depth in the flume the storm needed to be transformed to a storm at a water depth of 24m. After this transformation the storm was divided into steps of one hour, with the wave period the amount of waves was determined. The significant wave height and wave period were scaled and on the significant wave height a coefficient was used to compensate for energy loss at the paddle. This storm has been conducted 7 times, with 5 different seeding numbers. Every step irregular waves were generated with a JONSWAP spectrum. The transformed and scaled storm profile is further addressed by as the real storm.
The equivalent magnitude storm model with an isosceles triangular shape was used to calculate the theoretical storm based on the real storm. The peak of this theoretical storm is equal to the peak of the real storm and the wave period was calculated based on the assumption of constant wave steepness throughout the storm. This storm was divided in 29 steps with duration between 323 and 408 waves. Also this storm was conducted 7 times with 5 different seeding numbers.

The classical methodology of verification was executed as explained above. Since the duration of the steps for the other storms was in an order of 300 waves per step this method was modified a little to have similar durations per step. Therefore the test program consisted out of 12 steps of 330 waves, where per every three steps the wave height increased. The incremental increase was 60%, 80%, 100% and 120% of the peak significant wave height of the real storm.

For some of the breakwater structures was before placement of the armour layer a 3D model created of the structure and after placement another 3D model was created. Before every test, after every step and at the end of every test images were shot of the armour layer. Based on these images the moved cubes were counted and $N_d$ was calculated. In the damage assessment it was concluded that not every cube contributed equally towards erosion. Since erosion is considered as damage, a new damage parameter has been introduced that based on the movement of the counted cubes takes into account the contribution of each cube.

Damage that occurred during the tests with the real storm has been compared to the damage due to the classical testing method, to discuss the performance of the classical method to represent a storm. From this comparison was concluded that the classical method performed exactly as it should for this real storm. Although the theoretical storm is not a real measured storm it could be considered as one, comparing the classical testing method with this storm shows that the duration of the 100% step is an important aspect of the classical testing method.

The applicability of the theoretical storm model was judged by comparing the damage due to the real storm and damage due to the theoretical storm. From this comparison has been concluded that the final damage due to the theoretical storm is low, but not significantly different. On the other hand, the damage evolution showed some similarities but the build-up of the damage during the theoretical storm went much slower than for the real storm. Based on both this theoretical model is not accepted as a good model to describe a real storm.

Since the duration of the steps in the classical method is considered as an important choice in how much damage will occur during the tests with this method, the main characteristics of storms that influence the amount of damage have been discussed. From the tested storms is found that above a specific significant wave height the greater part of the damage happens, that the build-up seems to be important as a stabilizing factor and that the tail of the storm is of no importance for the damage.

If damage evolution needs to be predicted the classical methodology of verification should be replaced by a methodology with a theoretical storm, but first the tested theoretical model is not the right model to produce a theoretical storm to simulate the real storm and second it should be taken into account that when testing with a storm profile, the testing time will increase significantly.

Finally it has been decided that it is possible to improve the classical methodology of verification by considering the duration of the 100% step based on the wave climate. However there is no clear relation between the duration of a storm and the significant wave height of the peak, which means that there are many combinations of $H_{\text{peak}}$ and duration which have the same probability of exceedance. Also the duration of the build-up (60% and 80% steps) could probably be increased for a better stability of the breakwater, but this is still under discussion. Without changing anything the classical methodology has still a good performance and with the safety factors and the 120% step there is no need to doubt the safety of the method. So, the classical method can be considered as a good method with useful results, but there is room for improvement on how conservative both the method and the safety factors are.
Preface

This MSc thesis is written in order to complete the Master Hydraulic Engineering at the Delft University of Technology. It reports a research study I performed on the performance of different laboratory testing methodologies on the stability of rubble mound breakwaters with double layered armour consisting of randomly placed cubes. With this research I hope to have enhanced more insight on the strength and weaknesses of different test methodologies and that with the information I gathered and analyzed steps can be taken towards new or improved methodologies.

The completion of this research would not be possible without the support of the following people. First of all I would like to thank my thesis committee Prof.dr.ir. W.S.J. Uijttewaal, Dr.ir. B. Hofland and Ir. J. Van den Bos for their helpful feedback, enthusiasm and guidance.

In particular I would like to thank A. Marzeddu from the UPC with whom I have closely worked together and for his help and support in the steps towards and during the physical model tests. Further I would like to thank Dr. X. Gironella and Dr. V. Gracia for their leading and supporting role in this research project.

Finally, I also want to thank the members of the research team at the Maritime Engineering laboratory for their help and knowledge in successfully performing the tests in the laboratory.

Jordi de Leau
January, 2017
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<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Surface area</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$A_e$</td>
<td>Erosion area</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$b$</td>
<td>Width of section</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$d$</td>
<td>Water depth</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>Grading of stones</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$D_{equiv}$</td>
<td>Theoretical storm duration</td>
<td>$[hr]$</td>
</tr>
<tr>
<td>$D_n$</td>
<td>Nominal stone diameter</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$D_{real}$</td>
<td>Duration of a measured storm</td>
<td>$[hr]$</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency</td>
<td>$[Hz]$</td>
</tr>
<tr>
<td>$f_{peak}$</td>
<td>Frequency of the peak of the spectrum</td>
<td>$[Hz]$</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational acceleration</td>
<td>$[m/s^2]$</td>
</tr>
<tr>
<td>$H_{equiv}$</td>
<td>Height of the peak of a storm above a certain threshold</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$H_{mo}$</td>
<td>Wave height calculated with the zero order moment</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$H_s$</td>
<td>Significant wave height</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$H_{peak}$</td>
<td>Significant wave height of the peak of a storm</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$H_T$</td>
<td>Threshold wave height</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$k(k_0, k_1, ..., k_n)$</td>
<td>Coefficients in Taylor series</td>
<td>[-]</td>
</tr>
<tr>
<td>$k_{L_d}$</td>
<td>Layer coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$L$</td>
<td>Wave length</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$L(r)$</td>
<td>Coefficient as a function of $r$ to determine lens distortion</td>
<td>[-]</td>
</tr>
<tr>
<td>$L_{prototype}$</td>
<td>The length unit on prototype scale</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$L_{scaled}$</td>
<td>The scaled length unit</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$M_{equiv}$</td>
<td>Theoretical storm magnitude</td>
<td>$[hr*m]$</td>
</tr>
<tr>
<td>$M_{real}$</td>
<td>Magnitude of a measured storm</td>
<td>$[hr*m]$</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of layers</td>
<td>[-]</td>
</tr>
<tr>
<td>$n_i$</td>
<td>number of samples of set $i$</td>
<td>[-]</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of elements moved more than one nominal diameter</td>
<td>[-]</td>
</tr>
<tr>
<td>$N_{od}$</td>
<td>Dimensionless damage parameter</td>
<td>[-]</td>
</tr>
<tr>
<td>$N_{od+}$</td>
<td>New dimensionless damage parameter</td>
<td>[-]</td>
</tr>
<tr>
<td>$N_{od,n-1}$</td>
<td>The value of $N_{od}$ of the $n$-1 step</td>
<td>[-]</td>
</tr>
<tr>
<td>$N_p, N_a$</td>
<td>Number of elements in a certain area</td>
<td>[-]</td>
</tr>
<tr>
<td>$N_s$</td>
<td>Number of samples</td>
<td>[-]</td>
</tr>
<tr>
<td>$N_{Z}$</td>
<td>Number of waves</td>
<td>[-]</td>
</tr>
<tr>
<td>$P$</td>
<td>Layer porosity</td>
<td>[%]</td>
</tr>
<tr>
<td>$r$</td>
<td>Is the distance from a certain point to the center of the image</td>
<td>[pixels]</td>
</tr>
<tr>
<td>$R_c$</td>
<td>Breakwater crest height</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$s, \sigma_N$</td>
<td>Standard deviation of a sample set</td>
<td>[-]</td>
</tr>
<tr>
<td>$S$</td>
<td>Dimensionless damage parameter</td>
<td>[-]</td>
</tr>
<tr>
<td>$s_{om}$</td>
<td>Wave steepness associated to the offshore mean wave period</td>
<td>[-]</td>
</tr>
<tr>
<td>$s_p$</td>
<td>Wave steepness associated to the peak wave period</td>
<td>[-]</td>
</tr>
<tr>
<td>$t$</td>
<td>Average layer thickness</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$t_{1-(\frac{a}{2})^{N-1}}$</td>
<td>The 100 $\times$ $(1 - \frac{a}{2})$ percentile of the $t$-distribution with $N$-1 degrees of freedom</td>
<td>[-]</td>
</tr>
<tr>
<td>$T_p$</td>
<td>Peak wave period</td>
<td>$[s]$</td>
</tr>
<tr>
<td>$v$</td>
<td>Degrees of freedom for $t$-distribution</td>
<td>[-]</td>
</tr>
<tr>
<td>$var_i$</td>
<td>Variance of sample set $i$</td>
<td>[-]</td>
</tr>
<tr>
<td>$V_{50}$</td>
<td>Average volume of a batch of stones</td>
<td>$[m^3]$</td>
</tr>
<tr>
<td>$w_r$</td>
<td>Density of stone</td>
<td>$[kg/m^3]$</td>
</tr>
<tr>
<td>$W$</td>
<td>Mass of individual stone unit</td>
<td>$[kg]$</td>
</tr>
<tr>
<td>$x$</td>
<td>$x$-location in image of distorted point</td>
<td>[pixels]</td>
</tr>
<tr>
<td>$x_c$</td>
<td>$x$-location of center of image</td>
<td>[pixels]</td>
</tr>
<tr>
<td>$\bar{x}, \mu_N$</td>
<td>The mean of a sample set</td>
<td>[-]</td>
</tr>
<tr>
<td>$X_{avg,i}$</td>
<td>Mean of sample set $i$</td>
<td>[-]</td>
</tr>
<tr>
<td>$y$</td>
<td>$y$-location in image of distorted point</td>
<td>[pixels]</td>
</tr>
<tr>
<td>$y_c$</td>
<td>$y$-location of center of image</td>
<td>[pixels]</td>
</tr>
</tbody>
</table>
\( \alpha \)  
Energy scale parameter in JONSWAP spectrum 

\( \gamma \)  
Peak enhancement factor in JONSWAP spectrum 

\( \gamma_H \)  
Partial safety factor for the wave height 

\( \gamma_s \)  
Specific weight of stone 

\( \gamma_w \)  
Specific weight of water 

\( \gamma_Z \)  
Partial safety factor for the strength of the breakwater 

\( \Delta \)  
Relative density of stone \( \frac{\rho_{\text{stone}}}{\rho_{\text{water}}} \) 

\( \rho_{\text{stone}}, \rho_{\text{water}} \)  
Density of stone and water \( [\text{kg/m}^3] \) 

\( \sigma \)  
Peak width parameter in JONSWAP spectrum 

\( \sigma_{\text{Hs}} \)  
Coefficient of variation 

\( \phi \)  
Packing density 

\( \phi_{\text{spm}} \)  
Packing density as mentioned in the shore protection manual
1. **Introduction**

1.1. **Background**

The primary purpose of rubble mound breakwaters is to prevent waves coming in their lee. The stability of the seaside armour is critical for the functionality of breakwaters. When a rubble mound breakwater is designed, its final design is often modeled in a physical model to assess its stability and based on results of the physical model either the design is accepted or adjusted.

Traditionally a stability test of a structure such as a rubble mound breakwater considers a combination of wave height and period. Such a combination of wave parameters is usually described by the significant wave height calculated from a return period and a required lifetime. The wave period is generally obtained based on the assumption of constant steepness (Owen & Allsop, 1984; Wolters, van Gent, Allsop, & Hamm, 2002).

In the most common testing method, a storm is often simulated as, a number of test runs with a fixed water level, increasing wave height and sometimes increasing wave period in discrete steps until damage occurs or the wave height reaches 120% of the design wave height (Owen & Allsop, 1984). The duration of each testing step should be between 3 and 10 prototype hours (Jensen, 1984) and Owen & Allsop (1984) suggested durations between 1000 and 5000 waves. Although commonly applied, this method has never been improved, also no literature can be found whether this method mimics the reality correctly. This testing method will further be addressed as the classical testing method.

Design of a breakwater is done based on design conditions, which originate from a given return period and analysis of historical wave data. Since storms are never exactly the same, testing a designed breakwater based on one measured storm would never be conclusive on its stability in other storms; which is most of the times compensated by increasing the storms’ severity. But to characterize a storm that is representable for all storms happening at a certain location, theoretical storm models are necessary.

Martín-Hidalgo et al. (2014) and Martín Soldevilla, Martín-Hidalgo, Negro, López-Gutiérrez, & Aberturas (2015) have performed an analytical analysis towards the comparison of theoretical storm models, with main aspect the influence of storm evolution on progressive damage to structures. As result some theoretical time dependence models to characterize storms were proposed.

Although the models proposed by Martín Soldevilla et al. (2015) and Martín-Hidalgo et al. (2014) describe a real storm quite well when measurements of a real storm are available, no explanation is given on how to obtain a theoretical storm as design storm when only the desired lifetime of a structure or return period is given.

For the design of a rubble mound breakwater Van der Meer (1988) proposed a formula on the stability of two layers of cubic armour. In later research Van der Meer (1999) included in the same formula the packing density.

The packing density has been studied by Van den Bosch et al. (2002) and later by Medina et al. (2014). Both concluded that the packing density is very important for the stability of a cubic armour breakwater, a significant increase of porosity leads to a decrease of stability, but a significant decrease of porosity (or increase of packing density) will also lead to a decrease of stability. Frens (2007) discussed the fact that the definition of the packing density is not always clear due to the use of different criteria, and also pointed out that the placement method is important towards the packing density.

In the classical testing method the rough steps with the increasing significant wave height show somekind of build up of a storm and the last steps are the design conditions (which could be referred to as the peak of a design storm) and even 120% of the design conditions. The length of the measurements of the peak of the storm can be half an hour (±150 waves), one hour (±300 waves) or even three hours (±1000 waves), since the suggested length of the timeseries is a minimum of 1000 waves the classical method can contain somekind of overload. This overload could cause more damage and as a result lead to more conservative designs and although this way of testing has proven itself valuable (enough), testing in a more realistic way could give more information on how a structure will react to certain circumstances.

A more realistic way of testing would be by testing with real measured storms, but as mentioned before, one storm does not represent all the storms of a certain wave climate. Therefore a storm produced with the theoretical models proposed by Martín Soldevilla et al. (2015) and Martín-Hidalgo et al. (2014), could be a realistic storm to test with. These theoretical models are solely based on an analytical analysis in which the model of Melby & Kobayashi (2011) has been used. So, at first these analytical analysis is not supported by any tests and second the damage progression model of Melby & Kobayashi (2011) has been proposed for stone rubble mound breakwaters and not specifically for cube armour layers.
1.2. Research question(s)

The stability of a breakwater design is usually verified by laboratory tests. Hydralab is an infrastructure network within Europe that focuses to strengthen the coherence of experimental hydraulic research to better address climate change adaptation issues. Within this infrastructure UPC collaborates in a project that aims to improve the methodology of verification, introducing the effect of storm evolution.

The objective of this Master Thesis is to perform the first part of the experimental research for this project and to make recommendations about possible improvements for the method of verification. In this recommendations is focused on the aspects of the final damage and damage progression due to the simulated storms and the spread in the results. Within this objective the wave climate measured with a buoy (XIOM at Blanes) should be discussed since the simulated storms are all based on the measurements from this buoy, but also design conditions are based on a wave climate.

The expectation is that the existing classical methodology of verification is a method that leads to too much damage of a designed breakwaters and that new methodologies or improvement of the classical one could lead to more accurate results from test, which could eventually lead to more accurate designs of breakwaters.

Therefore the following research questions are proposed:

Main research question

How could storms be simulated in the laboratorial tests, to obtain the most useful results on the stability of cubic armoured breakwaters?

Sub-questions

1) How are the results of stability tests on designed cubic armoured breakwaters comparable, if they are tested through the classical methodology of verification and a simulated real storm?

2) Could real storms be standardized and mimicked in laboratorial tests by using the EMSIT model, if only looking towards the stability of designed cubic armoured breakwaters?

3) What are the important characteristics of a storm that influences the amount of damage done by this storm?

4) Should the classical methodology of verification be replaced or improved, to obtain more accurate results on the stability of cubic armoured breakwaters?

1.3. Approach

The research questions have been answered with the following approach.

The breakwater structure that is used in the present study is a popular breakwater type in Spain; the breakwater is a rubble mound breakwater with a double layer of randomly placed cubic armour. This breakwater structure is similar to the breakwater Van der Meer (1988) used in his physical modelling research, the reason for this was because the stability formula for cubes is based on his setup.

In this research a chosen stormprofile has been produced in the wave flume that causes enough but not total damage during the entire storm. This storm profile is chosen from the climate measurements of the XIOM buoy at Blanes and the representability with the storm climate has been discussed. Based on the peak of this storm profile the classical testing method has been executed and based on the storm profile the theoretical storm has been calculated with the theoretical model for “the equivalent magnitude storm model with an isosceles triangular shape (EMSIT)” and has been produced in the flume aswell.

After repetition of these tests the behaviour of cubic armoured breakwaters under the different loads, focusing on the stability of the armour layer, should be clear.

After completion of the physical tests the description of the damage has been analysed, such that the damage parameter that is used in the comparisons takes into account the relevant failure modes.

For all the model storm types that have been tested the damage within one storm type is discussed. With the obtained mean values and standard deviations the simulated real storm have been compared with the classical testing method, to discuss the accuratness of the classical testing method.
Also is the comparability of the simulated real storm and the theoretical storm discussed, whether the EMSIT model is an appropriate model to represent a real storm, where the focus is on the total damage but also on the damage progression.

The results from the theoretical storm model and the real storm have been discussed to see what the main characteristics of a storm are on development of damage to the armour layer.

Finally with all the results obtained from the separate storm model types and the comparisons conclusions have been drawn to answer the research questions.

1.4. Outline

Chapter 2 – Literature study
In this chapter the theoretical background of testing methodologies, physical testing in general, breakwater stability and damage assessment is given.

Chapter 3 – Research methodology
In this section the physical model set up, test programs, damage assessment and result analysis is described.

Chapter 4 – Climate data analysis
The climate data of the XIOM buoy at Blanes is analyzed and described. From this data the real storm profile is taken and therefore also discussed.

Chapter 5 – Results
The results are gathered by the damage assessment explained in chapter 3. The observations on the breakwater structure in general are explained and per storm the damage results are given.

Chapter 6 – Analysis
In this chapter the obtained results are analyzed, the storms are compared and the main characteristics a storm that influences the damage are explained.

Chapter 7 – Discussion
In this chapter various observations and choices in the research are discussed.

Chapter 8 – Conclusion and Recommendation
Based on the results the conclusions have been drawn and answers have been prepared for the research questions. The necessary recommendations are given if and how to continue from this research.
2. Literature study

2.1. Theoretical storm models

Martín-Hidalgo et al. (2014) and Martín Soldevilla et al. (2015) published two papers in which storm evolution is investigated. Based on a storm profile, the wave momentum flux has been determined to calculate the progressive damage of rubble mound breakwater.

Martín-Hidalgo et al. (2014) and Martín Soldevilla et al. (2015) propose a theoretical time dependence model to characterize storms. The model is based on real data recorded in the Spanish Mediterranean sea and it reproduces the intrinsic characteristics of a storm. Thus, knowing the basic storm parameters, significant wave height of the peak of the storm ($H_{\text{peak}}$) and the storm duration ($D$), the model provides a synthetic storm which should have the same effects on the breakwater as the real storm from which it is transformed from. In the theoretical analysis 44 years of historical climate data, measured at the NE Mediterranean insular Spanish coast was used.

A theoretical storm model is a model with which it is possible to theoretically describe a storm based on real characteristics of the storm.

These characteristics are:
- Significant wave height at the peak of the storm ($H_{\text{peak}}$)
- Storm duration ($D_{\text{real}}$)
- Storm magnitude, which is defined by the surface area under the storm's profile above the chosen threshold ($M_{\text{real}}$)
- Number of waves of a storm, and
- Storm shape

The latter is the shape that is assigned to the theoretical storm instead of which the real storm has. In earlier models triangular shape was standard, but in recent study (Martín Soldevilla et al., 2015) different shapes were introduced like parabola and trapezium shapes.

The most important model, the one that gave the best results according to Martín Soldevilla et al. (2015), was also the triangular storm shape. With the theoretical model proposed by Martín Soldevilla et al. (2015) the real storm is transformed to a theoretical storm.

The proposed theoretical model is:
Equivalent Magnitude Storm model with an isosceles triangle shape (EMS$_{IT}$)

This storm model is based on the magnitude of the storm and has an, as the name says, isosceles shape. The way this theoretical model works is that a triangular shape is drawn above a certain threshold (wave height above which is considered that a storm is happening) where the peak wave height of the storm denotes the equivalent height ($H_{\text{equiv}}$) of the theoretical model, which is the top of the triangle. The base of the triangle is the theoretical storm duration ($D_{\text{equiv}}$). And this $H_{\text{equiv}}$ and $D_{\text{equiv}}$ are chosen such that the magnitude of the theoretical storm ($M_{\text{equiv}}$) is equivalent to the magnitude of the real storm.

An isosceles triangle shape means that the top of the triangle is in the middle of the theoretical duration, which means that the angles of the lower two corners are equal.

![Figure 2 Example ETMS model](image-url)
Also shown in the Table 1 is that the Equivalent Magnitude Storm model with a scalene triangle shape (EMSIT) and the Equivalent Magnitude Storm model with a trapezoidal shape (EMS_{trap}) shown similar results.

To support the analysis that has been done by Martín-Hidalgo et al. (2014) and Martín Soldevilla et al. (2015) the EMSIT and the EMS_{trap} should also be focused on, but this will not be done in this master thesis.

2.2. Significant wave height and wave period dependency

The only things that are known about the characteristics of the theoretical storm are the duration and the significant wave heights. From the theoretical storm profile a test plan is wanted, so the profile should be transformed into steps with each a significant wave height and a peak period.

Since from the theoretical storm profile only the significant wave height is available a corresponding peak wave period should be determined. There is no direct correlation between the peak wave period and wave height, so no “waterproof” theory exists to determine a peak wave period belonging to a given significant wave height.

Wave period in the classical testing methodology

This wave height and wave period dependency is a known issue. Based on the assumption that the wave steepness is constant during a storm, it is common that the peak period used during the tests increases/decreases with the significant wave height according to steepness relationship.

\[ s_p = \frac{2\pi H_s}{gT_p^2} \]  

In the papers of Martín-Hidalgo et al. (2014) and Martín Soldevilla et al. (2015) also other methods have been used to obtain a wave period for a significant wave height. In this MSc thesis the peak period is only based on the assumption of a constant wave steepness and therefore the methods used by Martín-Hidalgo et al. (2014) and Martín Soldevilla et al. (2015) are not considered.

