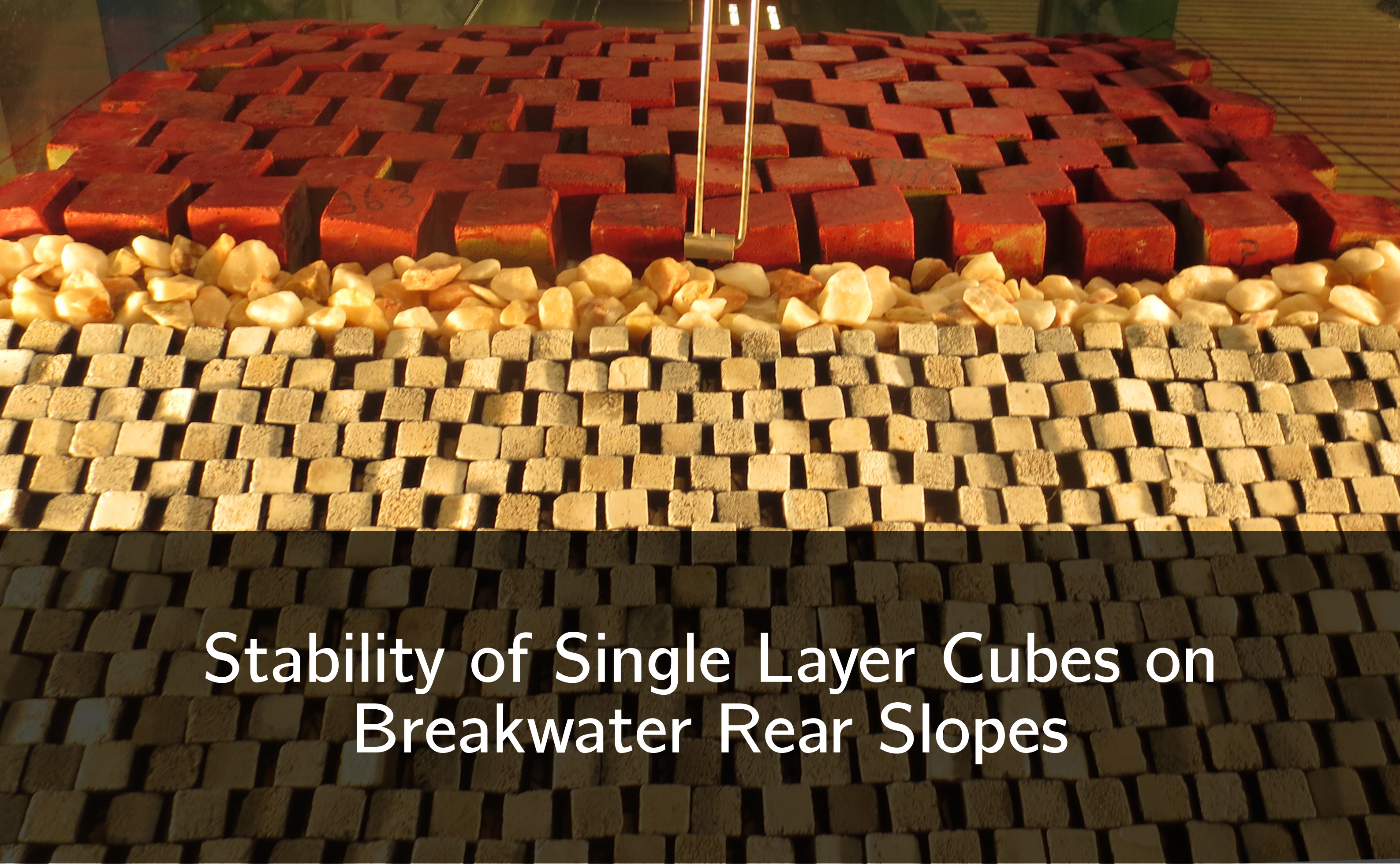

Stability of Single Layer Cubes on Breakwater Rear Slopes

Master Thesis

Lisette Bernice Hellinga

15 January 2016

Delft University of Technology
Faculty of Civil Engineering and Geosciences
Section of Hydraulic Engineering

Witteveen+Bos
Coasts, Rivers and Land Reclamation
Coasts and Rivers

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Abstract

Breakwaters with single layer concrete armour are very commonly applied nowadays. Much research is available on the stability of single layer armour units on the seaward slope. However, rear slopes design methods for single layer armour units are rare. On rear side slopes usually similar sized units as on the seaward slope are applied. Limited design methods are available for the stability of concrete armour units on the rear side of a breakwater. To obtain stability information on single layer cubes on the rear side, scale model tests have been performed in the wave flume of the University of Technology Delft.

The purpose of the model tests is to obtain a relation between the overtopping wave characteristics (overtopping volume of an individual wave event and the overtopping wave front velocity) and the stability of the cubes at the rear slope of low crested breakwaters. This relation can lead to a more optimal rear side breakwater design.