2.3. Stability of two layers of cubic armour

The first stability formula for the stability of two layers of cubic armour has been proposed by Van der Meer (1988). This formula uses the relative damage (N_{od}), number of waves (N_z) and the wave steepness (s_{om}) to calculate the stability number.

\[ \frac{H_s}{\Delta D_n} = \left( 6.7 \frac{N_{om}^{0.4}}{N_z^2} + 1.0 \right) s_{om}^{-0.1} \]  

The stability number is expressed by the significant wave height (H_s), the relative density of stone (\Delta) and the nominal diameter (D_n), which in case of cubes the length of the side of the cube is.

In case of no-damage N_{od} = 0, the equation reduces to:

\[ \frac{H_s}{\Delta D_n} = 1.0 \times s_{om}^{-1.0} \]
Van der Meer (1999) has observed, after research of the influence of the packing density of tetrapods on the stability that the packing density seems to be of importance in the stability. Therefore Van der Meer (1999) updated the stability formulae for tetrapods including the packing density and also concluded that eq. (2) should probably be revised to:

\[
\frac{H_s}{D_n} = \left(6.7 \frac{N_{e,d}^{0.4}}{N_{e,s}^{0.3}} + 1.0 \cdot \left(0.4 + 0.61 \cdot \frac{\phi}{\phi_{spm}}\right) \right) \cdot s_{m}^{0.1} \cdot \left(1 + 0.17 \cdot \exp(-\frac{0.61 R_s}{D_n})\right)
\]

(4)

\(\phi\) = Packing density
\(\phi_{spm}\) = Packing density as mentioned in the Shore Protection Manual (Engineers, 1984)
\(R_s\) = Crest height

This has never been confirmed by research.

What specifically should be noticed from these two formulae is that the number of waves and the packing density do influence the resulting stability number.

The number of waves used during a physical model test in the classical method is often just assumed. And for the theoretical storm/proposed storm profile the duration of the storm classifies the number of waves, but the storm profile could be much different in duration and therefore in number of waves.

The packing density for randomly placed cubes is quite a difficult variable; randomly placing cubes means that when the breakwater is reconstructed several times the configuration of the blocks will never be the same. This means that locally but also on the entire structure the packing density of the armour layer could be different.

### 2.3.1. Packing density

The packing density have been proven to be important for the stability of a cubic armour layer of a breakwater (Medina et al., 2014; Van den Bosch et al., 2002), but to determine the packing density or the porosity of such an armour layer is not that easy. The packing density is related to the layer thickness.

To calculate the average layer thickness \((t)\) Hudson (1974) proposed the following formula:

\[
t = n \cdot k_\Delta \left(\frac{w_r \cdot 100}{W}\right)^{\frac{1}{3}}
\]

(5)

With the number of layers \((n)\), a layer coefficient \((k_\Delta)\), mass density of stone \((w_r)\) and the mass of an individual unit \((W)\). To determine the packing density \((\phi_{spm})\) the porosity \((P)\) in percent is added to the equation.

\[
\frac{N_r}{A} = n \cdot k_\Delta \left(1 - \frac{P}{100}\right) \left(\frac{w_r \cdot 2}{W}\right)
\]

(6)

\[
\phi_{spm} = n \cdot k_\Delta \left(1 - \frac{P}{100}\right)
\]

(7)

Hudson (1974) had not done tests for regular cubes, so no \(k_\Delta\) is available for cubic armour layers. The type of armour layer that comes closest is the modified cube (Figure 3).

For the modified cube:
- Layer coefficient \(k_\Delta = 1.1\)
- Porosity \(P = 47\%\)
- Packing density \(\phi_{spm} = 1.17\)

Van der Meer (1999), proposed a quite similar formula:

\[
\frac{N_r}{A} = \frac{\phi}{D_n^2}
\]

(8)

With \(N_r\) = the number of units, \(A\) = the surface area and \(\phi\) = the packing density.
Since there have been some misunderstandings on how \( k_3 \) is defined (see Frens 2007), Medina, Gómez-Martín, & Corredor (2010) proposed a criterion, valid for randomly placed armour units; the armour porosity, \( p = (1-\phi/n) \). For this criterion the layer coefficient of \( k_3 = 1.00 \). This means that for a two layer system the thickness of the layer is assumed to be equal to 2Dn. The \( p \) for armour porosity here is different than the \( P \) (capital) used by Hudson (1974).

Important to note is that although maybe a certain porosity is wanted, which is also easy to realize on small scale, on prototype scale it is challenging to realize randomly placed cubes with \( p \leq 35\% \) (Medina et al., 2010; Pardo, Herrera, Molines, Medina, & Asce, 2014).

### 2.3.2. Safety factors

When breakwaters are designed there are different methods that can be applied to introduce extra safety in the design. When enough input data is available probabilistic design methods can be applied, but when this is not the case or one wants to safe time partial safety factors can be applied.

In the Coastal Engineering manual (Engineers, 2002) the following equations is used for the design of armour layers with cubes including the safety factors:

\[
G = \frac{1}{\gamma_Z} \cdot \left( 6.7 \left( \frac{N_{oa}}{N_Z} \right)^{0.4} + 1.0 \right) \cdot s_{am}^{-0.1} \cdot \Delta \cdot D_n \cdot \gamma_H \cdot H^2
\]

Where the safety factors \( \gamma_Z \) and \( \gamma_H \) depends on the probability of failure and the coefficient of variation.

<table>
<thead>
<tr>
<th>( P_f )</th>
<th>( \gamma_{FRS} = 0.05 )</th>
<th>( \gamma_{FRS} = 0.2 )</th>
</tr>
</thead>
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<td>1.10</td>
</tr>
<tr>
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</tr>
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</tr>
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<td>1.2</td>
<td>1.00</td>
</tr>
<tr>
<td>0.4</td>
<td>1.0</td>
<td>1.08</td>
</tr>
</tbody>
</table>

Table 2 Partial safety factors for stability failure of cube block armour

### 2.4. Damage assessment

The damage assessment will be done by a physical analysis explained below.

“Although it is relatively easy to define armour damage, it is not so easy to formulate a standardized quantitative definition for armour damage that is valid for all armour units, slopes, sizes, and number of layers.” (M E. Gómez-Martín & Medina, 2014)

First the criteria for qualitative damage will be defined.

The qualitative damage will be divided in four armour-damage levels, similar to the damage levels defined by M E. Gómez-Martín & Medina (2014).

1. Initiation of Damage, when the upper armour layer has lost some units;
2. Initiation of Iribarren’s Damage, when damage in the upper armour layer has spread over an area large enough to permit the extraction of units from the bottom armour layer;
3. Initiation of Destruction, when at least one unit from the bottom armour layer has been removed and the filter is clearly visible; and
4. Destruction, when several units have been removed from the filter layer.

The qualitative armour-damage to the breakwater will be based on pictures that will be taken during each test run.

Quantitative damage will be determined based on a method that is proposed in literature.

- **Visual counting method**, as reported by (Vidal et al., 2003) assuming constant armour porosity during the erosion process.

**Visual counting method**

With the visual counting method, the eroded area that can be observed visually in the breakwater section is defined using the moved elements \( (N) \) and using Eq. (10) to obtain the visual dimensionless damage parameter \( (N_{oa}) \):

\[
N_{oa} = \frac{N \cdot D_n}{[b]}
\]

(10)
With \( b \) = width of breakwater section to be considered. Note that the definition for an element to be counted as moved element, it should move more than one \( D_n \).

“The main drawback of the classical method is that it does not take into account changes in porosity of the armour layer.” (María Esther Gómez-Martín & Medina, 2006)

Van den Bosch et al. (2002) considered a new parameter \( N_{on} \) which included different failure modes of the elements. For this new parameter three different forms of damage are considered, where each form is multiplied with a constant to give it a weight to the particular form of damage.

**Dimensionless damage parameter** \( S \)

Damage can also be expressed with the dimensionless damage parameter \( S \), which is calculated with Eq. (11).

\[
S = \frac{A_e}{D_{n50}}
\]

In which:
- \( A_e \) = the erosion area in a cross-section in \([m^2]\]
- \( D_{n50} \) = the nominal stone diameter, in case of cubes this is equal to one side of the cube

**Lens distortion**

For the damage assessment Gopros are used to take pictures, but Gopros have a fish-eye effect which distorts the photographs. Lens distortion is in most cases due to lens imperfections and optical system misalignments. Possibly considered as the most important lens distortion for low-cost cameras (like Gopros), is the lens radial distortion (Alemán-flores, Alvarez, Gomez, & Santana-cedrés, 2014).

A standard and basic model for the correction of distortion is discussed by Alemán-flores et al., (2014).

\[
\left( \hat{x} - x_c \right) = L(r) \left( x - x_c \right), \left( \hat{y} - y_c \right) = L(r) \left( y - y_c \right)
\]

With \((x, y)\) is the location of the distorted point, \((\hat{x}, \hat{y})\) is the location of correction of the point, \((x_c, y_c)\) is the center of the image, \( r = \sqrt{(x - x_c)^2 + (y - y_c)^2} \) and the distortion’s model shape is defined by \( L(r) \). \( L(r) \) can be approximated with a Taylor series.

\[
L(r) = k_0 + k_1 r^2 + k_2 r^4 + \ldots
\]

The values for \( k \) \((k_0, k_1, k_2, \ldots, k_n)\) are the distortion parameters and should be calculated from image measurements, which can be done with computer programs that impose that the 3D lines in the image should be straight 2D lines (Alemán-flores et al., 2014).

### 2.5. Physical model testing

In physical model testing, the characteristics of the sea and the structure are reproduced as good as possibly to get a result that is representative for what could happen on prototype scale. Since most physical models are tested on a scaled down version there are important aspects to take into account.

#### 2.5.1. Scaling

The first/most important aspect is the element that is going to be tested/used. The armour unit shall be smaller size based on the scale which is conform Eq. (14).

\[
L_{scaled} = \frac{L_{prototype}}{scale}
\]

By changing the size it does not mean that the weight of the element is scaled down correctly as well. The solution for this is to determine the model unit specific weight with Eq. (15) (Hughes, 1993). Normally this should be equal to the prototype unit specific weight, but since the tests are done in fresh water while the prototype would be subjected to salt water, the difference in specific weight of water should be accounted for.

\[
\left( \frac{Y_e}{Y_w} \right)_{prototype} = \left( \frac{Y_e}{Y_w} \right)_{scaled}
\]
2.5.2. Testing procedure
The following procedure is the procedure for the classical testing method, but some parts of the procedure could be used for other methods as well.

Settlement of structure
After construction of the breakwater model the structure should be subjected to lower energy waves to induce settlement of the top layer and create better stability. By some literature is suggested to use waves with 50%-60% of the intended test conditions (Hughes, 1993).

The classical testing method
This method starts with the settlement step and each of the following steps has an increased significant wave height. Continue to increase the significant wave height until 120%. Depending on the requirements that the structure should fulfill the tests could be stopped before reaching 120% (Owen & Allsop, 1984). Until the 100% step represents a real storm and the 120% step is most of the times too see what happens when the breakwater is subjected to a higher load.

Different periods and water depths can be applied in different tests. The length per testing step should be in between 1000 to 5000 waves to represent typical storm durations (Owen & Allsop, 1984).

Repeatability
Although similar results due to the similar used forcing could be expected, various factors and specially the unequal placement of the armour layer causes significantly differences in stability (Hudson, Herrmann, & Sager, 1979). The suggested amount of repetitions is 3 to 5 per wave condition (Hughes, 1993).

2.5.3. Random realization wave pattern
For the generation of the waves in the wave flume the paddle is driven by a signal from a computer. This signal is a random pattern for the horizontal movement of the paddle. This random pattern is constructed from a JONSWAP spectrum (Hasselmann et al., 1973). Such a spectrum is described with the following equation.

\[
E_{\text{JONSWAP}}(f) = a g^2 (2\pi)^{-4} f^{-5} \exp \left[-\frac{5}{4} \left(\frac{f}{f_{\text{peak}}}\right)^{-\frac{5}{4}} \gamma \exp \left[\frac{1}{2} \left(\frac{f}{f_{\text{peak}}} - \gamma\right)^2\right]\right]
\]  (16)

Where \( \gamma \) is a peak-enhancement factor, the standard value of 3.3 has been used, \( \sigma \) = the peak-width parameter which is 0.07 on one side of the peak and 0.09 on the other side and \( \alpha \) is an energy scale parameter for which 0.0081 is used.

2.6. Student-\( t \) test
For the calculations of the confidence boundaries of a mean and the comparison of two means the student-\( t \) test is used.

Confidence boundaries
To calculate the confidence boundaries Eq. (17) is used.

\[
\bar{X} \pm t_{\frac{1-\alpha}{2},N-1} \cdot \frac{s}{\sqrt{N_b}}
\]  (17)

Where:
\( \bar{X} \) = the mean of the samples
\( s \) = the standard deviation of the samples
\( N_b \) = the number of samples
\( t_{\frac{1-\alpha}{2},N-1} \) = the 100(1-\( \alpha \)/2) percentile of the t-distribution with N-1 degrees of freedom

Knowing the confidence level (1-\( \alpha \)) the value for \( t \) can be determined with Eq. (18), the cumulative distribution function of Student’s \( t \) distribution.

\[
p = F(t|\nu) = \int_{-\infty}^{t} \frac{1}{\sqrt{\nu\pi}} \cdot \frac{1}{\left(1 + \frac{t^2}{\nu}\right)^{\nu/2}} dt
\]  (18)

Comparison of two means
When for example the damage due to the real storm is going to be compared with the damage due to the classical testing method, the means of the samples of each set are compared.
This can be done by calculating the t value with Eq. (19).

\[
t_t = \frac{X_{\text{avg},1} - X_{\text{avg},2}}{\left(\frac{(n_1 - 1) \cdot \text{var}_1 + (n_2 - 1) \cdot \text{var}_2}{n_1 + n_2 - 2}\right)^{1/2} \cdot \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}
\]

(19)

Where:
- \(X_{\text{avg},i}\) = the mean of sample set \(i\)
- \(n_i\) = number of samples of set \(i\)
- \(\text{var}_i\) = the variance of sample set \(i\)

When the t value is calculated it can be entered into Eq. (18) and the p-value can be determined. A decision should be made whether to use a two-tailed or one-tailed distribution.

A one-tailed distribution is used when assumed is that one of the two means is larger than the other one, this should be decided before gathering the data and when the other set ended up to have the larger mean the difference is due to chance and is called 'not statistically significant'. In the case of an one-tailed distribution the p-value obtained shows that there is a chance of \(p \times 100\%\) of observing a difference that is as large or even larger than observed even if the means of the populations are exactly identical.

A two-tailed distribution is used when on forehand none of the sets is assumed to be the larger one and therefore the difference can go in every direction. In the case of a two-tailed distribution the p-value obtained shows that there is a chance of \(2 \times p \times 100\%\) of observing a difference that is as large or even larger than observed even if the means of the populations are exactly identical.
3. Research methodology

3.1. Physical model set-up

3.1.1. CIEMito Wave Flume
The wave flume that has been used to execute the stability tests in is located at the Polytechnic University of Catalonia.

The specifications of this flume are:
- Length: 18m
- Width: 0.38m
- Height: 0.56m
- Maximum water depth: 0.36m
- Wave generation is conducted using a piston-type board.
- Maximum theoretical wave height: 0.28m
- Maximum theoretical wave period: 1.7s

3.1.2. Scaling
The tests that have been conducted did not serve the purpose of verifying a design. This means that there is no specific size of structure that needs to be scaled down such to fit in the wave flume. Although to have some kind of reference it is chosen to work with the same design for the breakwater structure as Van der Meer (1988) worked with, because the stability formula for cubes from the same paper is based on this design. Due to the size of this design the structure still needs to be scaled down by a factor of 3, giving a length scale \( N_L \) with prototype of 80. The material and fluid density have not been changed in this MSc thesis, so the scale parameters \( N_\gamma \) and \( N_\rho \) are both 1.

3.1.3. Cross-section
In Figure 4 the structure used by Van der Meer (1988) is shown and in Figure 5 the structure that is going to be used for this MSc thesis:

![Figure 4 Breakwater structure used by Van der Meer (1988)](image)

![Figure 5 Breakwater structure that is going to be used for this master thesis](image)

To be able to create the foreshore with a slope of 1:30 the width of the flume decreased to 34.5 cm which is the total width of the breakwater structure.
Core
The core consists of sand with $D_{50} < 0.7 \text{ cm}$.

Filter layer
Consist of rubble stone with the following characteristics, $D_{50} = 0.7 - 0.10 \text{ cm}$.

Armour layer
Exists out of 2 layers of cubic armour, the cubes are made out of resin with a piece of lead in the middle the dimensions are; volume $V_{50} = 3 \text{ cm}^3$, mean $D_{a50} = 1.451 \text{ cm}$ with a standard deviation 0.04 cm and the density of the cubes is $\rho = 2.242 \frac{g}{cm^3}$.

Water depth
The water depth in the flume is chosen to be 13.30 cm in front of the toe and 30 cm in front of the foreshore. This means that the water depth in front of the foreshore is 24m on prototype scale. The storm that is chosen for these experiments is measured at a water depth of 65m and therefore, due to processes that influence the wave height, SwanOne is used to calculate what the wave heights of the storm would be at the location where the water depth is 24m.

To move the real storm at a water depth of 65m to the location with a water depth of 24m the coefficient of wave increase/decrease shall be used. This coefficient will be determined with SwanOne by using as input a 1m wave height. This coefficient is different with different wave periods, so to determine the trend of this coefficient for wave periods; SwanOne calculated this coefficient for every second starting with 5 and ending at 15.

In Figure 6 the relationship of the peak wave period with the wave height propagation coefficient on the depth of 24m is given. This relationship is calculated with SwanOne and the trend line is determined with Excel. Using this trend line the real storm profile is transformed to the storm profile at a depth of 24m, by multiplying the significant wave heights with the coefficient described by the formula where $x$ corresponds to the wave period. On average the significant wave height has decreased with 20cm.
3.1.4. Cubes
The necessary elements for the armour layer were not yet present at the start of this MSc thesis, and therefore needed to be constructed.

Density
To overcome scaling errors in the weight of the elements the density of the element should be such that it is comparable to the density of the prototype elements, taking into account that in the flume fresh water is used. To determine this density the relative density $\Delta$ is used which should be equal for the prototype scale and experimental scale.

$$\Delta = \frac{\rho_{\text{element}} - \rho_{\text{water}}}{\rho_{\text{water}}}$$  \hspace{1cm} (20)

The cubes used in the research of Van der Meer (1988) had a $D_{n50} = 4.5$ cm and a weight of 204 grams, thus a density of 2.24 gr/cm$^3$. This means that the prototype density is 2300 kg/m$^3$, which seems to be a little underestimated assuming reinforced concrete, but since the target is to reproduce a scaled version of the breakwater structure as Van der Meer (1988) used the density of 2.24 gr/cm$^3$ is used as target density.

Material
Prototype elements are normally constructed out of concrete (a mix of cement and stones) and reinforcement bars. The size the cubes need to be for this MSc thesis do not allow the use of reinforcement bars and stones, therefore a mixture of cement, sand and scraped lead was tried to use to construct the cubes. The lead was a necessary supplement, because cubes constructed of only cement and sand did not reach the required density. For some reason the cubes made with a mixture of cement, sand and lead were not strong and consistent cubes, which made these cubes not useable.

The decision was made to use resin instead of cement and sand and since resin has the characteristic to harden quickly, it was possible to construct the cubes in 2 phases placing a piece of lead in the middle to reach the required density.

The density of the resin is 1.124 gr/cm$^3$, the density of the lead is 10.787 gr/cm$^3$ and with a cube volume of +/- 3 cm$^3$ a piece of lead with a weight of 7.6 gr was needed.

In Appendix III the construction of the cubes is considered.

Fairness
The construction of these cubes is completely done by hand and this causes inaccuracies in the final product, due to these inaccuracies and the rather different composition compared to prototype cubes it could be that the cubes are not “fair”. The term fair is used as in the same context for dices, that when rolling a dice not one side is more likely to be on top than the other sides. Since the cubes are comparable to dices, the cubes have also been tested on fairness. 7 randomly chosen cubes were numbered on each side like a dice and been thrown 200 times. From the first observation some of the cubes seemed fair but also some didn’t and this seemed to be because of the roughness of the top of the cube due to the construction process.

By sanding each side, and mainly the top side, of the cubes another set of 150 throws was done for each of the unfair dices and the sanding showed significant improvement.

So after sanding the cubed it can be said that if the dice are actually fair a $\chi^2$ of 8.8 will show up in 88.27% of all the tests, which is the highest $\chi^2$ value obtained for the 7 cubes. The fairness is quite important, because the intention is that prototype cubes are fair. But due to clustering of stones and/or air bubbles it quite easy to state that these are not completely fair as well

Moment of inertia
Comparing the design of the resin cubes (cube1) with cubes with evenly distributed weight (cube2) it can be said that the moments of inertia around any axis through the middle of the cube will be different.

With the piece of lead in the middle, surrounded by much lighter resin, the moment of inertia will be smaller than for a cube2. And due to the lower moment of inertia less force is needed to reach a similar angular velocity for cube1 as for cube2.
As mentioned before all the cubes are handmade and therefore the moment of inertia is not equal for every cube and hard to determine.

But with a simplified calculation the real moment of inertia can be approached, by assuming a cube with a piece of lead exactly in the middle in the shape of a sphere.

This shows that the moment of inertia for cube1 is about 1.36 gr*cm$^2$ and for a cube2 this is 2.28 gr*cm$^2$. This difference means that with less force the resin cube will have the same angular velocity as a cube with evenly distributed weight.

When the rotation happens around a point outside of the body of the cube the force needed to rotate the cube is the same in both cases, since the point of action of the total weight of the body is for both cubes in the middle and the total weight for both cubes is also the same.

Finally it can be concluded that when the resin cube is not supported at all it is more likely to rotate, but when it is lying on a slope it will not rotate around its middle but around the support points and since the cubes are generally always supported the different moment of inertia has not influenced the damage that occurred.

**Colors**
All the cubes contain a specific color, the colors used are:

- Black
- White
- Blue
- Red

The use of these colors makes it easier to see if something happens and where it happened. Also the cubes are all numbered with a unique number, by knowing the exact location of each cube at the beginning of a test run the movement of every cube could be tracked down.

The configuration of the colors is shown in Figure 8 and Figure 9. This is the configuration for the first tests, the location of the color separation is in all the other tests the same, but sometimes the colors are switched from location. In the damage assessment this did not caused any problems.

![Figure 8 Cubes set up for the first layer (bottom layer)](image1)
![Figure 9 Cubes set up for the second layer (top layer)](image2)

**Packing density and number of blocks**
It is tried to reach the same packing density ($\Phi$) of 1.17 used by Van der Meer (1988), which is equal to a porosity of 41.5%.

With the formula in section 2.3.1 proposed by Van der Meer (1999) and the formula proposed by Medina et al. (2010):

$$p = \left(1 - \frac{\Phi}{n}\right)$$  \hspace{1cm} (21)

$p = \text{porosity}$

$n = \text{number of layers}$

With the following formula the porosity is obtained:
\[ p = 1 - \frac{N_n + D_n^2}{n \times A} \]

\( N_n = \text{number of blocks} \)
\( A = \text{surface area of the slope} \)

With the dimensions of the structure, the porosity of 41.5% and the formulas a total of 690 cubes should be needed for the armour layer. The target is therefore to place 690 cubes for the armour layer due to the randomness of the placement it is possible that the cubes are placed too dense or to open and therefore it is possible that the amount of cubes varies around this number.

The placement of the cubes looked like the closed pyramid placement method discussed by Frens (2007). Frens (2007) applied this method on antifer elements to reach a porosity of 45% to 50%. But it was not tried to reach a certain pattern since the cubes should be randomly placed and therefore differ every test.

Due to measuring the filter layer in 3D and measuring the armour layer after placement in 3D it is possible to subtract one from the other to obtain the armour thickness and this can be done locally. The armour thickness is closely related to the porosity and therefore to the damage.

3.1.5. Equipment

For the measurement of the produced waves, 8 wave gauges will be used. Where 4 are placed near the wave paddle and 4 are located near the breakwater.

The damage assessment will be done by means of taking photographs, with comparing the photographs before and after a test the number of cubes that moved can be counted.

For the photographs, Gopros will be used.

The used Gopros are:
- Gopro Hero 4 Silver
- Gopro Hero 3+

One Gopro will be mounted in a steady position parallel to the slope of the structure, such that the view is perpendicular to the slope. This Gopro will take photographs before, during and after test runs.

The other Gopro has been used to take photographs from different angles. In total on average about 50-70 pictures are taken, this amount guarantees an accurate 3D model.

The settings of the Gopros are:
- 12 megapixels
- Wide

The reasons why Gopros are used are:
- The program that is used to generate 3D models, works good with pictures from a Gopro.
- The wave flume is quite small to work in and because of the size of the Gopro it is an excellent piece of equipment to work with.

The use of Gopros has also a disadvantage and that is the large inaccuracy because of the ‘fish eye’ mode.

3.2. Test Program

In Appendix I the test plan of each individual test is shown. In this chapter the plan per type of storm is briefly explained.

3.2.1. Realization of the random waves

For the realization of the random wave pattern the JONSWAP spectrum is used, which is constructed from the significant wave height and peak period. The spectrum is discretized in frequencies every 1 mHz, each frequency is associated to an amplitude and a transfer function is applied to translate each amplitude to the stroke of the paddle.

To every harmonic wave is a random phase applied, a random phase is applied to each frequency so each of the frequencies has its own unique phase. Although it is called random, within a seeding number the order of which frequency is associated with which phase does not change.
By summing up all the harmonic waves with each its own phase the pattern for the paddle movement is obtained and since the seed number affects the association of phases with frequencies, the seeding number changes the wave pattern.

In this research testing methodologies are compared and the conclusions drawn should not be covering only one seeding, but should be applicable for any seeding number. Also with testing methodologies it is tried to simulate the response of a breakwater to storms that could happen in reality. Storms in reality are always different and therefore there is not one specific seeding number that describes reality the best possible.

Based on the arguments above it has been decided to use different seeding for every test run, but due to big differences in the damage it has also been decided to have for every test type 3 test runs with identical seeding number to see if the big differences are because of the different seeding numbers.

### 3.2.2. Orientation Test

Since there was no clear idea on when and how much damage will occur, a first test has been done to see the response of the breakwater structure when it is subjected to a certain test program.

The first test has a lot in common with the classical testing method, because in this test the wave height increases per test and the wave period is given based on constant steepness.

The only difference is there are no big steps of 20% between every run, but the wave height in the flume is increased with half a centimeter each run starting with 1.875 cm (which is 1.5 m on prototype scale). The wave height has been increased until severe damage happened.

In Table 3 the orientation test is shown as how it has been executed.

### 3.2.3. Real storm

With the storm testing method the real storm has been reproduced on small scale in the flume. The real storm has been reproduced as accurate as possible by taking the characteristics ($H_s$, $T_p$) of every measured hour of the storm as one single step. Due to this choice the duration of the sea states is within 252 and 396 waves.

For the real storm the peak period associated with the significant wave height is used. This test program for the real storm has been executed 7 times, from which 3 have the same seed number for the random realization of the wave pattern and the rest have a different seed number.

In Figure 10 the test program for the real storm is shown. The bar height indicates the significant wave height and on the horizontal axis’s the step numbers and number of waves are given. On average the test steps are 327 waves long, and take 360 seconds to complete. The total duration of the storm is therefore 9166 waves which is almost 3 testing hours (excluding the time between each test step).

Note that the red and the blue bars indicate the entire program as planned, but only the blue steps were executed since the steps 19 until 22 in most cases did not show any increase of damage anymore.

<table>
<thead>
<tr>
<th>ID</th>
<th>$H_s$ [cm]</th>
<th>$T_p$ [s]</th>
<th>$N_e$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-1</td>
<td>1,875</td>
<td>0,75</td>
<td>500</td>
</tr>
<tr>
<td>O-2</td>
<td>2,375</td>
<td>0,85</td>
<td>500</td>
</tr>
<tr>
<td>O-3</td>
<td>2,875</td>
<td>0,94</td>
<td>500</td>
</tr>
<tr>
<td>O-4</td>
<td>3,375</td>
<td>1,02</td>
<td>500</td>
</tr>
<tr>
<td>O-5</td>
<td>3,875</td>
<td>1,09</td>
<td>500</td>
</tr>
<tr>
<td>O-6</td>
<td>4,375</td>
<td>1,16</td>
<td>500</td>
</tr>
<tr>
<td>O-7</td>
<td>4,875</td>
<td>1,22</td>
<td>500</td>
</tr>
<tr>
<td>O-8</td>
<td>5,375</td>
<td>1,29</td>
<td>500</td>
</tr>
<tr>
<td>O-9</td>
<td>5,875</td>
<td>1,34</td>
<td>500</td>
</tr>
<tr>
<td>O-10</td>
<td>6,375</td>
<td>1,40</td>
<td>500</td>
</tr>
<tr>
<td>O-11</td>
<td>6,875</td>
<td>1,45</td>
<td>500</td>
</tr>
<tr>
<td>O-12</td>
<td>7,375</td>
<td>1,51</td>
<td>500</td>
</tr>
<tr>
<td>O-13</td>
<td>7,375</td>
<td>1,51</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 3 Test plan orientation test
3.2.4. Classical testing method

In the classical testing method explained by Owen & Allsop (1984), the significant wave height of the peak of the storm with its corresponding wave period will be produced in the flume at 60%, 80%, 100% and 120%. The wave steepness has been kept constant such that the wave period follows the increase of the wave height.

Due to the transformation of the storm from the location with a water depth of 65m to a location with a water depth of 24m the peak of the storm decreased a little to 4.32 m with a wave period of 11.8 s.

Since in the tests with the real storm an error occurred between the target $H_s$ and produced $H_s$ due to the number of waves per step, it has been decided to not do complete steps of 1000 waves in this testing method but to split this 1000 waves in steps of 330 waves. In this case test step durations are in all methods comparable and therefore errors originating from this duration should be of similar order for all the methods. To keep the variation in the 1000 waves, the seeding for the random realization of the wave pattern is different per step.

In Table 4 the test program is given with the significant wave height per step and an associated peak period based on a constant wave steepness of 0.02 and this test program is also shown in Figure 11. The 120% steps are shown in green since these are not the steps that are interested for the comparability. In Table 4 the seeding is also given per step, but this is just to have an indication how the seeding differs in one test program and not the exact seeding number as has been used in the tests. Every test step is 330 waves long and due to constant wave steepness, the duration per step increases with the increase of the significant wave height. The total duration of the classical testing method is 3960 waves which is equal to 1 hour and 15 minutes (excluding the time between each test step).

<table>
<thead>
<tr>
<th>ID</th>
<th>$H_s$ [cm]</th>
<th>$T_p$ [s]</th>
<th>$N_z$ [-]</th>
<th>Seeding</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM60</td>
<td>3.24</td>
<td>1</td>
<td>330</td>
<td>1</td>
</tr>
<tr>
<td>CM60</td>
<td>3.24</td>
<td>1</td>
<td>330</td>
<td>2</td>
</tr>
<tr>
<td>CM60</td>
<td>3.24</td>
<td>1</td>
<td>330</td>
<td>3</td>
</tr>
<tr>
<td>CM80</td>
<td>4.32</td>
<td>1.16</td>
<td>330</td>
<td>1</td>
</tr>
<tr>
<td>CM80</td>
<td>4.32</td>
<td>1.16</td>
<td>330</td>
<td>2</td>
</tr>
<tr>
<td>CM80</td>
<td>4.32</td>
<td>1.16</td>
<td>330</td>
<td>3</td>
</tr>
<tr>
<td>CM100</td>
<td>5.4</td>
<td>1.32</td>
<td>330</td>
<td>1</td>
</tr>
<tr>
<td>CM100</td>
<td>5.4</td>
<td>1.32</td>
<td>330</td>
<td>2</td>
</tr>
<tr>
<td>CM100</td>
<td>5.4</td>
<td>1.32</td>
<td>330</td>
<td>3</td>
</tr>
<tr>
<td>CM120</td>
<td>6.48</td>
<td>1.42</td>
<td>330</td>
<td>1</td>
</tr>
<tr>
<td>CM120</td>
<td>6.48</td>
<td>1.42</td>
<td>330</td>
<td>2</td>
</tr>
<tr>
<td>CM120</td>
<td>6.48</td>
<td>1.42</td>
<td>330</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 4: Classical method with constant steepness.

![Figure 11 Test program for the classical testing method](image-url)

This test program for the classical testing method has been executed 7 times, from which 3 have the same seeding number for the random realization of the wave pattern and the rest have a different seeding number. When the classical method is mentioned it is considered that the first 9 steps are representing a storm and the last three steps are a safety/extra check.
3.2.5. **Theoretical storm**

The real storm is transformed into 1 theoretical storm with the EMSIT model discussed by Martín Soldevilla et al. (2015). Similar to the test program for the real storm, the test program for the theoretical storm is also divided in steps of 1 prototype hour. And since the wave steepness for the real storm is quite constant the wave steepness for the theoretical storm is chosen constant, although in the wave climate analysis on average the wave steepness decreases after the peak of the storm.

The peak of the theoretical storm is the same as the peak of the real storm and the 100% step of the classical testing method \( H_s = 4.32 \text{m} \) and \( T_p = 11.8 \text{s} \). The wave steepness is chosen according these characteristics 0.02.

In Figure 12 the test program for the theoretical storm is shown with the same note as for the real storm that the red part of the planned program has not been executed since not more damage did occur in the final blue steps. On average the test steps are 362 waves long, and take 370 seconds to complete. The total duration of the storm is therefore 10502 waves which is equal to 3 testing hours (excluding the time between each test step).

![Figure 12 Test program for the theoretical storm](image)

This test program for the theoretical storm has been executed 7 times, from which 3 have the same seeding number for the random realization of the wave pattern and the rest have a different seeding number.

3.2.6. **Damage variability test (DAMV)**

Due to the big variation in the damage within one test case, it has been decided to execute tests in which only one step of 1000 waves is done. In each test the input is exactly the same, the only difference the breakwater structure. The armour layer is randomly placed cubes, which means that the location and placement of each cube will differ every time this breakwater structure is rebuild. The influence of this very important aspect is tested with this test.

The characteristics for this test are:

- \( H_s = 4.32 \text{m} \)
- \( T_p = 11.8 \text{s} \)
- \( N_z = 1000 \text{ waves} \)

This test program has been executed 7 times and for every test run the seeding was kept the same.
3.3. Analysis of test results

This section explains how the analysis of the results is done. It is clearly depicted how the qualification and quantification of the damage is done and how to process of the analysis have taken place. Also is explained what the drawbacks and errors of the measurements and the choices in the analysis are and how these drawbacks and errors influence the analysis and conclusions that will be drawn.

3.3.1. Damage qualification

The damage qualification has been done as explained in section 2.4. The main purpose of the damage qualification is to qualitatively determine the damage during the test runs. Because time has limited the number of test runs that were possible to execute it was important that destruction did not occur. If destruction would occur, this meant that the filter layer would have been destroyed and therefore needed to be rebuilt.

To prevent the filter layer to be destroyed, the test cases were stopped if they reached the phase of initiation of destruction. This would mean that for the type of methodology for the stopped test, one test should be counted with high damage, but due to stopping the test early the exact number of damage cannot be assigned to the test. In statistical analysis this test is not representing its true value and is therefore not always countable.

3.3.2. Damage quantification

The quantification of the damage will be done with two methods. The first method is the standard and well known visual counting method. All the cubes that have moved more than one nominal diameter are counted and from this total number the parameter $N_{od}$ is determined. Each individual cube has a unique number written on all 6 sides and it is therefore easy to determine in the pictures that are taken before, during and after the tests where each cube moved to (if it moved at all).

The second method, proposed by this MSc thesis, is an elaboration on $N_{od}$. In the tests is noticed that the contribution of each individual counted cube towards erosion is different. In this method, at the initial location of moved cubes erosion assumed and at the final location of the cubes accretion. With this assumption erosion profiles can be drawn from which $N_{od+}$ (a new introduced damage parameter) and erosion areas can be calculated. The exact calculation of the erosion profiles is explained in Appendix IV.

As a summary, damage will be quantified with the parameters:
- Number of cubes moved more than one nominal diameter
- Dimensionless damage number $N_{od}$
- Dimensionless damage number $N_{od+}$
- Erosion area

3.3.3. Processing

The processing is separated in three parts, in the first part the gathering of raw data will be explained, the second part gives the processing steps of the raw data to useful data for analysis and in the last part the process of analyzing the data is given. The processing will be given in steps for only one test run, since this is the same for every test. When specific steps need more clarification this will be given in the same processing part and if there are steps that are done for only specific test runs these will be given separately.
Raw data
In Table 5 are the steps given for gathering the raw data.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Description</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Taking 40-60 pictures from different angles of the filter layer</td>
<td>Obtain 3D model of filter layer</td>
</tr>
<tr>
<td>2</td>
<td>Taking 40-60 pictures from different angles of the armour layer</td>
<td>Obtain 3D model of the initial state of the armour layer</td>
</tr>
<tr>
<td>3</td>
<td>Take 1 picture perpendicular to the slope of the structure</td>
<td>Initial location of the cubes in the armour layer</td>
</tr>
<tr>
<td>4</td>
<td>Calibrate the wave gauges</td>
<td>Obtain the wave pattern in the flume</td>
</tr>
<tr>
<td>5</td>
<td>Take 1 picture perpendicular to the slope of the structure</td>
<td>Location of the cubes in the armour layer after the corresponding step</td>
</tr>
<tr>
<td>(5b)</td>
<td>Taking 40-60 pictures from different angles of the armour layer, this is only done for specific steps of a test run</td>
<td>Obtain 3D models of the specific steps of a test run.</td>
</tr>
<tr>
<td>6</td>
<td>Take 1 picture perpendicular to the slope of the structure</td>
<td>Final location of the cubes in the armour layer</td>
</tr>
<tr>
<td>7</td>
<td>Taking 40-60 pictures from different angles of the armour layer</td>
<td>Obtain 3D model of the final state of the armour layer</td>
</tr>
</tbody>
</table>

Table 5 the steps needed to obtain the raw data

Processing raw data
Based on the raw data only qualitative damage assessment can be done, but since a quantitative description of the damage will give better supports for conclusions the raw data needs to be processed such this quantitative description of damage is obtained.

<table>
<thead>
<tr>
<th>Post processing pictures for 3D model</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>The pictures taken for the 3D model are uploaded to the website recap.autodesk.com (Autodesk, 2016)</td>
</tr>
<tr>
<td>9</td>
<td>Downloading .obj file, scale the model, reference the model</td>
</tr>
<tr>
<td>10</td>
<td>Convert the .obj file into a .xyz file</td>
</tr>
<tr>
<td>11</td>
<td>Subtract the filter layer model from the armour layer model (of any step)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Post processing pictures step 3 and 5</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>The pictures from step 3 and 5 are compared and moved cubes are numbered (visual counting method)</td>
</tr>
<tr>
<td>13</td>
<td>From the files with the pictures and the numbered cubes the layers with the numbers are exported to .png files</td>
</tr>
<tr>
<td>14</td>
<td>The initial location of the numbers and location of the numbers in a specific step are determined</td>
</tr>
<tr>
<td>15</td>
<td>Construct erosion/accretion matrix</td>
</tr>
<tr>
<td>16</td>
<td>Draw erosion profiles</td>
</tr>
</tbody>
</table>

Table 6 the steps for processing the raw data
3D models

The 3D models are constructed from multiple pictures taken with a Gopro; these pictures are taken from different angles and positions towards the structure. After uploading the pictures to the website recap.autodesk.com a model as in Figure 13 is produced and can be downloaded as an .obj file. This 3D model is not yet on scale and also not yet in the right position, to scale and position the models 4 markers were placed, 2 in front of the toe and 2 near the crest. The exact location of these markers was determined with respect to one marker the zero (Figure 14).

Since an .obj file is not readable by Matlab this file is converted into a .xyz file. The 3D models are obtained for some tests; the models obtained are the filter layer and the initial state of the armour layer.

The .xyz files in Matlab looked like Figure 15 and by subtracting the filter layer from the armour layer a model was obtained with only the armour layer with the slope of the structure horizontal (Figure 16).

The .xyz files like the one in Figure 15 are used to determine the variation in the filter layer, mainly focusing on the slope angle and the .xyz files like Figure 16 are used to calculate the layer thickness, which is translated into armour porosity.
Comparison of pictures (step 12)

Comparing the two states based on the pictures shows really clear where on the breakwater structure movement of the cubes has occurred. With the help of the numbers on the cubes the movement of every single cube (of the top layer) can be tracked down.

With the help of programs such as Photoshop and GIMP, the cubes that moved more than one nominal diameter (based on visual assessment) are numbered in the image of the initial state and in the image of the state considered. The cube is assigned to a unique number such that its position in both images is clearly visible (Figure 17).

Due to saving the unique numbers as separate layers in Photoshop/GIMP, the numbers can be exported as an image file with the location of the number in respect to the breakwater structure. With every number in its own image file Matlab is able to locate the position of each number in each step of every test run. With all these locations a tracking map of all the moved cubes is easily constructed.

Construct erosion/accretion matrix

When a cube is moving from one position to the other this can be described as erosion at the first location and deposition at the second, thus knowing the initial and final location of every moved cube erosion and accretion can be calculated.

The initial state of the structure can be represented by a matrix filled with zeros, where \( m \) is the length [mm] of the structure parallel to the slope and \( n \) is the width [mm] of the structure.

For all the moved cubes at the initial location a area gets subtracted by a certain value to get negative values in the matrix for erosion. At the final location a area gets added by a certain value to get positive values for accretion.

The size of the area and the values that are subtracted/added depends on the nominal diameter and the amount of voids that is assumed to be ‘eroded’ or ‘deposited’.

The assumption is made that the eroded cube, leaves an erosion volume of twice its own volume. This that when the cubes erodes the voids (which are of the same size of the cube) erodes with it, which is in line of a porosity of 0.5.

From visual observations it is seen that due to compaction of the cubes the accreted volume is less than the eroded volume which means that the porosity has become less. Therefore the amount of voids being accreted is assumed to be half of the eroded voids.

Since voids are ether next to a cube or below it, the total eroded volume of one cube is assumed to be cubic with the top of this volume being the top of the cube (Figure 18).

Taking into account the voids with erosion and with deposition is not an easy exercise. Voids are not located around the cube as shown in Figure 18 but is most of the time more concentrated.

Also for deposition it is hard to say how much voids are created; in most of the tests the accretion height is smaller than the erosion depth, this means that more volume is eroded and less volume is deposited and thus somewhere between erosion and deposition volume disappears, which could only be related to the voids. But that there is less deposition of volume is not the case for every cube, when a cube managed to close a hole it created a big void.

Finally when for every (counted) cube at the initial location a certain amount of volume is subtracted and at the final location a certain amount of volume is deposited the matrix can be plotted as a volume which looks like the final state of the breakwater structure. From this volume cross-sections can be taken to get erosion and accretion areas.
Draw erosion profiles
The constructed matrix with erosion and accretion looks like Figure 19. This matrix shows the erosion (blue) and accretion (yellow) for one comparison of one step with the initial state. Due to the width of the structure compared to the size of one cube it is decided to separate the structure into 3 sections, this way every test step contains 3 data points. This decision is a compromise between creating as much data points and independency of the data points with each other.

The more sections used, the bigger the dependency is and therefore it is less likely that each data point follows a normal distribution.

Most likely cubes, when they are extracted/sliding, trigger other cubes to move as well, which influences the independency. When averaging the erosion in one section into one line this line represents the erosion profile for this section (see Figure 20)

![Figure 20 Mean erosion area of a section](image)

3.3.4. Data analysis
With the raw data processed into describing values, the analysis of these values and thus of the different methods had been done. The steps that need to be taken to draw conclusions which will answer the research questions are given in this section.

Orientation test
At first the orientation test has been analyzed, the observations of the behaviour of the breakwater structure have influenced the execution of all the other tests.

Results specific model storm types
For every specific model storm type the damage parameters have been determined, for each damage parameter the student-t distribution is used to calculate its 95% confidence bounds.

1. The first step has been to check the gathered data for spurious errors. This step is only done on the counted moved cubes, because if no spurious errors are detected in this data no errors should be expected in the other data since the latter relies on the first. If spurious errors are detected these should be considered as outliers and should be neglected.

2. In the second step $N_{od}$ is calculated as is discussed in section 2.4. The nominal diameter is 1.451 cm and the width is the width of the section.

3. The erosion/accretion matrix has been used to calculate $N_{od+}$. This matrix is constructed from all the counted cubes that are included in the $N_{od}$ value and due to the different failure modes (e.g. sliding and extraction) not every cube counts the same in the $N_{od}$ value.

The erosion volume is divided by the volume of one cube (taking into account the same amount of pores as was taken into account for the construction of this matrix). The new number of moved cubes that is obtained is always equal or less than the counted number of moved cubes and with this new number, $N_{od+}$ is calculated.
N_{od}^+ is a similar parameter as N_{on} discussed by Van den Bosch et al. (2002), but due to this method of obtaining $N_{od}^+$ no exact value can be given to how much each cube counts or the weight of each failure mode towards the total $N_{od}^+$.

5. From the erosion profiles the erosion area can be calculated, by summing up all the values below zero.

Comparisons
With the obtained results per specific model storm type, the comparisons that are necessary to answer the research questions can be done.

To conclude whether or not the simulated real storm is comparable in breakwater response to the classical testing method, or/and to verify the usage of the classical testing method, the damage results from the classical testing method have been compared with the results from the simulated real storm.
The 120% step also has been compared, to see how the damage in this step relates to the damage due to the simulated real storm.

Comparing the simulated real storm with the EMSIT model would lead to an answer for the second research sub-question. Although here final damage results are important, the evolution of the damage is just as important. The EMSIT model was chosen as the best model describing damage evolution and therefore the damage evolution of both the real storm as the EMSIT model have been compared as well. Although in literature (Martín Soldevilla et al., 2015) the quantification of the amount of damage is used for the damage evolution, in this MSc thesis also the normalized damage evolution is considered such that the total amount (if different for the real storm and EMSIT model) does not matter.

To answer the third sub-question, also qualitative results are getting important. The classical testing method has been compared to both the real storm and the EMSIT model, considering the wave climate, spread in the results, damage progression, but also efficiency aspect as testing time.

Damage development
The development of the damage for the theoretical storm and the real storm is discussed. For the specific storms is determined which parts and which characteristics of the storms are important to the development of damage. These characteristics can contribute to decisions of future improvement of testing methodologies.

Damage variability
The variability in the observed damage influences the confidence level that can be used to draw proper conclusions. With high variability a lower confidence level is necessary to draw conclusions and with lower variability a higher confidence level can be used.

When a breakwater structure is designed, the design is based on $N_{od}$ and the most common value to use is $N_{od} = 0.5$. In the classical testing method the damage after the 80% step (CM80) shows an average $N_{od}$ of 0.5, so this data will be used for the variability.

Although the damage parameter $N_{od}$ is widely used to describe damage, a difference of 0.5 in this value for instance is hard to grasp what its influence is. The stability formula of Van der Meer (1988) is commonly used in the design of breakwaters with cubic armour layers. With the data available the formula can also be reverted and from the measured $N_{od}$ values could the significant wave height be calculated, which otherwise would have been used to calculate the nominal diameter on a given damage value.

The wave steepness depends on the significant wave height as well, therefore Eq. (23) is an implicit formula. First the measured significant wave height is used and after performing the calculation this significant wave height is updated.

$$H_s = \left( 6.7 \ast \frac{N_{od}^{0.4}}{N_{2.5}^{0.4}} + 1 \right) \ast s_{\text{sw}}^{-0.1} \ast \Delta \ast D_n$$

(23)

All the other values have been used as input in the tests or measured from the tests. The number of waves for CM80 is 1980, the nominal diameter is 1.451 cm or on prototype scale 1.16 m, delta is chosen to be 1.25 and the mean period is measured from the tests.
3.3.5. Statistical analysis

To make the results more acceptable statistical analysis is done such that the results have a certain confidence level.

Hypotheses and confidence levels

In comparing results with each other hypotheses have been introduced. For every comparison two hypotheses are given, with the statistical analysis one of the two hypotheses is accepted where the other is rejected with the given confidence. Also is given the introduction of the hypothesis, clarify what is exactly compared and how certain the results are of the comparison.

Spurious errors

Any of the data points in the data set could be an outlier and it is possible to statistically check this. Assuming the mean to be the actual mean two hypotheses are introduced:

- $H_0: \bar{e}_i = 0$
- $H_1: \bar{e}_i \neq 0$

Where $\bar{e}_i = X_i - \hat{\mu}$, $X_i$ is the data point and $\hat{\mu}$ is the expected mean. The distribution of the errors is assumed to be normally distributed and spurious errors are treated so when these are outside the 95% range around the mean (Figure 21). Thus $H_0$ is accepted if Eq. (24) holds.

$$-1.96 < \frac{X_i - \hat{\mu}_N}{\sigma_N} < 1.96 \quad (24)$$

Comparison means

For the comparison of the means the following hypotheses are introduced.

- $H_0: \mu_1 = \mu_2$
- $H_1: \mu_1 \neq \mu_2$

The t-value is calculated for the difference between the means as is explained in section 2.6. With this t-value the p-value can be obtained from the cumulative distribution function for the student-t distribution. This p-value indicates the confidence level for the comparability (1-p).

The confidence level chosen is 90%, which means that $H_0$ is accepted if $p$ is smaller than 0.1.

Confidence boundaries

For each calculated mean the confidence boundaries are also calculated with the student-t distribution explained in section 2.6. The confidence level for the boundaries is the same as that for the comparison of the means. This way the boundaries of different means have been compared and when overlapping, the means are comparable with the 90% confidence.

Two- or one-tailed distribution

For the comparison of the 120% step with the simulated real storm it is already expected that the mean of the damage due to this 120% step is the higher mean, this because this step is an overestimating step, and therefore the one-tailed distribution is used. Due to this the p-value for this comparison will be smaller, but when the simulated real storm happened to have the larger mean the only thing that can be said is that the difference is due to change and not significant.

For all the other comparisons the two-tailed distribution is used because there is no indication that in any of these comparisons, one of the means is the larger mean.
Measurement errors

Visual counting
One important but not directly obvious measurement error is the human error in counting the moved cubes. The types of errors that can occur are:
- Missing one or two cubes in the counting process
- Subjective decision making in whether a cube moved more than one nominal diameter or not

The first error can cause that damage is underestimated, since missing cubes with counting will result in a lower total amount of moved cubes.
The second error can go both ways since the one cube can be counted while it did not move more than one nominal diameter and the other cube can be disregarded while it moved more than one nominal diameter.

To give an exact value to these 2 errors, some tests should be counted multiple times and the difference in the total moved cubes will lead to an exact value.

Recounting multiple tests is too much time consuming and therefore this error is taken by granted.

Lens distortion
The use of a Gopro for making the pictures in step 3,5 and 6 (Table 5), was a convenient choice because of the size of the flume and the Gopro was able to be placed in the flume without being an unwanted obstacle.

The disadvantage of the Gopro is the lens distortion also known as the fish eye view. In the visual counting method this does not oppose a problem, but when composing an erosion matrix from the locations of the moved cube there could be an error in the location determined by Matlab and the real location due to the lens distortion. This actually means that the scale in the picture (picture size compared to real life size) changes with distance to the center of the image

By taking multiple pictures of a chessboard pattern, Matlab was able to determine the radial distortion parameters, $k = (-0.2395, 0.0712, -0.0106)$.

Implementing the parameters from Matlab into Eq. (25), did not give realistic values and since it is not clear on how Matlab corrects the distorted image with these values the radial distortion parameters given by Matlab are not used. But the correction done in Matlab is useful to calculate the radial distortion parameters that fit into Eq. (25). With Matlab the undistorted location of some random points is determined and with a system of equation the $k$ values have been determined.

<table>
<thead>
<tr>
<th></th>
<th>x (original)</th>
<th>y (original)</th>
<th>x (undistorted)</th>
<th>y (undistorted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>2783</td>
<td>2199</td>
<td>2848</td>
<td>2266</td>
</tr>
<tr>
<td>Point 2</td>
<td>2490</td>
<td>1883</td>
<td>2501</td>
<td>1894</td>
</tr>
<tr>
<td>Point 3</td>
<td>2265</td>
<td>1670</td>
<td>2266</td>
<td>1671</td>
</tr>
</tbody>
</table>

Table 7 Points chosen to determine the radial distortion parameters

Inserting the known values in Eq. (25) & (26) with $r = \sqrt{(x - x_0)^2 + (y - y_0)^2}$ a system of equations have been solved. $(\tilde{x}, \tilde{y})$ is the location of the undistorted point and $(x,y)$ is the location of the original point.

$$ L(r) = k_0 + k_1 \cdot r^2 + k_2 \cdot r^4 + k_3 \cdot r^6 $$  \hspace{1cm} (25)
\[
\begin{pmatrix}
\hat{x} - x_c \\
\hat{y} - y_c
\end{pmatrix} = L(r) \begin{pmatrix}
x - x_c \\
y - y_c
\end{pmatrix}
\]

(26)

\[
x - x_c = (x - x_c)L(r) \quad \& \quad \hat{y} - y_c = (y - y_c)L(r)
\]

(27)

\[
\begin{bmatrix}
\frac{x_1 - x_c}{x_1} \\
\frac{x_2 - x_c}{x_2} \\
\frac{x_3 - x_c}{x_3}
\end{bmatrix} - 1 = \begin{bmatrix}
r_1^2 & r_1^3 & r_1^6 \\
r_2^2 & r_2^3 & r_2^6 \\
r_3^2 & r_3^3 & r_3^6
\end{bmatrix} \begin{bmatrix}
k_1 \\
k_2 \\
k_3
\end{bmatrix}
\]

(28)

Solving this system of equation gives the following radial distortion parameters; \(k_1 = 2.95 \times 10^{-8}\), \(k_2 = 9.13 \times 10^{-14}\) and \(k_3 = -4.51 \times 10^{-20}\). Two things are necessary to point out; the first is that the \(k\) values are determined based on only 3 points and second it is assumed that the calculation with Matlab is correct and that the calculated locations are the real locations. With this assumption the real location and the location according to Eq. (27) is calculated for every 10th pixel in the area of interest (The area in the image in which the breakwater structure is located).

In Figure 24 is the difference between the “real” distance to the middle of the image (calculated with Matlab) and the distance calculated with the determined \(k\)-values. There is a clear trend which means that a different set of \(k\)-values could show a better fit.

Solving the following equations:

\[
x_{rel} = x - x_c, \quad \hat{x}_{rel} = \hat{x} - x_c, \quad y_{rel} = y - y_c, \quad \hat{y}_{rel} = \hat{y} - x_c
\]

(29)

\[
r^2 = x_{rel}^2 + y_{rel}^2, \quad \hat{r}^2 = \hat{x}_{rel}^2 + \hat{y}_{rel}^2
\]

(30)

\[
\hat{x}_{rel} = x_{rel} \times L(r), \quad \hat{y}_{rel} = y_{rel} \times L(r)
\]

(31)

Gives:

\[
\hat{r} = r \times L(r)
\]

(32)

Plotting the values for \(\hat{r}\) versus the values for \(r\) the \(k\)-values can be determined with a trend fitting line; the R-squared value for the trend line is 0.9986.
With the formula the real location of the moved cubes is estimated and with the difference between the real location and the location given in the distorted image the error due to the distortion has been calculated. In Table 9 the mean error and maximum error for the initial and final location is given per type of test and for the total amount of tests. In Figure 25 the error due to distortion based on the location in an image is shown, it is clear that the maximum values for the errors are located near the toe of the structure and therefore less interesting in the calculation for the erosion.

### Table 8: k-values for the radial distortion

<table>
<thead>
<tr>
<th>k₀</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>k₁</td>
<td>9.753×10⁻⁸</td>
</tr>
<tr>
<td>k₂</td>
<td>-1.35×10⁻¹⁴</td>
</tr>
</tbody>
</table>

With the formula the real location of the moved cubes is estimated and with the difference between the real location and the location given in the distorted image the error due to the distortion has been calculated. In Table 9 the mean error and maximum error for the initial and final location is given per type of test and for the total amount of tests. In Figure 25 the error due to distortion based on the location in an image is shown, it is clear that the maximum values for the errors are located near the toe of the structure and therefore less interesting in the calculation for the erosion.

### Table 9: Mean and maximum error for the location of the moved cubes due to radial distortion

<table>
<thead>
<tr>
<th></th>
<th>Error Initial location</th>
<th>Error Final location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Max</td>
</tr>
<tr>
<td>Class330</td>
<td>2.35%</td>
<td>8.42%</td>
</tr>
<tr>
<td>Real storm</td>
<td>1.77%</td>
<td>6.8%</td>
</tr>
<tr>
<td>Theoretical storm</td>
<td>2.23%</td>
<td>8.91%</td>
</tr>
<tr>
<td>Total</td>
<td>2.1%</td>
<td>8.91%</td>
</tr>
</tbody>
</table>

A Rough estimate for the error in the erosion calculation has been done.

- Mean error is 2.1%.
- Mean distance is 469 pixels for the initial location
- Mean distance is 512 pixels for the final location

Estimate for the scale:

- Minimum width structure 1368 pixels
- Maximum width 1578 pixels
- Width structure is 345 mm
- Scale is between 1:3.96 and 1:4.57

With the mean distance and the estimate for the scale determined above, the mean distance from the middle of the image is within 102 and 118 mm for the initial location and within 112 and 129 mm for the final location. The mean error for the location of the moved cubes due to radial distortion is than between 2.1 and 2.7 mm. The main effect of this is that the locations of the cubes are spread a little bit more than when a correction for this distortion is applied.

The parameter N₀d¹⁺ it is not about the exact location but about the location of a cube relative to another cube. In N₀d¹⁺ no matter where on the image always the same size for the cube is considered, but due to the change of scale with distance to the center of the image, the size of the cube further away of the center should be assumed smaller.
In Figure 26 is shown how the cube size should have been assumed in the calculation for $N_{od+}$ and in Figure 27 is shown how it is assumed. If the yellow area is considered as erosion and the red area as deposition in the extreme case 8.9% less erosion is assumed. This means that if this extreme case applies for 11 cubes, 1 cube less erosion is assumed.

Water refraction
The pictures that have been taken before, during and after the test runs were all taken with the water still in the flume, since emptying and refilling the flume is very time consuming.

Due to the breakwater structure being for a part below the water level the view of the breakwater below the water level is refracted and this means that the locations of the moved cubes are not the exact location.

With Snell’s law the error due to the refraction can be calculated.

The values $n_1$ and $n_2$ depend on the substance through which the light is travelling.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Refractive index, $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (1 atmosphere pressure)</td>
<td>1.00029</td>
</tr>
<tr>
<td>Water (20 degrees C)</td>
<td>1.33</td>
</tr>
</tbody>
</table>

Normally when an object is noticed under the water line this object is shifted in the observation from its actual position. Since the water depth declines in the direction from the toe to the crest the shift declines accordingly. Due to this phenomena the observed slope, below the water level is actually compressed compared with the actual slope. This actually means that the scale in the picture (picture size compared to real life size) changes with water depth.

Without the water the observed slope length in the observation line is 13.69 cm, this is off course a scaled version of the actual slope length. With the water the observed length in this same line is 13.43 cm. This means that the points observed at the toe level are actually shifted to the left by 1.97%.

From point A to point B the error decreases from 1.97% to 0% respectively. Assuming the decrease is linear with the length of the slope, the following expression gives the error a location $x$ (in mm) from point A.

$$\text{error} = -0.000106x + 0.019661$$  \hspace{1cm} (33)
Similar as for the lens distortion the relative position of a cube with another is important. In the $N_{od+}$ value no matter what the position of the cube in the image is, the size of the cube is always considered constant, but due to the change of scale with water depth the size of the cube at deeper water should be assumed bigger. In Figure 30 is shown how the size of the cube should have been assumed in the calculation for $N_{od+}$. In Figure 31 is shown what has happened since this is not done.

This means that if the red area is erosion and the yellow area is deposition in the extreme case 1.7% less erosion is assumed than should be. Or if this extreme case would happen to 58 cubes, 1 cube less erosion is assumed than should be.

**Reshaping/scaling of the images**

The reshaping and scaling of the images has been done the same for every image, the only difference is that as input for the reshaping and scaling some (x,y) locations in the picture were needed. These locations were picked based on visual interpretation and it could be that these locations were not picked exactly correct.

By multiple times trying to pick the same point in one of the pictures, the mean distance for the picked locations from the expected actual location is 5.31 pixels with a standard deviation of 2.35 pixels. With the same scale as for lens distortion; between 1:3.96 and 1:4.57, the mean distance is between 1.162 and 1.34 mm and the standard deviation between 0.51 and 0.59 mm.

**Slicing structure in multiple sections**

The drawback of laboratory testing is that it is very time consuming to gather a lot of data. This could be solved partially by slicing the breakwater structure into multiple sections in the obtained results. This action leads to multiple data points, but since there are now points that belongs to the same tests, these points are not completely independent of each other.

And the more slices taken from the breakwater structure, the less normal distributed the total data set is.

A goodness of fit test for all the storm types showed that not slicing the structure gave a better fit with the normal distribution than slicing the structure into 3 sections.

**Wave loads**

When in every test the exact same input parameters and seeding number for the realization of the random wave pattern would have been used, the wave loads would be an input that would not change. But due to the use of different seeding numbers and different test programs the wave loads are a variable as well. In the process between the input of the parameters and the output of the waves there are steps that influences the output wave pattern and because of these influences causing a difference between the input significant wave height ($H_{s, in}$) and output significant wave height ($H_{s, out}$).

The steps between input and output are:
- Construction of JONSWAP spectrum
- Conversion JONSWAP spectrum into wave pattern
- Paddle movement to create wave pattern

Due to the construction of the JONSWAP spectrum and translating this into a wave pattern the $H_{s, out}$ is generally 6.5% lower than the $H_{s, in}$. Only in 3% of the test steps the $H_{s, out}$ was higher than the $H_{s, in}$, with a maximum of 0.9% higher. There is no explanation why this is happening, since there is no clear relation between this error and any of the input parameters. Although it is assumed that the number of waves of the test step has an influence on this, since the highest errors (>10%) occur in the steps with low number of waves (around the 300) and in the steps with 1000 waves the maximum error is 8%. Also the standard deviation in the error of the steps with 1000 waves is half of the standard deviation of the steps with low number of waves. It should be noted that only 27 steps have been done with 1000 waves, while more than 400 steps are done with a low number of waves.
The translation from the paddle movement to waves in the flume is also not without a loss. The paddle hangs in the flume and the openings next to and below the paddle are tried to be closed with rubbers to prevent leakage. But still there is leakage happening and this results in loss of energy.

The strange thing is that this loss of energy is lower for the steps with 1000 waves than for the steps with a low number of waves.

- 6.3% difference in $H_s$ due to loss of energy, for the steps with a low number of waves
- 4.5% difference in $H_s$ due to loss of energy, for the steps with 1000 waves

With a calibration that has been done at the very beginning of the tests, coefficients were applied on the input significant wave height. With this coefficient the $H_{s,in}$ was generally 11% higher and should account for the losses in the significant wave height, such that $H_{s,out}$ is close to the target significant wave height.

Due to this coefficient the output significant wave height is on average:

- 1.84% lower than the target significant wave height, for the steps with low number of waves
- 1% higher than the target significant wave height, for the steps with 1000 waves

3D models
Similar as with reshaping and scaling of the images, for scaling and positioning the 3D models the reference points needed to be picked.

In the process of scaling and positioning the model the choice was made to apply uniform scaling, this meant that no deformation of the model was possible. After referencing the errors due to picking the reference points, but also due to model distortions were obtained for each reference point.

The average error for each reference point is 2.53 mm with a standard deviation of 0.77 mm.

Also for some structures two 3D models were made with different images. If no errors were made and these two 3D’s of the same structure could are subtracted a matrix would be obtained with only zeros.

By subtracting and averaging the residual, the mean error per set of 3D models is obtained. This is done for three sets which had a mean error of 0.0578 mm (standard deviation of 0.5582 mm), 0.3413 mm (standard deviation of 0.611 mm) and 0.2835 mm (standard deviation of 0.7259 mm).
4. Climate data analysis

4.1. Selected storm profile

The storm that is going to be used in this master thesis was measured by UN/UPC with a buoy (XIOM at Blanes) in the Mediterranean Sea. This storm will be transformed to theoretical storms and both the real storm as the theoretical storm will be reproduced in the wave flume. This storm is chosen because it was one of the second biggest storms that caused damage.

After the orientation test it is observed that below the significant wave height of 2.7m no damage will occur, thus is chosen to shift the threshold level to 2.7m. The storm profile changes significantly (see Figure 33).

The breakwater that has been used for the tests is designed based on the characteristics of the peak of this storm.
Buoy characteristics:
- Location: Blanes 41.64°N 2.81°E 65m depth
- Measurement type: Wave
- Sampling rate: 20' every hour
- Main output parameters: Wave statistics and spectra
- Instrument type: Datawell waverider
- The coast is located in the direction of 326 degrees, about 3.5 km away from the XIOM buoy
- The direction parallel to the coast from NE to SW is 235 degrees

Storm characteristics:
- At the 26th of december, 2008 at 11:00 AM the significant wave heights rised above the threshold, this is the start of the storm
- At 16:00 PM on the 27th of december, 2008 the significant wave heights decreased to below the threshold, this is the end of the storm
- The total duration of the storm is 29 hours
- Threshold(H_T) is 270 cm
- H_s,peak is 465 cm
- The peak period associated with the H_s,peak (T_{peak}) is 11.8 s

4.2. Peak-Over-Threshold

The storm’s profile was taken from wave climate data from a XIOM buoy located near Blanes. From this wave buoy more than 20 years of wave climate data is available.

For modeling the data with extreme value theory the Peak-Over-Threshold (POT) method is applied also used by Ferreira & Soares (1998) (cited by Ferreira & Guedes Soares, (2000)).

The POT method uses the generalized Pareto distribution to fit the peaks into an extreme value distribution (Coles 2001).

With this method using a threshold of 2.7m and the available wave climate data the extreme value distribution in Figure 34 is determined. The threshold of 2.7m is used, because this is also the threshold of the real storm (At = 24hrs has been assumed to assure independence between consecutive storms).

The probability of a certain significant wave height being lower than a given significant wave height is given with the following formula:

\[
Pr[H_{s,peak} \leq H_{s,peak}'] = 1 - \left( 1 + C \cdot \frac{H_{s,peak} - A}{B} \right)^{-\frac{1}{\tau}}
\]

With A is the threshold and C and B are coefficients in this case:
- A = 270 cm
- B = 71.46
- C = -0.1266

The probability of occurrence of the significant wave height of the peak of the selected storm will then be

\[
1 - Pr[H_{s,peak} \leq 465] = 0.0352 \text{ or once in 28.45 years.}
\]
This method is also applied to draw an extreme value distribution for the storm duration. The storm duration is defined as the duration of significant wave heights being higher than the threshold. When two consecutive storms are happening within $\Delta t$, the duration of the wave heights below the threshold between the two storms are also taken into account in the total duration of the storm.

The same probability formula used for the significant wave heights holds here as well.

- $A = 0$
- $B = 14.36$
- $C = -0.0667$

The probability of occurrence of the duration of the selected storm will then be $1 - \Pr(D \leq 29) = 0.114$ or once in 8.76 years.

### 4.3. Representability

The selected storm profile is one of the biggest storms in significant wave height and duration in the measured data. Considering the theoretical storm models in which the magnitude of a storm is important, this selected storm profile has the biggest magnitude.

But important to note, the highest measured significant wave height belongs to a different storm with a shorter duration and due to this shorter duration the magnitude of this storm is lower than the selected storm. The classical method is based on the significant wave height and wave period, so testing with the peak of the other storm would mean that a bigger nominal stone diameter is needed.

The theoretical model is based on magnitude and significant wave height of the peak, a smaller magnitude does not directly indicate a smaller nominal stone diameter, but one can imagine that a combination of the duration of the selected profile and the highest significant wave height would lead to the biggest nominal stone diameter based on the measured data.

### 4.4. Wave Steepness

The wave steepness seems to be a good way to connect the significant wave height to a wave period during scale model testing.

In the classical testing method an increased wave height is used per test run sometimes also with increasing wave period, since during the build-up of a storm the wave steepness stays approximately constant (Owen & Allsop, 1984). For testing with the entire storm, during the build-up of the storm the wave steepness can be kept constant but how to continue from the peak of the storm is still unknown.

The measured significant wave height and peak wave period each hour of a storm are used to calculate the wave steepness every hour of a storm and the behavior of the wave steepness of every storm with a threshold of $H_s = 1.5\text{m}$ is compared to see if there is any relation between the wave steepness and storms.

Steps taken:

- Wave steepness calculated from peak wave period and significant wave height
  \[ s_p = \frac{2 \pi H_s}{g T_p^2} \tanh \left( \frac{2 \pi d}{L} \right) \]  
  (35)

- The duration of storm($i$) is normalized with the duration of the longest storm in the data
  \[ \frac{D(i)_{\text{storm}}}{\max(D_{\text{storm}})} \]  
  (36)

- These steps are also taken for the mean wave period.

- The wave steepness per storm and the mean for all the storms are plotted to see if there is a trend;
  - For the part before the peak of the storm
  - For the part after the peak of the storm, and;
  - For the entire storm

- Also only the storms with a duration of at least 3 hours are observed, since a 1 hour storms will have a constant trend and 2 hour storms easily tend towards either an increasing or decreasing trend.
Figure 36
(a) Wave steepness with peak period normalized over the entire duration of a storm
(b) Wave steepness with peak period normalized over the duration before the peak of the storm
(c) Wave steepness with peak period normalized over the duration before the peak of the storm

Figure 37
(a) Wave steepness with mean period normalized over the entire duration of a storm
(b) Wave steepness with mean period normalized over the duration before the peak of the storm
(c) Wave steepness with mean period normalized over the duration before the peak of the storm
Both the trend for the wave steepness with the peak period as for the one with the mean period shows similarities. During the entire storm in before the peak the wave steepness is constant, see Figure 36 a&b and Figure 37 a&b and after the peak there is a clear decrease (about 10%) of the wave steepness visible Figure 36 a&c and Figure 37 a&c.

Wave steepness for the peak wave period
- The mean is 0.0216
- Constant before the peak at 0.0228
- Decrease after the peak from 0.0233 to 0.0177

Wave steepness for the mean wave period
- The mean is 0.0427
- Constant before the peak at 0.0451
- Decrease after the peak from 0.0450 to 0.0378

Comparing the wave steepness of the selected storm with the calculated mean of all the data, shows that the selected storm has quite a similar behavior as the mean, although it seems to be more constant (see Figure 38).

\[ \text{Wave steepness for the peak wave period} \\
\begin{align*}
\text{The mean is 0.0216} \\
\text{Constant before the peak at 0.0228} \\
\text{Decrease after the peak from 0.0233 to 0.0177}
\end{align*} \]

\[ \text{Wave steepness for the mean wave period} \\
\begin{align*}
\text{The mean is 0.0427} \\
\text{Constant before the peak at 0.0451} \\
\text{Decrease after the peak from 0.0450 to 0.0378}
\end{align*} \]

Comparing the wave steepness of the selected storm with the calculated mean of all the data, shows that the selected storm has quite a similar behavior as the mean, although it seems to be more constant (see Figure 38).

![Wave steepness comparison](image1.png)  ![Wave steepness comparison](image2.png)

**Figure 38** Comparison mean wave steepness and wave steepness selected storm a) Wave steepness with peak period b) Wave steepness with mean period

### 4.4.1. Comparing storms with specific trends

It could be possible that the storms (threshold H\(_T\) = 2.7m) with an increasing trend for the wave steepness are compensating with the storms with a decreasing trend in the wave steepness. Therefore all the storms with an increasing trend, decreasing trend and constant trend are compared separately.

In Figure 39, Figure 40 and Figure 41 all the storms are separated with a constant, decreasing and increasing trend respectively. The storms are separated on a rough linear approximation of the trend and when this linear trend passes the boundaries of increase/decrease of 0.001 per hour in steepness the trend is assumed to be either increasing or decreasing.

With these boundaries set and looking to storms with duration of at least 3 hours of 33 storms;
- 24 storms have a constant trend
- 8 storms have a decreasing trend
- 1 storm has an increasing trend

Note that the boundaries on which decreasing, increasing and constant trends are separated are very important in choice, slightly smaller or higher boundaries will change these numbers easily.

So based on this data it can be said that by far the majority has a constant wave steepness during a storm. But when the wave steepness shows a decreasing trend (0.001 per hour) the difference the steepness decreases with 20%. There is only 1 storm that has wave steepness with an increasing trend; this storm has a short duration (2 hours), which makes this graph (Figure 41) not representable.
4.4.2. Conclusion

The chosen storm profile is one of the biggest storms that happened at this location in the past >20 years, not only in the peak of the storm but also in its duration. So the probability that a storm with such a significant wave height for the peak, duration and thus high magnitude will happen is quite low. But such combinations do happen and are therefore important in how severe the test methodology is on which a breakwater structure is tested.

The average trend of the wave steepness is constant during storm build-up and decreasing after the peak. The wave steepness of the chosen storm profile has similarities in the beginning of the storm but towards the end it stays quite constant while the trend is downwards. Therefore has been chosen to use constant wave steepness for the classical testing method and theoretical storm, but should be realized that in other storms this is/should be different.
4.5. $H_s,\text{peak}$ and duration

The theoretical storm models of Martín Soldevilla et al. (2015) contain two main characteristics to describe a storm, these are the $H_s,\text{peak}$ and the duration ($D$).

To be able to translate a given required lifetime to a design storm, there should be a way to calculate $H_s,\text{peak}$ and $D$ with the required lifetime and available data based on extreme value distributions. Or if there is a correlation between $H_s,\text{peak}$ and $D$ in the available data the $H_s,\text{peak}$ can be obtained with an extreme value distribution and $D$ from the correlation.

4.5.1. Correlation

After determining the storms above a threshold of 2.7m, the corresponding $H_s,\text{peak}$ and $D$ is determined. The plot of every storm on these characteristics in one graph is shown in Figure 42.

Based on this figure some correlation is visible between the significant wave height of the peak of the storm and the duration of that same storm. The first thing that could be noticed is that there seems to be a lower limit, the longer the storms become the higher the peak significant wave height should be. Second there seems to be an upper limit, the shorter the duration the lower the peak.

Both are quite logical since the longer a storm lasts the more time it has to develop a higher peak. And last it seems there is more spread when storms are longer and peaks are higher.

Limits

The limits shown in Figure 42 are described by the following formulas.

Upper limit:

$$H_{s,\text{peak}} = 13.953D + 283$$  \hspace{1cm} (37)

Lower limit:

$$H_{s,\text{peak}} = \frac{270}{0.048D^2 - 0.8075D + 272.87} \quad \text{for } D \leq 10$$

$$H_{s,\text{peak}} = 270 \quad \text{for } D \geq 10$$  \hspace{1cm} (38)

In section 6.4 the part of a storm that matters will be discussed. And since there could be storms that are much longer due to a tail that is not interesting the duration of this part of each storm is considered in a new graph drawn in Figure 43. As visible in the figure, the upper limit of Figure 42 does not apply here, but the lower limit still does, although it looks like there is a duration limit between 20 and 25 hours.
4.5.2. Stability formula

With the stability formula from Van der Meer (1988) the relation between significant wave height, duration and nominal diameter can be determined:

\[
6.7 \left( \frac{N_{ad}^{0.4}}{N_{ad}^{2.3} + 1.0} \right) s_{om}^{-0.1} = \frac{H_s}{\Delta D_n}
\]

(39)

With:

- \(N_{ad}\) = Relative damage, 0 is no damage; 1-2 is severe damage
- \(N_s\) = Storm duration in number of waves, generalized Pareto distributed
- \(s_{om}\) = Mean offshore wave steepness, 0.0427 is average steepness of all storms above \(H_T = 2.7\) m
- \(H_s\) = Significant wave height in meters, generalized Pareto distributed
- \(\Delta = 1.25\), the relative stone density

Taking \(Z=0\) and solving this equation for \(N_s\) given a certain significant wave height (without using the distributions), nominal diameter and taking a damage number of 1, makes it possible to transform \(N_s\) to \(D\) using \(H_s\) and \(s_{om}\). The formula that remains can be plotted into the same graph as in Figure 43 (see Figure 44).

As is visible in Figure 44, that for a certain nominal diameter applies; the more severe (higher significant wave height for the peak) the storm the lower the duration should be.

The problem is that for one diameter multiple combinations of \(H_s\) and \(D\) are applicable and the question that remains is how to decide which combination is the best choice. Therefore also a contour plot is made in the same figure based on amount of storms in certain regions. With this contour plot and extrapolating the historical data a choice could be made for a certain \(H_s\) and \(D\) combination.
5. **Results**

5.1. **Introduction**

In this chapter the results from the tests are shown and based on these results the research questions will be answered. First a brief explanation will be given about the results of the orientation test, after shall per storm model the results be discussed and with these results the necessary comparisons will be made. The damage in the orientation test will be described qualitatively. The damage for all the other tests will be described in the following parameters:

- Number of cubes moved more than one nominal diameter ($N_{od}$)
- $N_{od}$ based on $N$
- $N_{od+}$, the amount of erosion each cube of $N$ causes is taken into account
- Erosion, erosion calculated with $N_{od}$

5.2. **Orientation test**

The orientation test was performed in order to scale the storm, if necessary, such that the behaviour of the structure leads to wanted results. It consisted of a modeled measured storm as described in section 3.2.2.

The main observations from this test are:

- The armour layer was more compacted than the target, due to tendency of the cubes to position themselves with the flat sides against each other; this resulted in the use of 764 cubes instead of 690.
- During the fourth time series ($H_s = 3.375$ cm, 2.7m on prototype scale) 1 cube started rocking
- At the peak of the highest set of this test ($H_s = 6.875$ cm, 5.5m on prototype scale) initiation of destruction did not occur.

These observations lead to the following choices;

To reduce the amount of cubes that have been used in the armour layer the cubes per horizontal line have been reduced from 19 to 17 cubes.

The significant wave height of the fourth time series has been chosen as the threshold for the storm profiles, although it is possible that steps with lower significant wave heights can still lead to damage. Calculating the value of $N_{od}$ with the Van der Meer stability formula for the significant wave height of 2.7m gives $N_{od} = 0.1$, which is equivalent to the movement of 2 cubes over the entire width of the structure.

If damage occurs in the first time step of the storm ($H_s = 3.375$ cm) the problem is that it is not clear if this should have happened at this step or a previous step, but if this is only for a couple of cubes it shall in the end be only a minor part of the total damage.

The main reason for this choice is that the total duration of the real storm profile is now significantly smaller.

Since no initiation of destruction did occur during the orientation test, it has been decided not to change the scale of the storm to increase/decrease severity.

5.2.1. **Damage**

In the Figure 45 & Figure 46 the structure before the test and after the test is shown and initiation of Iribarren’s damage is clearly visible, initiation of destruction did not occur since the filter layer is not visible.
5.3. **Breakwater structure**

The breakwater structure needed to be rebuilt before every test. Before placing the cubes the filter layer needed to be checked whether the orientation is still correct and be adjusted if necessary. When placing the cubes special attention has been paid to the porosity/amount of cubes of the armour layer. Due to rebuilding variation could occur in the orientation of the filter layer or in the porosity/amount of cubes of the armour layer. These variations are highlighted in this section.

5.3.1. **Filter layer**

With some of the 3D models of the filter layers the orientation of the filter layer has been checked. In Figure 47 and Figure 48 respectively the mean cross section of the filter layers and the mean of the means with 95% upper and lower boundary are shown.

![Cross-section filter layers](image1)

![Cross-section mean of the filter layers with confidence boundaries](image2)

The average deviation from the mean with 95% confidence is 1.76 mm and the maximum deviation is 2.81 mm (is $0.19\cdot D_{50}$ and $0.14\cdot t_{filter}$). The deviation is not the most important issue, since this could also be a shift to the right or to the left which could have occurred due to the reconstruction of the 3D model. One of the most important issues is the slope of the structure; the steeper the slope the more likely damage can occur.

In this steepness the roughness of the filter layer also plays a role, the steeper the slope the more important this roughness is and the lower the roughness the easier cubes tend to slide. For the latter the filter layer is before placing the cubes some kind of reorganized, such that the roughness increased. This roughness is on such a small scale that it is assumed to be similar for all tests, since it could not be measured.

The slope angle is defined as:

$$\text{slope angle} = \tan^{-1}\left(\frac{\sum_{n=1}^{20} (n \cdot 10 + 50) - x(n - 1) \cdot 10 + 50)}{10} \right) \tag{40}$$

The maximum angle of the slope in the observed filter layers is 30.18˚ and the minimum angle is 28.93˚. So, there is a difference of 1.25˚ between minimum and maximum angle of the slope which could cause that in the cases with a higher slope angle more damage occurs compared to the cases with lower angle.

In reality this 1.25˚ difference would mean that for the case with the maximum slope angle the length in cross-sectional direction of the breakwater structure will be 5% shorter on the seaside. For a breakwater with a crest height of 10 meters this would mean 0.9 meter less on the sea side.
5.3.2. **Armour layer**

In prior literature has already been proven that the porosity of an armour layer with cubes is quite important in the stability of the armour layer (Van den Bosch et al. 2002). The porosity of an armour layer can be determined with the amount of cubes in the layer and the layer thickness. Since the amount of cubes used per test is kept more or less constant in the construction of the armour layer the layer thickness is a direct indication for the porosity.

In reality the layer thickness often cannot be measured and is calculated with a $K_d$ factor (for cubes 1.1 is usually assumed) (Verhagen et al. 2002).

In the formula:

\[ t = K_d \times n \times D_{50} \]  \( (41) \)

With $n = 2$ layers and $D_{50}$ is 1.451 cm the layer thickness $d$ according to the formula is 3.19 cm.

When the layer thickness is measured often the standard hemisphere method is used, where the diameter of the hemisphere is equal to half the cube size. But since the availability of the 3D models made it possible to find the thickness of the layer at any point on the slope, the average layer thickness is calculated by averaging all the points on the slope where the thickness is known.

The areas considered in the 3D’s are always 250*260 mm$^2$ with about 384 cubes used in this area and an average layer thickness of 32.76 mm, the average porosity is 0.45.

The minimum layer thickness is 29.77 with the same amount of cubes this means a more compacted armour layer, the porosity is 0.39. And for the maximum layer thickness of 35.42, a less compacted armour layer, the porosity is 0.49.

5.4. **Distribution of the data**

Since the normal distribution is a very pleasant distribution to work with, the assumption that the distribution of the damage is normal is very favourable. However the outcome of a check if the damage indeed follows a normal distribution is negative. There are multiple ways to continue with this observation, the following 2 are treated and discussed in this thesis.

1) The Central limit Theorem; when independent stochastic variables, from which none is dominating, is summed, the result is a stochastic variable that is normally distributed, regardless the distributions of the summed variables.

2) Applying a transformation to the input data points such that the outcome better fits a normal distribution.

5.4.1. **Central limit Theorem**

By slicing the breakwater structure into three sections, the result of a test run is 3 variables of which each variable could contain its own distribution. The central limit theorem actually states that by not slicing the breakwater into multiple sections, or summing up the obtained 3 variables, the one variable that is left should be more normally distributed than looking towards the 3 variables separately.

This of course implies that the total set of data points is only 7 points per methodology type and therefore the confidence bands will be bigger, which is not desirable since it makes comparisons harder to do.

When calculating the Anderson-Darling statistic, which shows how well data fits to a particular distribution, it was quite clear that the use of 3 sections did not lead to a good fit of the normal distribution. Although the data points obtained from using one section did not show great results in the goodness of fit test, the results were significantly better.

5.4.2. **Transformation of input data**

By transforming the data points obtained from the test, the transformed data is more normally distributed than the original data. This way the data obtained due to splitting the breakwater structure in multiple sections can be preserved.

The disadvantage is that for any conclusion drawn from the transformed data, the transformation should be taken into account. Also when comparing different test sets with each other both test sets should be undergoing the same transformation.

<table>
<thead>
<tr>
<th>Test set</th>
<th>Standard deviation</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real storm</td>
<td>0.663</td>
<td>21</td>
</tr>
<tr>
<td>Theoretical storm</td>
<td>0.637</td>
<td>21</td>
</tr>
<tr>
<td>CM100</td>
<td>0.67</td>
<td>18</td>
</tr>
<tr>
<td>CM120</td>
<td>0.56</td>
<td>15</td>
</tr>
</tbody>
</table>

*Table 10: Standard deviation of the relative damage of different test sets*
Since the mean for the damage of every test set is different not the total damage is used to determine the transformation function, but the relative damage compared with the mean of the test set. Using the relative damage of each test run from each set to determine the transformation is only possible if it is assumed that real standard deviation of the relative damage of separate test sets is equal.

This can be checked with the F-test for the stability of the variance.

\[ F_t = \frac{Var_1}{Var_2} \]  
(43)

\[ F(v_1, v_2, 2.5\%) < F_t < F(v_1, v_2, 97.5\%) \]  
(44)

With \( v_1 = n_1 - 1 \) and \( v_2 = n_2 - 1 \) the stability of the variances can be checked. The biggest difference in standard deviation is between the theoretical storm and the CM120. The degrees of freedom for the theoretical storm are 20 and for the CM120 are 14. The \( F_t \) value should be between 0.38 and 2.84, which it is since this is 1.28. In Table 11 is indicated which test sets do have comparable standard deviations.

It shows that the standard deviations of the relative damages are comparable for all the different cases and therefore the same transformation can be applied on each of the test sets.

<table>
<thead>
<tr>
<th></th>
<th>( F(v_1, v_2, 2.5%) )</th>
<th>( F(v_1, v_2, 97.5%) )</th>
<th>( F_t )</th>
<th>Comparable ( \sigma^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real storm – Theoretical storm</td>
<td>0.41</td>
<td>2.46</td>
<td>0.92</td>
<td>Yes</td>
</tr>
<tr>
<td>Real storm – CM100</td>
<td>0.4</td>
<td>2.56</td>
<td>1.04</td>
<td>Yes</td>
</tr>
<tr>
<td>Real storm – CM120</td>
<td>0.38</td>
<td>2.84</td>
<td>0.72</td>
<td>Yes</td>
</tr>
<tr>
<td>Theoretical storm – CM100</td>
<td>0.4</td>
<td>2.56</td>
<td>0.89</td>
<td>Yes</td>
</tr>
<tr>
<td>Theoretical storm – CM120</td>
<td>0.38</td>
<td>2.84</td>
<td>1.28</td>
<td>Yes</td>
</tr>
<tr>
<td>CM100 - CM120</td>
<td>0.36</td>
<td>2.9</td>
<td>0.7</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 11 F-test for the stability of the variance

The transformation that should be applied is Eq. (45), with this transformation the transformed data set shows a fit with the normal distribution with a significance level of 0.027. In Figure 49 the fit of the untransformed data and the transformed data with the normal distribution is shown.

\[ 0.54045 + 0.752311 \times LN \left( \frac{X + 0.97532}{1.72513 - X} \right) \]  
(45)

The use of this transformation makes it possible to use the full set of data points, which are obtained by slicing the breakwater structure in 3 sections, to be considered normally distributed. Since more data points are used the confidence band is smaller, which is preferable. But the use of this transformation will complicate matters, since every conclusion drawn will be on transformed data and not on the real data.

To make results and conclusions better understandable the transformation of data will not be used and the central limit theorem will be applied, reducing the amount of data points per test set since less data points fit better to a normal distribution.
5.5. **Damage parameter**

- $N_{od}$
  The means for the various model storm types vary between 1.72 and 3.95. According to Van der Meer (1988) this is on the high side of severe damage and even much more. The qualitative damage analysis is therefore not really in agreement with the damage definition of Van der Meer (1988).

- $N_{od+}$
  The means vary between 1.15 and 2.29. For the real storm and the theoretical storm the standard deviation is relatively smaller than the standard deviation for the original $N_{od}$, for the classical testing method this is relatively the same. This parameter takes into account that movement of N cubes causes less than N cubes of erosion, although the formulae for stability are based on $N_{od}$, erosion is actual damage.

As a result of all the tests $N_{od+}$ is on average $35.2\% \pm 2.3\%$ (95% confidence) lower than $N_{od}$.

- $A_{e}$
  This parameter is an extension of $N_{od+}$ and calculated since erosion is actual damage. It depends on the erosion in any direction, so it does not matter how pores are taken into account with extraction since the extraction of pores is counted equally no matter in what direction it is. But erosion could happen on a large part of the upper armour layer, which means the value for this parameter is really high, but not cause Initiation of destruction. While if a small part of the upper armour layer is eroded, small value for the area, Initiation of destruction could still have happened.

The usability of erosion area could be questioned, since the way erosion area is obtained is done by a new method. To discuss the use of this method, two 3D models and its erosion area is compared with the erosion area calculated with $N_{od}$.

In Figure 50 the measured erosion profile with the 3D (assumed to be real), is plotted in the same graph as the calculated erosion profile with $N_{od}$. Between 0 and 40 mm an erosion area is calculated, with an almost similar erosion depth as is measured, but the measured erosion area is quite a bit wider. Also at 180 mm erosion is calculated which looks comparable to the measured erosion at 160 mm, but again more erosion is measured than calculated.

The erosion area is:

- For the measured profile: 376 mm$^2$
- For the calculated profile: 235 mm$^2$

![Figure 50 Erosion area measured with 3D and calculated with $N_{od}$ plotted in the same graph](image)

![Figure 51 Erosion area measured with 3D and calculated with $N_{od}$ plotted in the same graph](image)
In Figure 51 another measured profile is plotted against a calculated profile, there seem to be even more similarities and the erosion area for both are almost the same.

The calculated erosion profile looks promising since there are locations with similar looking erosion, but the erosion is underestimated. This could be due various reasons; number of cubes taken into account for erosion, settlement not taken into account, amount of pores contributing to erosion etc. Since the performance of this method is not good enough the erosion area will not be used in the comparisons, but if more work is done on improving this method how the parameter is calculated, possibly in future work this could be used.

In the comparison of final damage of methods, \( N_{od^+} \) is used and for the damage evolution \( N_{od} \) is included as well since for more steps this parameter is known.

### 5.6. Real storm

With the real storm 7 tests have been conducted, from which 2 tests were finished after the second peak. It is assumed, based on the damage progression of the other 5 storms that after the second peak no more damage would have occurred and that stopping these test earlier did not influence the results.

#### Qualitative damage description

All of the tests ended in the region of Initiation of Iribarren’s damage, some were still close to the region of initiation of damage and one of the tests was very close to initiation of destruction.

#### Visual counting

Seven test sets have been done for the real storm, with the assumption that the data is normally distributed the following parameters are obtained.

For \( N \);

\[
\mu_N = 63.29 \quad \text{with} \quad \sigma_N = 33
\]

All the data points in the data set are within the boundaries for spurious errors and thus none of them is assumed to be an outlier. From the data points is now the dimensionless damage parameter determined, the mean is equal to \( N_{od} = 2.67 \) with a standard deviation of 1.39. With the student-t test the 90% confidence margin is ±1.02.

A notable observation is that according to Van der Meer (1988) severe damage is occurring for a \( N_{od} = 1-2 \); the original \( N_{od} \) is already quite beyond that and \( N_{od^+} \) is on the upper side of severe damage.

\( N_{od^+} \)

Looking at the \( N_{od^+} \) value the mean value is 1.74 with a standard deviation of 0.77. These values are significantly lower than the original \( N_{od} \) values, which makes sense since there is some kind of recovery process where cubes fill the holes created by extraction of other cubes. And for the \( N_{od^+} \) value this actually means that 2 cubes only cause 1 cube of erosion.

The 90% confidence margin for this mean is ±0.57.

#### 5.6.1. Damage evolution

The real storm and the theoretical storm should be compared also based on the damage evolution, since the damage evolution could tell a lot about the comparability of the real storm with the theoretical storm.

Because the damage progresses with the duration of the storm, the exact damage is not considered but the normalized damage is considered. So with the comparison of the evolution, the amount of damage is not of importance, but only the evolution.

For the damage evolution both the parameters \( N_{od} \) and \( N_{od^+} \) are used.
The evolution of the two parameters look quite identical, this is because the amount of damage is not of importance anymore and $N_{od+}$ is based on the original $N_{od}$.

The increase of damage is quite linear until some steps before the second peak of the storm, from that point there is little increase towards maximum damage.

Looking to the damage evolution in terms of $N_{od}$ which is not normalized, Figure 54 is obtained.

The things that can be noticed from this figure are:

- Increase of the damage is rather linear
- At a certain moment in time (test step 16) no more damage is happening.

There is a point where decrease of damage seems to happen, but this is explained by the fact that 2 storms do not have more data from this point on and therefore the mean of all the storms decreases.
5.7. Theoretical storm

Qualitative damage description
Most of the test runs were in the region of Initiation of Iribarren’s damage, but only just. There were areas where the extraction of units of the bottom armour layer was possible but these were just small areas. And one of the test runs was still in the region of Initiation of damage.

Visual counting
Seven test sets have been done for the theoretical storm, with the assumption that the data is normally distributed the following parameters are obtained.

- For N; $\hat{\mu}_N = 41$ with $\sigma_N = 16.4$

None of the data points are outside the boundaries where they should be assumed an outlier according to the statistical check.

The mean value for $N_{id} = 1.72$ with a standard deviation of 0.69, the 90% confidence margin is ±0.51.

Nod+
The mean for the $N_{od+}$ for the theoretical storm is 1.15 with a standard deviation of 0.42. The 90% confidence margin for the mean is ±0.31.

5.7.1. Damage evolution
Similar as for the damage evolution during the real storm the damage evolution for the theoretical storm will be shown with both parameters, although it is already known that the two parameters will follow a similar evolution.
The damage evolution for the theoretical storm follows a more exponential growth up to a certain point, where (almost) the maximum damage is reached. This point is after the step after the peak, from that point there is little to no increase of damage.

Looking to the damage evolution in terms of $N_{od}$ which is not normalized, Figure 57 is obtained.

The things that can be noticed from this figure are:
- Increase of the damage seems exponential
- At a certain moment in time (test step 17) no more damage is happening.

![Figure 57 Damage evolution of the theoretical storm in $N_{od}$](image-url)
5.8. Classical testing method

For the classical testing method the steps until the 100% steps have been discussed since these should represent the storm, but also the 120% steps have been discussed to see how these steps influence the damage. When discussing the 100% steps this is mentioned as CM100 and when considering the 120% this is abbreviated as CM120.

Qualitative damage description

During the CM100 one of the test runs reached Initiation of destruction where this is 2 test runs for the CM120. Due to reaching Initiation of destruction the tests were stopped and therefore for these 3 tests no exact data is available which can be used for the statistical analysis.

For the CM100, most of the tests were in the region of Initiation of Iribarren’s damage with one very close to initiation of destruction and one still in the region of initiation of damage.

For the other CM120 tests, all the tests were already deep into the region of initiation of Iribarren’s damage.

Visual counting method

With the assumption that the data is normally distributed the following parameters are obtained.

- For the CM100 \( \mu_N = 53.17 \) with \( \sigma_N = 25.15 \)
- For the CM120 \( \mu_N = 93.8 \) with \( \sigma_N = 35.54 \)

Again none of the data points are considered outliers, the \( N_{od} \) values for these steps are:

- For the CM100; mean \( N_{od} = 2.24 \), \( \sigma_{N_{od}} = 1.06 \), 90% margin is \( \pm 0.87 \)
- For the CM120; mean \( N_{od} = 3.95 \), \( \sigma_{N_{od}} = 1.49 \), 90% margin is \( \pm 1.3 \)

\( N_{od}^+ \)

The \( N_{od} \) values for the CM100 and CM120 are respectively:

- Mean \( N_{od}^+ = 1.43 \), \( \sigma_{N_{od}^+} = 0.74 \), 90% margin is \( \pm 0.61 \)
- Mean \( N_{od}^+ = 2.29 \), \( \sigma_{N_{od}^+} = 0.83 \), 90% margin is \( \pm 0.79 \)

Three peaks

The 100% steps of the classical testing method executed in this research can be considered as three different peaks, because every step is 330 waves long which is comparable to the duration of the peak of the real storm.

The damage after each of these steps is:

- 1st 100% step; mean \( N_{od} = 1.33 \) with a standard deviation of 1.15
- 2nd 100% step; mean \( N_{od} = 1.89 \) with a standard deviation of 1.06
- 3rd 100% step; mean \( N_{od} = 2.24 \) with a standard deviation of 1.06

Initiation of Destruction

It should be taken into account that for the CM100 one storm and for the CM120 2 storms reached initiation of destruction. This means that these tests were not able to use in the statistical analysis, but they actually should since these tests will increase the mean damage level.

Therefore is chosen to take the values of test nr 2 from the CM120 tests to replace the storms that were neglected. For this test are the highest damage values found, without this test reaching initiation of destruction. Therefore the damage values for the storms that reached initiation of destruction and were neglected should have even higher values.

The damage values are now:

<table>
<thead>
<tr>
<th></th>
<th>CM100</th>
<th></th>
<th>CM120</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{od} )</td>
<td>Mean</td>
<td>Stand. Dev.</td>
<td>90% Margin</td>
</tr>
<tr>
<td>( N_{od} )</td>
<td>2.77</td>
<td>1.71</td>
<td>±1.25</td>
</tr>
<tr>
<td>( N_{od}^+ )</td>
<td>1.7</td>
<td>0.99</td>
<td>±0.72</td>
</tr>
<tr>
<td>( N_{od} )</td>
<td>4.52</td>
<td>1.57</td>
<td>±1.15</td>
</tr>
<tr>
<td>( N_{od}^+ )</td>
<td>2.58</td>
<td>0.84</td>
<td>±0.62</td>
</tr>
</tbody>
</table>

*Table 12 Damage values classical testing method, with assumptions for the neglected storms*

Remember that this are not the exact values, since the damage values for the neglected storms are probably higher than what is assumed.
5.9. Discussion on the damage

5.9.1. Overview damage results
In this section a short recap is given on the damages of all the different storms.

\( N_{\text{nd}} \)
In Table 13 the mean and standard deviations of the different storms is given, for these values the probability density functions are displayed in Figure 58.

<table>
<thead>
<tr>
<th>Storm type</th>
<th>Mean</th>
<th>Stand. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real storm</td>
<td>2.67</td>
<td>1.39</td>
</tr>
<tr>
<td>Theoretical storm</td>
<td>1.72</td>
<td>0.69</td>
</tr>
<tr>
<td>CM100</td>
<td>2.77</td>
<td>1.71</td>
</tr>
<tr>
<td>CM120</td>
<td>4.52</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Table 13 Mean and standard deviation for \( N_{\text{nd}} \) of the different storms

\( N_{\text{nd+}} \)
In Table 14 the mean and standard deviations of the different storms is given, for these values the probability density functions are displayed in Figure 59.

<table>
<thead>
<tr>
<th>Storm type</th>
<th>Mean</th>
<th>Stand. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real storm</td>
<td>1.74</td>
<td>0.77</td>
</tr>
<tr>
<td>Theoretical storm</td>
<td>1.15</td>
<td>0.42</td>
</tr>
<tr>
<td>CM100</td>
<td>1.7</td>
<td>0.99</td>
</tr>
<tr>
<td>CM120</td>
<td>2.58</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Table 14 Mean and standard deviation for \( N_{\text{nd+}} \) of the different storms
5.9.2. Damage variability
Before the comparisons have been done, the damage variability has been observed. Looking towards the damage, within one type of testing methodology, the variability is really high. This variability will not only make it hard to do proper comparisons, but it also tells something about the possibility that tests of the stability of breakwaters will give unwanted results.

The damage variability is observed for the moment in the classical method that the average damage is about 0.5 $N_{od}$ since this is the value on which breakwaters are designed. And to see the influence in this variability due to the placement of the cubes, tests have been conducted where the only variable was the placement of the cubes.

$N_{od}$ is 0.5
In Table 10 it is clear that the damage variability in terms of $N_{od}$ is high for the CM80 tests. The statistical parameters are:

- $\mu_{CM80} = 0.5$ & $\sigma_{CM80} = 0.45$

Looking towards the relative damage with respect to the mean, the standard deviation for CM80 is 0.89.

With Eq. (39) the following values are obtained;
- For CM80, the mean significant wave height is 3.06 m with a standard deviation of 0.375 m

Calculating the confidence boundaries, it can be said that with 90% confidence using a design significant wave height within the boundaries of 2.78 m and 3.33 m will result in similar damage due to the CM80, if all other conditions are kept similar. This means a difference between the upper and lower boundary of 0.55 m for CM80.

Using a 90% confidence level for the parameter $N_{od}$ does not necessarily mean that the variations in this parameter has a similar relation with the design wave conditions.

Influence placement of the cubes
The results of the tests to see the influence of the placement of the cubes are shown in Table 16.

- $\mu_{DAMV} = 4.5$ & $\sigma_{DAMV} = 2.08$

The relative damage with respect to the mean is 0.46. With these values it is clear that the contribution of the placement of the cubes is of enormous importance towards the variability.

Due to the impossibility to keep the configuration of the randomly place cubes as a constant the influence of other variables, like seeding number, have not been determined.
6. Analysis

6.1. Verification of the classical testing method

The classical testing method has been used for many years now, without verifying the accurateness of its outcomes. By comparing the test runs with the real storm, assuming these results are closest to what in reality would happen for this one storm, with the classical testing method it should verify or not whether with the classical testing method accurate results (close to reality) are obtained.

In the previous sections the results from the tests with the real storm and the test with the classical method are shown, in this section these results will be compared.

![Figure 60: Probability density function of the Nod+ for the real storm and the CM100 and CM120](image)

With the assumption that Nod+ is normally distributed Figure 60 has been drawn. Based on the figure it already shows that the classical method seems to do exactly what it should, it is comparable in the 100% steps and the 120% steps introducing safety by showing some more damage.

A P-value of 0.93 for the difference between \( \mu_{real} \) and \( \mu_{100\%} \) is obtained (Table 17), which means that with more than 95% confidence it can be said that the means are different.

<table>
<thead>
<tr>
<th>CM100</th>
<th>( N_{odd}^{+} )</th>
<th>t-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nod+</td>
<td>0.084</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>CM120</td>
<td>1.95</td>
<td>0.037</td>
<td></td>
</tr>
</tbody>
</table>

Table 17: t-values and P-values for the differences between the real storm and the classical testing method

The assumption for the damage values for the neglected storms is a choice based on the fact that these reached initiation of damage and there is no exact data available. What can be assumed is that these values are probably underestimated. In the case the real damage values were known, assuming that the damage values chosen are underestimated, the p-values would be lower and therefore increasing the certainty that the null hypothesis is rejected correctly.

What already was noticed based on the figures is now also supported by the statistical analysis, the 100% steps are comparable with the simulated real storm and the 120% steps can be used as a safety margin since it is showing more damage than the simulated real storm.
6.1.1. Safety factors

If it is assumed that the breakwater structure used in this research was designed for a purpose, in the design process one considered a certain $N_{od}$ which should be on the safe side of the mean $N_{od}$ for the structure. This safety is introduced with Eq. (9) and based on the test results for the classical method, the $N_{od}$ that was expected if no safety factor was used to increase the cube size.

In the lowest criteria a safety factor is applied of 1.08, which actually means that the original $d_0$ was 1.074 m. With this $d_0$ and using the values $s_{om} = 0.0427$ and $\Delta = 1.25$ which is obtained from the research data and $N_x = 4000$ (which is used by Verhagen (2003) as was used as duration of a storm), the $N_{od}$ value that was used to design on was 4.15.

With the $d_0 = 1.16$ m the new expected $N_{od}$ is the $N_{od}$ that was found in the test series of the classical testing method 2.77 with a standard deviation of 1.71. Based on these values and the assumption that $N_{od}$ is normally distributed a probability of 0.21 is found while executing the classical method as was done in this research the breakwater shows more damage than $N_{od}$ is 4.15.

This means two things:

1) There is a 21% chance that the breakwater in a test is seen as too weak while it is stable enough

2) There is a 79% chance that the breakwater is tested as stable which leads to no changes in the design and then if the same distribution of damage holds for prototype scale, there is a 21% chance if a storm is happening with the design conditions that the breakwater will show equal or more damage than $N_{od}$ is 4.15.

The first one will probably lead to a safer design or at least a reconsideration of the design. The second one is exactly why safety factors are used, they should decrease the change of failing (showing higher $N_{od}$ than which was designed for) when a storm happens with the design conditions.

So, with the safety factor of 1.08 a probability of failure of 0.21 is considered, while the coastal engineering manual considers a probability of failure of 0.4 (Engineers, 2002). The safety factor used in the coastal engineering manual is therefore extra safe.

6.2. Comparison of the real storm and the theoretical storm

The comparison of the real storm with the theoretical storm has been done on two aspects, the first one is the final damage of the storms and the second is the damage evolution. The comparability of both aspects will be discussed separately, since the outcome will be handled independently of each other. If for instance the final damage is not comparable but the evolution of the damage is the theoretical storm is comparable in shape but not in magnitude.

6.2.1. Final damage

With the assumption that $N_{od+}$ is normally distributed, Figure 61 has been drawn. The figure already shows that the precision of the damage due to the theoretical storm is significantly higher and that on average de damage is lower.

The t-value obtained for the difference in the means is 1.78; this resulted in a two-tailed p-value 0.1. So it can be concluded that with 90% confidence the means are the same.

Although with 90% confidence the means are the same, it shows that when it is possible to conduct more tests to increase the precision for the damage due to the real storm, this could lead to less confidence and therefore not stating that the means are the same or to an increased confidence that the means are the same.
6.2.2. Damage evolution

In the sections with the results for the damage due to the real storm and theoretical storm, the damage evolution under both storms is shown.

Instead of calculating the t-value and p-value of the difference for every single step, it is much easier to plot the means with the confidence boundaries. If the boundaries for a specific confidence level cross each other, it can be said that with that specific confidence level the means are the same. If at any duration this cannot be said, the damage evolution is assumed not to be similar.

![Figure 62 Comparison of the damage evolution for the real storm with the damage evolution for the theoretical storm.](image)

In the figure, it is quite clear that the damage evolution of both storms is not comparable. For the theoretical storm, it takes longer to develop, which could probably be accounted to the slow build-up while the real storm reaches its peak already around 2300 waves.

If the first part (0-2000 waves) of the theoretical storm would be taken out, the storms have similar behaviour, but since from the total damage analysis is seen that the amount of damage for the theoretical storm seems to be lower, the magnitude should probably be increased. The first part of the damage evolution of the theoretical storm is taken away and it is assumed that the damage that happened in this part did not happen at all. The comparison of this shortened version with the damage evolution of the real storm looks like Figure 63. This is based on assumptions and the figure is only meant for visual representation and not as actual data.

In the figure, it looks like when the build-up of the theoretical is shortened in time (so with less waves reaching the peak of the storm), the damage evolution is quite comparable.

![Figure 63 Shorted version of the damage evolution due to the theoretical storm compared with the damage evolution due to the real storm](image)
Also comparing the storms based on the real damage values, so not the normalized values, Figure 64 was obtained.

Again it is clear that the damage during the real storm increases faster than during the theoretical storm. Another interesting observation is that both storms reach a certain point where the damage converges and no more/little damage is happening after this point. For the real storm before this point the damage reaches a higher level than at this point, this is because 2 of the 7 tests were stopped around this point due to initiation of destruction.

If the focus is laid on this convergence point, and the damage evolution of the theoretical storm is shifted such that the convergence points are located at the same location in the number of waves (minus 1000 waves), Figure 65 is obtained. The figure shows that on 2 locations the confidence boundaries are not overlapping but on all the other part of the storms they are. So considering both Figure 63 and Figure 65 it can be concluded that the theoretical storm can be comparable with the real storm if the buildup of the storm is shortened.

**Delta-N_{od}**

The evolution of the damage of the storms is not directly comparable, only by shifting the theoretical storm some similarities are visible. To try to understand the damage evolution better the delta-N_{od} as a function of the significant wave height and the previous N_{od} has been observed.

In Figure 66 and Figure 67 the delta N_{od} is plotted against the N_{od} of the previous step. The dots plotted on the line are the significant wave height of the step in which this delta N_{od} happens, with the color indicating the height. What can be seen is that there are some extremes for both cases and that the significant wave height is at least 4.6 cm for these extremes.

Some things can be noticed from these plots.

1) The extremes of Delta-N_{od} are significantly higher for the real storm than for the theoretical storm
2) If for both the real storm and theoretical storm a certain high delta N_{od} line is drawn (considering higher delta N_{od} for the real storm) the delta-N_{od} above this line only happen with a significant wave height higher than 4.5 cm (3.6 m on prototype scale)
3) The higher the previous N_{od} the less extremes (above the black line) are occurring.
Figure 66 Delta $N_{od}$ as function of $N_{od,n-1}$ and the significant wave height plotted as dots for the real storm

Figure 67 Delta $N_{od}$ as function of $N_{od,n-1}$ and the significant wave height plotted as dots for the theoretical storm

Not only the final damage of the real storm is higher, the delta-$N_{od}$ is on average also almost twice as high for the real storm as it is for the theoretical storm and the extremes for the real storm are also much higher.

The average delta-$N_{od}$ with 95% confidence margins is $0.27 \pm 0.082$ and $0.14 \pm 0.036$ for the real storm and the theoretical storm respectively. This indicates that on a 95% confidence level the means of the delta-$N_{od}$ for both the storms are not comparable.
6.3. **Comparison of the theoretical storm with the classical testing method**

Since the theoretical storm is not really comparable (in damage) to the simulated real storm, it can be seen as a storm on itself. The peak of this storm is the same as the peak of the simulated real storm and therefore the same as the 100% step of the classical testing method. Since the test program in the classical method is only based on the peak of a storm, the same classical method used for the simulated real storm should be used for the theoretical storm.

In the comparison of the classical method with the simulated real storm the total 100% step of 1000 waves is considered comparable with the final damage of the simulated real storm. And since the theoretical storm is not really comparable in final damage with the simulated real storm, the total 100% step is probably also not really comparable with the theoretical storm. Due to lower damage for the theoretical storm the separate 100% steps of the classical testing method are considered.

The three different 100% steps were already mentioned as three different peaks. In Figure 68 the probability density functions damage in the three 100% peaks drawn with the probability density function of the damage in the theoretical storm. The 1st peak is denoted as CM100a, the second with b and the third with c. Based on the figure it can be said that 2 times 330 waves with 100% shows the most comparable results.

6.4. **Damage development characteristics**

The classical testing method is a method that is commonly used to test breakwaters on their stability, but in the comparison of the classical testing method with both the simulated real storm as with the theoretical storm it can be concluded that for different storm shapes different set-ups of the classical testing method applies.

To decide on how this could be improved the main characteristics of a storm on the development of damage has been observed.

**Damage convergence**

For both the theoretical storm as the simulated real storm the damage converges to a certain point from which on not more damage is happening.

For the simulated real storm this is step 16, this is 2 steps after the second peak. From this step on the significant wave height does not become higher than 3.9m, which is 90% of the peak of the storm.

For the theoretical storm this is step 17, this is 2 steps after the peak of the storm and from this step on the significant wave height does not become higher than 4.06m, which is 94% of the peak of the storm.

**Damage concentration**

When considering the part of a storm in which most of the damage has happened, it is noticeable that for both the theoretical storm as for the simulated real storm 80% of the damage happened above an average significant wave height that is 77% of the significant wave height of the peak of the storm.

Combining the results of both storms, with 90% confidence it can be said that 80% of the damage happened above a significant wave height that is 75% of the significant wave height of the peak of the storm. Considering the peak of the to be 4.32m as was used for the laboratorial tests the significant wave height above which 80% of the damage happens is 3.24m.
Knowing that in the tail of the simulated real storm below 3.9m and in the tail of the theoretical storm below 4.06m no more damage is happening, it is quite clear that the concentration of damage is located around the peak including more of the build-up than the tail of the storm. In Figure 69 is indicated where theoretically the 80% of the damage occurs.

On average 0.5% of the remaining 20% happens in the tail (below 90% $H_{\text{peak}}$) of the storm and 19.5% in the build-up (below 75% $H_{\text{peak}}$). The theoretical storm contains 13 steps and the simulated real storm contains 12 steps in this 80% part.

Large damage steps
For the theoretical storm and the simulated real storm the steps in which 6+ cubes moved more than one nominal diameter are considered as steps with large damage. On average the significant wave height for these steps is 3.89 m (90% of the peak of the storm). Changing the definition of large damage from 6+ cubes to 10+ cubes the average significant wave height becomes lower and which is 3.85m. The real storm contains 8 steps above this significant wave height and the theoretical storm 7 steps. But when the damage of the real storm after the 7th step is considered the theoretical and real storm are still not comparable.

Storm build-up
The storm build-up of the theoretical storm and the simulated real storm is completely different. The theoretical storm has 14 steps (5090 waves) before the peak and the simulated real storm has 7 steps (2036 waves) before the peak. Hughes (1993) advises to first do test runs on 50-60% of the significant wave height of the peak for settlement of the armour layer giving it an increased stability. So it can be assumed that with more steps in the storms build-up the armour layer has more time to settle and gain stability.

In the tests to look at the influence of the construction of the armour layer to the damage variability no test runs were executed for increasing the stability of the armour layer (no storm build-up). In these tests a set of 1000 waves with the 100% wave conditions was executed and should therefore be comparable to the classical testing method except the part before the peak. Although much less waves were used the average damage was much higher, this could also indicate the influence of the storm build-up in the stability of the armour layer.

Since the theoretical storm is only different compared with the simulated real storm (which is comparable with the classical testing method) based on storm build-up the results of the theoretical storm, real storm and damage variability tests are plotted against their storm build-up. Figure 70 shows that if the build-up is longer the final damage is becoming lower and converges. The same holds for the standard deviation. This would mean that if the build-up is long enough the results are lower and with more precision. The graph shows an interesting trend, but since it is based on only 3 point from which each point represent a different storm (assumed to be similar except for the storm build-up) conclusions based on this are fragile.
7. Discussion

In this chapter various aspects noticed during the research that should be taken into account in the conclusions are discussed.

Damage parameter

The original $N_{od}$ is well known and commonly used, but the values obtained in the results seem to contradict the qualitative damage analysis. But it is not really clear why the obtained values are not in agreement ($N_{od} = 1-2$ is severe damage) with the qualitative analysis.

The contribution of every cube that moved more than one nominal diameter to damage is taken into account with $N_{od+}$, but in this value small settlement perpendicular to the structure and movement of the cubes of the under layer is not taken into account.

Large damage

With the start of the laboratory tests an orientation test was executed to get an idea about the amount of damage occurring, since this test did not show really high damage the severity of the simulated real storm was not adjusted. In all the storms and repetitions there were some tests that showed quite significant damage and on average the damage level (final damage) was quite high $>1.5 N_{od}$. Normally breakwater structures are designed on a value of $N_{od} = 0.5$, therefore the conclusions drawn on the results of this research could have been different if the averaged damage level (final damage) was around $0.5 N_{od}$.

Assumed damage values

In the classical testing method during the 100% step, one test reached initiation of destruction and during the 120% step; two tests reached initiation of destruction. The values for these tests have been replaced by the highest damage values measured in the research. The test from which these values originate did not reach initiation of destruction and therefore these values could be underestimated. These tests should be taken into account, because they reached high damage levels and neglecting these tests would mean an underestimation of the average damage of the classical testing method.

Testing time

The time it takes to execute a test has not been discussed before in this report, but the 4th sub-research question also incorporates the effort that is needed to obtain the results. Regardless of the results, if a certain method reaches really accurate results but the time necessary is too much, the effort for such a method could be considered not worth it.

The classical testing method is a method that contains 4 steps of 1000 (or more) waves. The theoretical storm is a method that contains (in this case) 29 steps of ±300 waves. Not only the total number of waves, 4000 compared to 8700 waves, but also the numbers of steps are much more for the theoretical storm than for the classical testing method. Focusing on the number of waves, the theoretical storm would already take twice as much time than the classical testing method and considering that every step of 300 waves need to be started, which will take time as well, the theoretical testing method will take considerably more time than the classical testing method.

Storm build-up

The storm build-up could be a stabilizing factor in a storm. The build-up of the theoretical storm is much longer than the build-up of the simulated real storm. In reality a breakwater is subjected to many waves in the same category as the build-up of the design storm before the design storm occurs. This could mean that the stabilizing factor of the build-up in reality is similar for any storm shape. Therefore it could be that if the simulated real storm had a build-up as long as the build-up in the theoretical storm the structure would be more stable during the tests with the simulated real storm, maybe resulting in comparable damages for the theoretical storm and simulated real storm.

$H_{peak}$ and duration storm combination

In the climate data analysis some focus is put on the combination of a certain significant wave height with certain storm duration to calculate the required cube size. This is a very complicated matter and therefore no solution is given on how to incorporate the duration. This combination is important in the comparison of the real storm with the classical testing method, since for the first one it matters but for the latter only significant wave height matters. And different storm duration will lead to different results.

Measurement errors

Measurement errors are an integral part of doing research. In section 3.3.6 the important measurement errors have already been pointed out. When considering $N_{od}$ the errors in the results are mainly due to the errors in the wave loads and the errors in visual counting. Considering $N_{od+}$ the errors in the wave loads and the errors in visual counting are causing the same effect.
as for $N_{tol}$ but for $N_{tol}+$ also the measurement errors due to distortion of the images, refraction of water and picking points in the images occur.

The errors in the wave loads, visual counting and picking points in the images are random errors and are therefore not really a problem. The errors due to the distortion of the images and refraction of the water are bias errors and could become a problem if the pictures are taken from a too close distance. The bias errors are therefore easier to determine and should have been taken out the calculations. Now the error for the distortion of the picture is in the extreme case $1/11$ cube and for the water refraction $1/58$ cube. The distortion of the picture leads to compression of the real image and the water refraction stretches the image below the water level so the errors work against each other.

**Laboratory tests**

Finally, the entire research is based on laboratory tests with a scale of 80 with the reality; the big assumption in laboratory tests is that it represents the reality. All the damage results that have been used in the comparisons are produced with laboratory tests and there is no data available on how such a breakwater would react on prototype scale if subjected to the same storms on prototype scale. Dai & Kamel (1969) did research on the scale effects for tests with rubble mound breakwaters and concluded that the bigger the scale the more significant the viscous forces are which influenced the overtopping results, but the damage did not follow any trend and therefore the scale effects on damage remained unknown.
8. Conclusions and recommendations

The results and analysis of the results is described in chapter 4. In chapter 7 discussions are given on various aspects and based on the observations in these chapters the conclusions on the comparison of testing methodologies are presented in section 8.1 and in section 8.2 recommendations are given towards further research of comparing testing methodologies and finding new or improved methodologies.

8.1. Conclusions

Based on the results and the analysis the research questions have been answered in this section.

*How are the results of stability tests on designed cubic armoured breakwaters comparable, if they are tested through the classical methodology of verification and a simulated real storm?*

In answering this question the main focus was laid on the final damage results of both the simulated real storm and the classical testing methodology.

The statistical analysis shows that the classical testing method with 330 waves per step (increasing the wave height every three steps) and constant wave steepness is doing exactly what it is supposed to do. With 93% confidence it can be concluded that the damage in the steps that should represent the real storm (100% steps) is comparable with the damage due to the real storm.

Based on the formula of Van der Meer (1988) including the safety factors, the safety factors consider the damage variability quite well and are even much safer. This means that the 120% step can be used for safety but this is not necessary, but this step could still give information about the stability under higher load.

*Could real storms be standardized and mimicked in laboratorial tests by using the EMSIT model, if only looking towards the stability of designed cubic armoured breakwaters?*

In this question not only the final damage of both the EMSIT model as the simulated real storm are important but also the evolution of the damage throughout the storm.

The first part of this answer focuses on the final damage. Comparing the theoretical model with the simulated real storm on final damage it can be said that the final damage for the theoretical model is lower but not significantly different and was found that with 90% confidence the both storms are the same.

Second the damage evolution is compared.

Looking at the damage evolution of \( N_{\text{od}} \) with the 90% confidence boundaries (in section 6.2.2) for the real storm and the theoretical storm, the damage evolution is clearly not similar. Shifting the theoretical storm or actually deleting the first part of this storm, makes the damage evolutions look more similar. Finally comparing the delta-\( N_{\text{od}} \) of both storm types shows that the increase of the damage is faster for the real storm and with 95% confidence not comparable with the theoretical storm.

Finally the use of a theoretical model also contains some practical issues. For a certain stone diameter there are multiple combinations of significant wave height for the peak and storm duration which should be tested, since the storms in the future are still unknown.

So, the EMSIT model is in final damage comparable to the simulated real storm, but under predicts the damage. Also considering the evolution of the damage, first the EMSIT model does not correctly predict the damage for the simulated real storm and second it also under predicts the damage increase per step. Therefore it can be concluded that the EMSIT model is not an appropriate model to mimic real storms in laboratorial tests.

*What are the important characteristics of a storm that influences the amount of damage done by this storm?*

Two different storm shapes have been tested, the theoretical storm and the simulated real storm. While observing the damage evolution throughout these storms, the following characteristics for damage evolution were found.

A specific part of the storm with the higher wave heights contributes for a significant part to the final damage. In this research this part started when the storm build-up reaches the \( H_t \) that is 75% of the \( H_{\text{peak}} \) and it ends when the tail of the storm becomes lower than 90% of the \( H_{\text{peak}} \). So the main contribution in the final damage is before and around the peak and the tail of the storm is not important.

The main contributing steps in the final damage are the steps in which large damage happens (6+ cubes moved). The average significant wave height of these steps is 90% of the \( H_{\text{peak}} \), this shows why after the peak below 90% of the \( H_{\text{peak}} \) no more damage occurs. Considering these important steps, it can be concluded that the duration of the 100% step of the classical testing method is quite important.
Finally the build-up of a storm seems to be a part that contributes significantly to the stability of a breakwater. With a longer build-up the stability of a breakwater increases and therefore the final damage becomes lower, the damage variability also become lower increasing the precision of the results. Since the focus of this research was not on this part of the storm, so this conclusion is still very fragile.

Should the classical methodology of verification be replaced or improved, to obtain more accurate results on the stability of cubic armoured breakwaters?

The classical methodology of verification already shows that it works well for the chosen simulated real storm. But the theoretical storm could also be considered as a simulated real storm and since the classical testing methodology is completely based on the peak of a storm, the classical method in this research should also apply for the theoretical storm. It does when a shorter 100% step (660 waves) is considered.

So, the set-up is easy, but the duration of the steps (1000, 2000 or variable amount of waves per step) should be considered really good. Using a large amount of waves for the 60% and 80% step is a logical choice in terms of stabilizing the structure and in reality most probably a breakwater structure is subjected first to multiple storms with lower wave conditions than the design conditions, before a storm with design conditions happens.

The duration of the 100% step should be well considered, this step should represent not only the peak of a storm but also the higher steps around the peak. So, not only a design wave height is important but also a design storm's duration. The duration can be linked to the wave height of the peak of the storm with a contour plot and extrapolating historical data. The main problem is, that for a specific probability of exceedance multiple combinations of $H_{\text{peak}}$ and duration are possible.

Another improvement is not necessarily in the methodology but more in the design process. On the assumption that the tested breakwater structure was designed with safety factors and that the results of the classical testing method were expected, it can be concluded that the safety factors of the Coastal Engineering manual are much safer than the tests showed. If a safety factor of 1.08 was applied a probability of failure of 0.4 was assumed (Engineers, 2002), the variability of the damage showed that 1.08 is related to a probability of failure of 0.21 almost half of what was assumed. The safety factors could be less conservative, which would lead to less safe structures but will reduce the costs of the structures.

Finally if one is interested in the damage evolution for instance for maintenance purposes, the classical methodology of verification could be replaced by a storm model. But at the moment the EMSIT model is not a proper model for this and one should consider the extra time it takes to test with such a model and that due to the damage variability the results are not very accurate. So the question that should be asked, is it worth it to spend extra time on not really accurate results?

With the four sub-questions answered, the main research question can be answered:

How could storms be simulated in the laboratorial tests, to obtain the most useful results on the stability of cubic armoured breakwaters?

The classical methodology of verification is a commonly used method to test breakwater designs; with this research it showed that it is able to represent a real storm on stability of a breakwater. The 100% step of this methodology can be considered as the representation of a real storm. The safety factors proposed (Engineers, 2002) already introduce more than enough safety regarding the 100% step and could maybe have some updating, also because the 120% step gives information on the strength of the breakwater.

But the research also showed that the duration of the 100% step is important to consider. In a storm the part in which the most damage happens is around the peak with the main contributing steps having a high significant wave height compared to the peak. So, the longer this part and the more steps with a high $H_s$, the more damage can be expected.

Observed is, that the tail of a storm does not contribute anymore in the damage and therefore a set-up that only contains the build-up of a storm and the steps around the peak (above a certain significant wave height) is sufficient. The classical method already consists of such a set-up.

From the climate data analysis it can be concluded that the wave steepness during the storm build-up stays constant and in the tail of a storm decreases and since the tail of the storm is considered as not important for the damage it can be concluded that a constant wave steepness in tests can be used.
Finally storms could be simulated with theoretical models, such that the damage evolution can be obtained. However the EMSIT model is not a correct model to use and testing with such a model will costs quite a lot more time while the results are not that accurate.

**General conclusion**

It is possible to improve the classical methodology of verification by connecting the duration of the part in which the greater part of damage happens to the duration of the 100% step. However there are many combinations of $H_{\text{peak}}$ and duration which have the same probability of exceedance. Also the duration of the build-up (60% and 80% steps) could probably be increased for a better stability of the breakwater, but this is still under discussion. Without changing anything the classical methodology has still a good performance and with the safety factors and the 120% step there is no need to doubt the safety of the method. So, on how could storms be simulated in laboratory tests to give useful results the classical testing method can be considered a good method, but there is room for improvement on how conservative both the method and the safety factors are.

Focusing on the prediction of damage evolution the classical methodology of verification should be replaced by a methodology with a theoretical storm. The tested theoretical model is not the right model to produce a theoretical storm to simulate the tested real storm and it should be taken into account that when testing with a storm profile, the testing time will increase significantly. So if is preferred to know the damage evolution and it is considered that the extra testing time is necessary, a correct model to simulate storms still needs to be found.
8.2. Recommendations

Theoretical model
The theoretical storm from the EMSIT model was not comparable in damage evolution and mainly in its damage build-up:
- The used theoretical storm could be scaled to increase its severity, but this would mean that the EMSIT model does not apply on the scaled storm.
- Other theoretical models proposed by Martín Soldevilla et al. (2015) should be tested if these perform better.

Classical testing method
The amount of waves in this method is kept the same for all the tests with this method, therefore it is recommended to research the influence of using more waves since it is recommended to use 1000 to 5000 waves per step.

Storm build-up
Based on only three points a trend is found on the influence of the storm build-up on the final damage and the precision of the results. It is recommended to execute more test sets with different durations for the storm build-up. The results of these test will than confirm the trend or show that no trend is present. If there is indeed a trend present, many of the conclusions drawn should be reconsidered.

Spread in results
The damage results of the real storm and the classical testing methodology contain a significant spread, much more than the results of the theoretical storm. This could indicate that the theoretical storm need to be tested more, to have a similar spread or the real storm and classical testing methodology needs to be testes more to get a better precision. Therefore is advised to conduct more tests for the real storm, if the precision gets better, the classical testing methodology needs to be tested more as well, if the precision stays the same or get worse, the theoretical storm needs to be tested more.

Large damage results
The damage results from the laboratory tests in this research were quite large; normally a breakwater structure is designed on a N_{od} of 0.5. To be more in line with the N_{od} = 0.5, it is advised to repeat a similar research with or bigger cubes, or less severe storms.

Damage assessment
It is advised to work more on new techniques of measuring damage (like 3D) and finding correct damage parameters which can be used in the designs of new breakwater structures, since N_{od} does not seem to be covering the exact damage. Also the method in which erosion area is calculated based on the moved cubes looks promising and could be developed more, this would lead to a method in which accurate erosion profiles could be obtained without the need of 3D methods.

H_{a,peak} and duration storm combination
If theoretical storm models are preferred to design breakwaters on, more research should be done on how to assign a certain significant wave height of the peak of the storm to the duration of the storm. Already a start was made with a contour plot of the amount of storms plotted with significant wave height of the peak as a function of the duration of the storm (Considering the duration in which 80% of the damage happens). To choose a combination of duration and significant wave height of the peak for a certain lifetime and probability of failure, such a contourplot should be extrapolated. Also a combination has a lower probability of occurrence then if only the significant wave height is considered, so when working with combinations other orders of probabilities should be considered.
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Appendices

Appendix I – Test plan

Appendix II – SwanOne

Appendix III – Process of the cubes

Appendix IV – Erosion calculation
I. Test plan
In this appendix the protocol for conducting a test is described and the test plan, results and measurement per test are given.

I.1. Protocol
The steps that have been taken to conduct each test are described here.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Repair the filter layer if necessary</td>
</tr>
<tr>
<td>2</td>
<td>Take picture for the purpose of the 3D model of the filter layer</td>
</tr>
</tbody>
</table>
| 3   | Construct the armour layer.  
|     |   - Two layers  
|     |   - 17 cubes per line  
|     |   - 5 lines per color |
| 4   | Take picture for the purpose of the 3D model of the armour layer |
| 5   | Fill the flume with 30 cm of water. |
| 6   | Take 1 picture perpendicular to the slope of the structure |
| 7   | Calibrate the wave gauges |
| 8   | Input the test step characteristics into the generation program, which is developed at LIM/UPC.  
|     |   - Significant wave height  
|     |   - Peak wave period  
|     |   - Number of waves  
|     |   - JONSWAP gamma coefficient = 3.3  
|     |   - JONSWAP alpha coefficient = 0.0081  
|     |   - Discretization step of the spectrum = 1 mHz |
| 9   | Let the generation program calculate a wave pattern |
| 10  | Start the measurements of the wave gauges |
| 11  | Start the time series |
| 12  | After the waves run out stop the measurements of the wave gauges |
| 13  | Wait until the water is still and take another picture |
| 14  | Repeat steps 8-13 until the test plan is finished |
| 15  | Empty the flume |
| 16  | Deconstruct the armour layer |
| 17  | Transfer the pictures to the hard drive |
| 18  | Convert the measurements from the wave gauges to readable txt. Files |

I.2. Test plans
The test plans, measurements and results are given on the following pages.
### Table 18 1st test plan for the real storm

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**Master Thesis**

**Coastal Engineering**

**TU Delft**
### Theoretical storm

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Table 37 6th test plan for the classical testing method

Classical testing method
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II. SwanOne

In this appendix the transformation of the storm from offshore is described. The real storm is measured at a depth of 65m, because the water depth in the flume can only be 30cm this means that with a scale of 1:80 the storm has to be moved to a depth of 24m.

SwanOne is a tool which has been used to determine the change of significant wave height and peak period when the storm is propagating to a depth of 24m.

II.1. Currents

To determine the currents at the location of the storm the closest buoy that has measured sea currents in the Mediterranean Sea is used. The Tarragona buoy is located 155km from the XIOM Blanes Buoy at 1.47° E, 40.68° N. In Table 46 the characteristics of the buoy are given and in Table 47 the maximum currents per month are given measured in a period between 2004 and 2016.

Compared to the XIOM Blanes Buoy, the direction 154-200 means that the current is coming from the coast, which seems possible but the current could never be this high.

The maximum current going straight towards the coast is going into the direction 326 degrees from March 2006 with a velocity of 0.832 m/s.

The maximum long shore current is going into SW direction and is about 0.796 m/s measured in November 2005.

These currents are measured at a point where the water depth is 688m and 50-55km from the coast, the currents at the location of the XIOM Blanes Buoy are most probably lower than this.

<table>
<thead>
<tr>
<th>Tarragona Buoy 2004 - 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurement frequency</strong></td>
</tr>
<tr>
<td><strong>Code</strong></td>
</tr>
<tr>
<td><strong>Depth</strong></td>
</tr>
<tr>
<td><strong>Initiation of measurements</strong></td>
</tr>
<tr>
<td><strong>Last measurements</strong></td>
</tr>
<tr>
<td><strong>Sensor type</strong></td>
</tr>
<tr>
<td><strong>Model</strong></td>
</tr>
</tbody>
</table>

Table 46 Characteristics Tarragona Buoy

<table>
<thead>
<tr>
<th>Month</th>
<th>Maximum mean current velocity (cm/s)</th>
<th>Propagation direction of current</th>
<th>Year</th>
<th>Day</th>
<th>Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>89</td>
<td>199</td>
<td>2015</td>
<td>28</td>
<td>02</td>
</tr>
<tr>
<td>February</td>
<td>85.5</td>
<td>180</td>
<td>2016</td>
<td>28</td>
<td>00</td>
</tr>
<tr>
<td>March</td>
<td>83.2</td>
<td>326</td>
<td>2006</td>
<td>05</td>
<td>16</td>
</tr>
<tr>
<td>April</td>
<td>73.4</td>
<td>211</td>
<td>2016</td>
<td>16</td>
<td>07</td>
</tr>
<tr>
<td>May</td>
<td>91.4</td>
<td>154</td>
<td>2005</td>
<td>07</td>
<td>00</td>
</tr>
<tr>
<td>June</td>
<td>69.1</td>
<td>163</td>
<td>2010</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>July</td>
<td>78.5</td>
<td>160</td>
<td>2005</td>
<td>07</td>
<td>10</td>
</tr>
<tr>
<td>August</td>
<td>67.9</td>
<td>129</td>
<td>2006</td>
<td>05</td>
<td>19</td>
</tr>
<tr>
<td>September</td>
<td>69.1</td>
<td>222</td>
<td>2015</td>
<td>30</td>
<td>17</td>
</tr>
<tr>
<td>October</td>
<td>69.1</td>
<td>267</td>
<td>2005</td>
<td>17</td>
<td>07</td>
</tr>
<tr>
<td>November</td>
<td>79.6</td>
<td>213</td>
<td>2005</td>
<td>06</td>
<td>10</td>
</tr>
<tr>
<td>December</td>
<td>98.4</td>
<td>185</td>
<td>2014</td>
<td>09</td>
<td>00</td>
</tr>
</tbody>
</table>

Table 47 Maximum mean currents per month measured in 2004 to 2016
II.2. Wind

The wind data is taken from a simulation point (SIMAR-2118140) close to the XIOM Buoy Blanes, at the location 2.83° E, 41.67° N. This simulation point contains wind data from 01-01-1958 to 15-06-2016.

For every hour during the storm the mean wind velocity and direction is known.

Table 48 Wind velocities during the December storm of 2008

The maximum wind velocity during the storm is 16.91 m/s from the direction 72 degrees, happening at the same time as the peak of the storm.

II.3. Comparing input parameters

Since the currents and wind velocities during the storm are not known at this location it has been decided to determine the influence of these two parameters on the results of SwanOne.

First run input:
- Bottom Profile starting at -65m (BOTTOM.txt)
- Angle coast to normal 180 degrees
- No Currents
- Water depth = 0m
- Wave setup = yes
- Wind Parameters
  - 0 m/s (Total maximum)
  - 0 degrees
- Wave characteristics
  - Hm0 = 1 m
  - Tp = 9.4 s
  - Phi = 0
- Output locations
  - 1510m (location of depth -24m)

For the following runs the same input as the first run is used, only one or more thing is changed explained per run.

Second run input:
- Wind, max velocity 16.91 m/s from the direction 72 degrees (244.7 degrees when the angle of the coast to normal is taken 180 degrees)

Third run input:
- Long shore current, with flow velocity starting with 1m/s decrease to 0 close to the coast.

Fourth run input:
- Cross shore current, with flow velocity starting with 1m/s decrease to 0 close to the coast.

Fifth run input:
- Combining the changes in the second run and third run
Sixth run input:
- Combining the changes in the second run and fourth run

The significant wave height at a depth of 24m from the different runs:

<table>
<thead>
<tr>
<th>Run</th>
<th>First</th>
<th>Second</th>
<th>Third</th>
<th>Fourth</th>
<th>Fifth</th>
<th>Sixth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Current</td>
<td>no</td>
<td>no</td>
<td>along</td>
<td>cross</td>
<td>along</td>
<td>cross</td>
</tr>
<tr>
<td>Depth [m]</td>
<td>Hs[m]</td>
<td>Hs[m]</td>
<td>Hs[m]</td>
<td>Hs[m]</td>
<td>Hs[m]</td>
<td>Hs[m]</td>
</tr>
<tr>
<td>24</td>
<td>0.91772</td>
<td>1.17639</td>
<td>1.091</td>
<td>1.17639</td>
<td>0.91554</td>
<td>0.91772</td>
</tr>
</tbody>
</table>

From the results it can be seen that the wind plays an important role in the determination of the significant wave height. The wave height can be 20cm higher, but SWAN gives already a higher significant wave height at the depth of 65m than the input significant wave height of 1m. It is not entirely clear why this is happening. However, every time when inputting a wave direction SwanOne gives an error, maybe this has something to do with it.

The cross-shore current does not play a role at all and the alongshore current does only play a small role. Since the current does not really play a role and the inputting wind into SwanOne gives some things that are not really clear, it is chosen to not use these parameters in the wave propagation.

The peak wave period does not change from a depth of 65m to 24m.

Error when inputting wind direction:

Reference to non-existent field 'bndannot'.

Error in bndcnd_annot_refresh (line 13)
close(handles.figures.input.bndannot);

Error while evaluating UIControl Callback
III. Process of the cubes

In this appendix the process of creating the cubes is explained. For the armor layer of the rubble mound breakwater on prototype scale reinforced concrete is used as the material to construct the cubes. To reconstruct the cubes on small scale the same density should be used which is $2.25 \text{ gr/cm}^3$.

The perfectness of recreating reality on small-scale is very important since a difference of 1mm on small scale is a difference of 8 cm on prototype scale.

Because for this research damage is to rubble mound breakwaters is observed the result of the tests are fully dependent on the elements in the armor layer. The way the cubes, that are going to be used for the tests, are constructed is explained in the following paragraphs.

III.1. Concrete cubes

Process

The process that has been done to construct the concrete cubes with the right density is explained here.

1) A mold is constructed from hard plastic
2) Trial and error with construction of cubes with a mixture of cement, sand, water and lead

The mold

From a plate of hard plastic, cubes (1.5x1.5x1.5 cm$^3$) are cut with a laser. The plastic plate is connected to a wooden plate and this together forms the mold.

The mixture

The mixture for the concrete consists of cement, sand, water and lead. Based on a recipe of the structural lab of UPC a first batch of concrete cubes has been made.

The mixture is poured on the mold, by vibrating the mold the air bubbles in the mixture can get out and what remains is a dense mixture that needs to dry for a couple of days.

When the cubes are finished the cubes are taken out of the mold, are weighted and are put in a measuring cylinder containing water to measure the exact volume of the blocks. With the weight and the volume the density is calculated.

Results

The concrete cubes tend to stick to the mold and when taking the cubes out of the mold, the edges seem to break easily. Different ratios between water, cement, sand and lead are used to create a more solid cube and to get the right density.

At the end the right density was achieved but due to the vibrating the mixture seems to separate, the lead tend to sink to the bottom. Due to too much lead near the bottom the bonding of the cement, sand and lead is worse near the bottom, making the cubes less solid near the bottom.

There were no good thoughts on how to solve this, since vibrating is necessary to prevent air bubbles inside the cubes, it has been decided to continue with resin to create the cubes.
III.2. Resin cubes

To construct the cubes from resin multiple tests has been conducted to find the right material characteristics and to reach the right density.

Process
The process that has been done to construct the resin cubes with the right density is explained here.

1. A mold is constructed from silicon
2. Multiple cubes are constructed with only resin
3. The density of the resin after drying is determined
4. Trial and error with construction of cubes with resin and lead
5. The metacenter of single cubes is determined
6. The total amount of needed cubes is constructed with added colors

The mold
The cubes that have been cut from the hard plastic mold are almost of the exact same size as the cubes, needed for the tests, should be. These cubes have been glued to a wooden plate in a regular order and on all 4 sides of this wooden plate, vertical boards have been pinned (see Figure 72), this is the mold for the silicon. In this mold fluid silicon has been poured and after drying of a couple of days, a quite similar mold as for the concrete cubes had been created. The big advantage of this mold is that the material is now silicon which is flexible and makes it easier to take out the cubes.

Resin
The first set of cubes that have been made where the cubes existed only of resin. From this first set the exact density of the resin could be determined and also the exact volume of the cubes.

Density of resin: 1.124 gr/cm³
Volume of cubes: 2.9333 cm³

Lead
The first lead available was scraped lead from a bigger lead block; this is the same lead as has been used in the concrete block.

The second lead used is fishing lead; it is a type of lead that is squeezed around the fishing line to add weight, such that the hook with bait is not going to float. It is a relative expensive type of lead because it is specially made for fishing and not for the purpose of adding weight to cubes.

The third lead is a string of lead, directly ordered from the factory. The lead comes in a long string with a diameter of 7mm; from this string easily parts can be cut with the exact weight needed per cube. Because a string is much less labor-intensive to deliver than fishing lead this is a much cheaper option.

Every type of lead was weighted and measured carefully to determine the density, although lead should have a homogeneous density it is not wanted that by differences in densities the cubes have different densities.

The density of the lead string is 10.787 gr/cm³. Theoretically density of lead should be 11.34 gr/cm³.

Structure cubes
To represent the real concrete cubes on small scale not only the density should be similar, but also the way the weight of the cube is divided in the cube. The ideal cube has its center of mass exactly in the middle. When mixing resin with scraped lead the lead immediately sinks due to the mayor difference in densities. To overcome this problem:
- First a layer of resin is made of about 3 mm and left to dry
- Lead is placed on top of the layer of resin, and
- The remainder of space is filled with resin again

With the scraped lead it is quite hard to get the center of mass exactly in the middle and therefore pieces of lead of the exact weight are used. These pieces should be placed in the middle as much as possible to get the center of mass in the middle as much as possible.
Metacenter

Due to the specific method of constructing the cubes it is important to know if the metacenter is in or close to the middle of the cubes.
To determine this some of the cubes are turned into dices (Figure 73) and for these cubes the statistics are analyzed. If the metacenter is exactly in the middle, every side of the cube should be facing upwards an equal amount of times within a certain amount of tosses.
Off course within tossing a real “fair” dice a couple of hundred times, the amount of tossing for example one compared to two could also be different.

Histograms

3 cubes have been tossed 200 times each. In Figure 75 the histograms per dice are shown.

For dice 1 and dice 3 the distribution is quite good, which could indicate that the metacenter is in the center of the cube. However for dice 2 the times 1 is tossed and 5 is tossed differs a lot.

The probability of a certain number being tossed a certain number of times in 200 tosses is given in the probability density graph in Figure 74. In Figure 75 is the probability shown of tossing a certain number the amount of times that it was tossed during this research.
Chi-Square Goodness of Fit Test

The chi-squared goodness of fit test is a statistical test that is used to determine how “close” observed values are to the values that are expected.

\[
\chi^2 = \sum \frac{(observed - expected)^2}{expected}
\]

The expected value can be determined with the binomial distribution. The probability of rolling a given number, say 1, on any given toss is 1/6. This means that the expected counts of 1 in 200 tosses is 33.33.

<table>
<thead>
<tr>
<th>Number</th>
<th>Expected count</th>
<th>Observed count dice 1</th>
<th>Observed count dice 2</th>
<th>Observed count dice 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33.33</td>
<td>40</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>33.33</td>
<td>28</td>
<td>29</td>
<td>41</td>
</tr>
<tr>
<td>3</td>
<td>33.33</td>
<td>39</td>
<td>41</td>
<td>34</td>
</tr>
<tr>
<td>4</td>
<td>33.33</td>
<td>32</td>
<td>42</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>33.33</td>
<td>31</td>
<td>50</td>
<td>31</td>
</tr>
<tr>
<td>6</td>
<td>33.33</td>
<td>30</td>
<td>33</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 50 Expected counts and observed counts per dice

To see the difference between the observed and the expected counts a chi-gram is plotted in which the observed minus the expected counts are divided by the square root of the expected counts.

Figure 76 Expected counts and observed counts

Figure 77 Chi-gram of the three dice
The Chi value for the 3 dices is 3.7, 23 and 5.44 respectively.
The Chi squared cumulative density function is plotted in Figure 78.

![Chi square CDF with 5 degrees of freedom](image)

Figure 78 Chi square CDF

With the cumulative density function and the obtained Chi values the probabilities that the dice (cubes) are fair can be calculated.

<table>
<thead>
<tr>
<th>Dice</th>
<th>Chi</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.7</td>
<td>0.4066</td>
</tr>
<tr>
<td>2</td>
<td>23</td>
<td>0.9997</td>
</tr>
<tr>
<td>3</td>
<td>5.44</td>
<td>0.6354</td>
</tr>
</tbody>
</table>

The Chi squared test shows that if the dice are actually fair $\chi^2$ is 3.7 in 40.7% of all the tests, is 23 in 99.97% of all the tests and 5.44 in 63.54% of the tests. This means that dice 2 is something to be concerned of.

**Extra tests**

Because 1 of the 3 dice used, shows a high probability to be unfair, extra tests have been executed with other cubes.

<table>
<thead>
<tr>
<th>Dice</th>
<th>Chi</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>13.1213</td>
<td>0.9777</td>
</tr>
<tr>
<td>5</td>
<td>14.9815</td>
<td>0.9896</td>
</tr>
<tr>
<td>6</td>
<td>18.2818</td>
<td>0.9974</td>
</tr>
<tr>
<td>7</td>
<td>4.4805</td>
<td>0.5175</td>
</tr>
</tbody>
</table>

Also these values (except for the probability of dice 7) could question the fairness of the cubes.

Cubes 2, 4, 5 and 6 are closely observed whether there is a correlation between the tossed values of each cube and something in the structure of the cubes.

In this observation is found that all the 4 cubes have one single number been tossed much less as the others and this number seems to be on the bottom of the corresponding cube. Also for all these cubes the top seems to be a little bit uneven.

After sanding the top of these cubes tests are redone now by tossing the cubes 150 times each.

<table>
<thead>
<tr>
<th>Dice</th>
<th>Chi</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.72</td>
<td>0.2569</td>
</tr>
<tr>
<td>4</td>
<td>8.8</td>
<td>0.8827</td>
</tr>
<tr>
<td>5</td>
<td>5.12</td>
<td>0.5986</td>
</tr>
<tr>
<td>6</td>
<td>0.96</td>
<td>0.0343</td>
</tr>
</tbody>
</table>
Conclusion

It seems that after the resin has dried, some cubes are uneven on the top side. This unevenness prevents these cubes to roll on the top side (when the cubes are used as dice). After sanding the topside, removing the unevenness, the cubes had become more “fair”. If the dice are actually fair the chi-squared values will be less than 9.236 in 90% of all the tests. Since the highest value obtained is 8.8 it can be assumed that the dice are fair.

From this it could be concluded that resin cubes with lead have the mass center in the middle of the cube, but it is recommended to sand the top side to remove all unevenness.

This is still all based on statistics and therefore all the statements made above cannot be proved to be true for 100%.

Moment of Inertia

Since the weight of one resin with lead cube is not equally distributed in this cube, the moment of Inertia shall be different than that for concrete cubes.

\[ I = \sum m_i r_i^2 \]

With \( m \) is the mass of the \( i \)-th element and \( r \) is the radius of the mass.

Assuming the piece of lead has the exact shape of a sphere and is located exactly in the middle of the cube and the cube’s dimensions are \( 1.415 \times 1.415 \times 1.415 \text{ cm}^3 \), it simplifies the calculations significantly.

\[ V_{bol} = \frac{4}{3} \pi r^3 \]

In Table 51 are the properties shown of a simplified resin cube with sphere piece of lead in the middle

<table>
<thead>
<tr>
<th>Element</th>
<th>Density [gr/cm³]</th>
<th>Weight [gr]</th>
<th>Volume [cm³]</th>
<th>Radius [cm]</th>
<th>( I ) [gr*cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin cube</td>
<td>1.12</td>
<td>3.18</td>
<td>2.84</td>
<td>0.71</td>
<td>1.06</td>
</tr>
<tr>
<td>Resin sphere</td>
<td>1.12</td>
<td>0.42</td>
<td>0.37</td>
<td>0.22</td>
<td>0.033</td>
</tr>
<tr>
<td>Resin cube hollow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead sphere</td>
<td>10.787</td>
<td>4.06</td>
<td>0.37</td>
<td>0.22</td>
<td>0.33</td>
</tr>
<tr>
<td>Resin cube with lead</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.36</td>
</tr>
</tbody>
</table>

To compare this moment of inertia with what a solid concrete cube would have the properties for such a cube are as follows:
- Dimensions 1.415*1.415*1.415 cm³
- Density 2.24 gr/cm³
- Weight 7.6 gr
- \( I = 2.28 \text{ gr/cm}^2 \)

The difference between the moment of inertia of a standard concrete cube is quite big and should be taken into account when it seems to influence the results.

Surface roughness

Due to the use of other material for the cubes it could be imagined that the surface roughness of the material used is different than the roughness of standard used cubes.

By placing standard cubes and the resin cubes on a wooden board and comparing the friction angles between the different materials, when there is no big difference the roughness of the resin cubes will not be considered as influencing the results.

The cubes that will be considered are:
- Cubes from the last try using cement (Concrete Cubes 1)
- Concrete cubes used in earlier research with different dimensions (Concrete Cubes 2)
- Resin cubes; initial and after being scratched
In Table 52 the observations of the friction tests are shown. The friction coefficient is the inverse tangent of the friction angle (or angle of inclination).

The mean friction coefficients of the tested cubes are:
- Concrete Cubes 1: 0.31
- Concrete Cubes 2: 0.21
- Resin Cubes (scratched): 0.316

The cubes that were used in earlier research seem to have a smaller friction coefficient, while if the resin cubes are scratched the cubes have almost a similar friction coefficient compared with the cubes that would have been used as a first choice.

<table>
<thead>
<tr>
<th>Concrete Cubes 1</th>
<th>Number</th>
<th>Weight [gr]</th>
<th>Inclination ['']</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.42</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6.9</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6.6</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6.97</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>6.97</td>
<td>22</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Concrete Cubes 2</th>
<th>Number</th>
<th>Weight [gr]</th>
<th>Inclination ['']</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.9</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>16.55</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>17.02</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resin Cubes</th>
<th>Number</th>
<th>Weight [gr]</th>
<th>Inclination ['']</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>6.8</td>
<td>initial 34</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6.84</td>
<td>scratched 20</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6.85</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>6.86</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 52 Observations of friction tests
IV. Erosion calculation

In this appendix the method how erosion area is calculated from the moved cubes is explained.

For all the executed tests the number of cubes that moved more than one nominal diameter is counted. Due to
different behavior in the movement of the cubes, some cubes are extracted and others are just sliding down, these
different movements causes erosion in different amounts. If erosion is considered as damage, in most of the
experiments it was visible that when multiple cubes were sliding (more than one nominal diameter) all these cubes
were considered damage, but were actually causing less erosion (see Figure 80 & Figure 81).

Figure 80 Original configuration

Figure 81 Configuration after test

IV.1. Number of cubes moved

Although, considering erosion as damage, the number of moved cubes does not seem to be comparable the pictures
in which these cubes are counted can be very helpful.

The cubes are counted using Photoshop or GIMP, in which the moved cubes in the first step and in the step
considered are numbered. Every number is saved as a separate layer in the file and when exporting all the layers from
the first step and the step considered, there is for every moved cube 1 file with the initial location and 1 file with the
final location.

Analyzing these layers makes it possible to track every cube movement for the cubes that moved more than one
nominal diameter. Assuming that at the initial location the cube leaves a certain volume of erosion and at the final
location deposits a certain volume, it is possible to calculate erosion areas.

IV.2. Methodology

In steps is given how to calculate erosion areas.

1) Number all the blocks, moved more than one nominal diameter using
Photoshop or GIMP.
2) Export the layers to image files, in this case .png files.
3) Import the image files into Matlab
4) Matlab can recognize blocks in an image based on color, by changing
the images to black and white pictures the number of the moved
block is recognized with Matlab (Figure 82).
5) This has to be done for both the initial step and the final step and let
Matlab calculate the location of the numbers.
6) Resize and reshape the image of the breakwater structure, such that it
is possible to measure real distances in the image.
7) Create a matrix of the same size with only zeros
   a. at the initial location of the cubes extract a certain amount
      such that a total volume is extracted (take into account porosity)
   b. at the final location of the cubes add a certain amount, such that a total volume is added (take into
      account porosity)
8) Finally, average over the entire width (or over multiple sections of the width) to obtain a mean erosion area.
In Figure 83 the matrix with the subtracted and added volumes is visible.

![Figure 83 Matrix with extracted and added volumes](image)

In Figure 84 the mean of the erosion area over the entire width is shown.

![Figure 84 Mean erosion area](image)

### IV.3. The Matlab scripts

There are some Matlab scripts used to arrive at the final erosion profiles.

**LoadLayers.m**

With this Matlab file the exported layers from the photoshop file are imported into Matlab and converted to black and white images. Due to the use of green numbers the threshold for black and white is set on 0.9, the number will be black and the rest of the image white.

Input for this script is:

- `root1` is the folder where the exported layers for the initial condition are located (in most cases, \ddmmjj\_01).
- `root2` is the folder where the exported layers for the step that will be compared with are located.
- `rootscript1` is the folder where this script is located.
- `nameinitial` is the name of the image (without extension) of the initial condition.
- **step** is given when comparing the 100% step of 120% step of the classical method (‘100%’ for the 100% step, ‘120%’ for the 120% step and ‘ ’ if other than the classical method is compared).

Note: for the input step the number of the step in the storm could be given, this is not yet done since only the end steps of the storms are used for comparison.

The output of the script is a Matlab file called ‘Blocks_gr_nameinitial_step’ and is saved in the folder with the layers of the initial condition.

Important is to check if the variables Blocks_first_gr and Blocks_last_gr are of the same sizes, when this is not the case it means that the number of layers in root1 and in root2 are not equal which could have various reasons.

**Tracking3.m**

With this script the initial and ‘final’ locations of the cubes in the aspect of the picture are determined and plotted in a scatter and on the image of the initial condition with arrows in which way they moved.

Input for this script is:
- **rootscript1** is the folder where this script is located.
- **rootinitial** is the folder where the exported layers for the initial condition are located (in most cases, \ddmmjj_01).

The following input should be the same as given in the first script.
- **nameinitial** is the name of the image (without extension) of the initial condition.
- **step** is given when comparing the 100% step of 120% step of the classical method (‘100%’ for the 100% step, ‘120%’ for the 120% step and ‘ ’ if other than the classical method is compared).

Output for this script is multiple Matlab files which are saved in the folder with the layers of the initial condition:
- **Scatter_nameinitial_step** is the figure of the scatterplot
- **Tracking_nameinitial_step** is the figure of the initial condition with the locations and the arrows plotted on it
- **locations_nameinitial_step** is a Matlab file of the initial location and final location of the moved cubes

**Reshape2.m**

This script is needs a little more attention. In this script the breakwater structure in the image of the initial condition is reshaped and scaled (see Figure 85) to the real width (W) and length (L) of the breakwater structure in view perpendicular to the slope, where the length in pixels is equal to the length in mm. Finally a matrix is constructed of the same size as the breakwater structure (W x L) with values for erosion/deposition.

![Figure 85 Reshaping and scaling](image)

Because a Gopro is used for making the pictures, there is also lens distortion due to the fish eye effect. There is no compensation for this effect. Some comments on the influence of not compensating this:

- The distance of the Gopro with the breakwater structure is such that much of the surrounding is also captured in the picture and since the breakwater structure is located in the ‘middle’ of the picture the fish eye effect is minimized (see Figure 86).
- The matrix that represents the erosion and deposition is constructed based on the locations (initial and final) of the cubes; these locations could be shifted from the real locations due to the lens distortion. Because the lens distortion is minimized (see Figure 86) and nothing else in this matrix depends on this lens distortion the error is quite small.
The shape of the trapezium is defined with the input for this script which is:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ext_x</td>
<td>Increase the width of the part that is reshaped, such that the entire structure fits in the trapezium</td>
</tr>
<tr>
<td>ext_ys</td>
<td>Increase the height of the trapezium on the top side</td>
</tr>
<tr>
<td>ext_ye</td>
<td>Increase the height of the trapezium on the bottom side</td>
</tr>
<tr>
<td>shift</td>
<td>If a small tilt is occurring in the reshaped image fill in a value for this to compensate this (Figure 87)</td>
</tr>
<tr>
<td>x_cor</td>
<td>If the location of the cubes in the reshaped images is shifted, compensate with this variable</td>
</tr>
<tr>
<td>Dn</td>
<td>The nominal diameter of the cubes</td>
</tr>
<tr>
<td>porex</td>
<td>Multiply cube volume to take porosity into account for extraction (2 is porosity of 50%)</td>
</tr>
<tr>
<td>porset</td>
<td>Multiply cube volume to take porosity into account for deposition (1.5 is porosity of 33%)</td>
</tr>
<tr>
<td>slices</td>
<td>This is the number in which the structure is divided. 1) for statistical analysis to have more data and 2) to prevent the extreme erosion to be smoothed out</td>
</tr>
<tr>
<td>x_1</td>
<td>X location of point 1 on the picture (Figure 88)</td>
</tr>
<tr>
<td>y_1</td>
<td>Y location of point 1 on the picture (Figure 88)</td>
</tr>
<tr>
<td>x_2</td>
<td>X location of point 2 on the picture (Figure 88)</td>
</tr>
<tr>
<td>y_2</td>
<td>Y location of point 2 on the picture (Figure 88)</td>
</tr>
<tr>
<td>x_3</td>
<td>X location of point 3 on the picture (Figure 88)</td>
</tr>
<tr>
<td>y_3</td>
<td>Y location of point 3 on the picture (Figure 88)</td>
</tr>
<tr>
<td>x_4</td>
<td>X location of point 4 on the picture (Figure 88)</td>
</tr>
<tr>
<td>y_4</td>
<td>Y location of point 4 on the picture (Figure 88)</td>
</tr>
<tr>
<td>x_5</td>
<td>X location of point 5 on the picture for scaling in y direction</td>
</tr>
<tr>
<td>y_6</td>
<td>Y location of point 6 on the picture for scaling in y direction</td>
</tr>
<tr>
<td>x_min</td>
<td>Minimum x values of the reshaped/scaled image to be cropped (Figure 89)</td>
</tr>
<tr>
<td>x_max</td>
<td>Maximum x values of the reshaped/scaled image to be cropped (Figure 89)</td>
</tr>
<tr>
<td>y_min</td>
<td>Minimum y values of the reshaped/scaled image to be cropped (Figure 89)</td>
</tr>
<tr>
<td>y_max</td>
<td>Maximum y values of the reshaped/scaled image to be cropped (Figure 89)</td>
</tr>
<tr>
<td>rootscript</td>
<td>Folder where the script is located</td>
</tr>
<tr>
<td>rootinitial</td>
<td>Folder where the layers of the initial condition are located</td>
</tr>
<tr>
<td>nameinitial</td>
<td>Name of the image of the initial condition (should be the same as in the other scripts)</td>
</tr>
<tr>
<td>step</td>
<td>Name of the step of final condition (should be the same as in the other scripts)</td>
</tr>
</tbody>
</table>
Figure 87: Tilt correction

Figure 88: Points for the input of the x and y coordinates

Figure 89: Cropping of the resized image
The output of the script is (these files are saved into the folder where the layers of the initial condition are located):

1) A Matlab file (Volume\_nameinitial\_step.m) containing the matrix with the erosion and deposition. This matrix is constructed by subtracting a certain value (\(porex\) times nominal diameter) at the area of the initial location of the cube and adding a certain value (\(pores\) times nominal diameter) at the area of the final location of the cube.

2) A Matlab figure (Erosion profile\_nameinitial\_step.fig) of the cross-section of the breakwater in which the erosion and deposition is averaged over the entire width.

3) A Matlab figure (Reshaped tracking\_nameinitial\_step.fig) of the reshaped and scaled image with the scatter plot of the initial and final locations of the cubes.

4) A Matlab file (Displacement\_nameinitial\_step.m) with the distance moved of every cube.

**IV.4. Conclusion**

When comparing the tracks, the pictures and the matrix with volumes, it looks like the matrix should be quite correct and therefore the erosion area should be correct.

Some considerations to be taken into account are:

- In reshaping the image rotation is not compensated for, this is in the extreme cases about 1.5°. In these cases there is a slight tilt in y-direction in the image, which means that when observing the cross-section of the structure every mm, the cross-sections are not exactly aligned.

- The amount of extracted and added volumes now is chosen that when a cube is extracted it is extracted with the volume of the cube plus the same amount of volume accounting for the porosity and when the cube is deposited it only deposits with half of the same volume of porosity. This is chosen since during the tests many times the location where the cubes deposited did not show a lot of accretion, which means that the porosity has decreased.

- Only the cubes that moved more than one nominal diameter are taken into account and therefore erosion/deposition caused by the cubes that moved less are not taken into account.

- In many tests the erosion did not happen constant over the entire width, so next to the mean should maybe also extremes be visible/taken into account or slicing the width in to multiple sections and consider these section separately.