The test programme consists of different configurations, in which the following parameters have been varied:

- Wave steepness: three typical values for steepness have been tested $s_{op} =$ 0.015, 0.027 and 0.039;
- Relative crest width: relative crest width ranges were $W_c/H_s = 1.1 - 6.3$;
- Relative free board: relative free board ranges were $R_c/H_s = 0.4 - 1.3$;
- Rear slope angle: two slope angles of 1:2 and 1:1.5 have been tested;
- Packing density; packing densities of 73% and 69% have been tested

A total of 11 breakwater configurations have been tested. Each configuration was tested with a sequence of waves with increasing wave height until failure of the armour layer occurred. The focus was on the determination of start of damage of the rear armour cubes, but also on filter material wash out. Together with the stability

tests, wave overtopping volume tests have been performed. The overtopping volume per wave was measured in a special designed box. The overtopping wave front velocity at the crest is measured by correlating the signals of two wave gauges.

The number of displaced cubes in the rear slope armour layer has been determined with image analyses and expressed in the damage number N_{od}. The influences of the various parameters and overtopping characteristics on the rear slope damage are presented in stability graphs. Due to lack of sufficient data points, no trend line could be established. However, the graphs can be used as a guideline for conceptual breakwater design. The critical overtopping characteristics are in a wide range. Therefore, the quantitative influence of the overtopping velocity and -volume on the rear slope damage is unclear. This suggest that other aspects may influence the stability of the rear slope, for example the transmission through the breakwater or the shape of the overtopping flow around the rear slope.

The analysis of the test data shows that damage on the single layer cubes on breakwater rear sides occurs later than expected. The expected cube dimensions were calculated for various configurations. First, the armour dimension of randomly placed rock is calculated with the formula of van Gent and Pozueta [2004]. Secondly, the difference in stability of randomly placed rocks and regular placed cubes was estimated applying a factor obtained from the known stability numbers on seaward slopes of both armour layers. The estimated cube dimension was used in a first test series. During this test series (almost) no damage was observed. Therefore, the remainder of the experiment was carried out with a 37% smaller cube diameter.

The damage seems to be limited to first rows below the water level, which may indicate that cubes on the rear side below this level could be lighter .

Preface

My name is Lisette Hellinga, Master student Hydraulic Engineering at Delft University of Technology. I have written this thesis as part of my graduation research. The research took place from March 2015 until January 2016.

After my Bachelor Civil Engineering, I chose to study Hydraulic Engineering because of my interest in hydraulic structures and coastal processes. Especially in The Netherlands, we see these subjects all around us and are aware of the importance. This makes design of coastal structures a meaningful task, which really appeals to me. Besides, I like to work with programming software as a mean to solve problems, which is also applicable in this field. During my internship, I was introduced to the design of breakwaters, which triggered my interest for this subject. After this, I decided to focus even more on the design of breakwaters in this graduation research.

My graduation committee made it possible to bring this research to a higher level and motivated me along the way. I would like to thank Wim Uijttewaal (Professor at the Delft University of Technology), Henk Jan Verhagen (Associate Professor at the Delft University of Technology), Coen Kuiper (Part-time lecturer at the Delft University of Technology), Bert van den Berg (Project Engineer at Witteveen+Bos) and Marcel van Gent (Head of department Coastal Structures & Waves at Deltares) for their support and for making this research possible. Secondly, I would like to thank everybody who helped me by during my research; family and friends.

Lisette Hellinga
Delft, The Netherlands
January 2016

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List of Symbols

Symbol	Unit	Description
a	$[-]$	Scale factor in Weibull distribution
b	$[-]$	Shape factor in Weibull distribution
C_D	$[-]$	Drag coefficient
C_l	$[-]$	Lift coefficient
D_n	$[m]$	Nominal diameter
D_{n50}	$[m]$	Median nominal diameter
E	$[m^2/Hz]$	Wave energy
f	$[Hz]$	Wave frequency
f_p	$[Hz]$	Peak wave frequency
f_c	$[-]$	Friction at the crest
F	$[N]$	Force on a single cube
g	$[m/s^2]$	Gravitational acceleration
h	$[m]$	Water layer thickness
h	$[m]$	Water depth
$h_{x\%}$	$[m]$	Maximum water layer thickness exceeded by x % of the incident waves
H_{m_0}	$[m]$	Spectral significant wave height
H_s	$[m]$	Significant wave height (H_{m0} is used in this report)
L	$[m]$	Local wave length
n	$[-]$	Porosity
n_P	$[-]$	Packing Density
n_x	$[-]$	Scaling factor for unit x
N	$[-]$	Number of waves

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Symbol	Unit	Description
N_{od}	$[-]$	Damage number: number of displaced units per unit width
N_{om}	$[-]$	Damage number: number of moved units per unit width
N_{ow}	$[-]$	Number of overtopping waves
N_s	$[-]$	Stability number of an armour unit
P_{ov}	$[-]$	Probability of overtopping
P_V	$[-]$	Exceedance probability of an overtopping volume per wave
q	$[l/s/m]$	Average specific overtopping discharge
$q_{x\%}$	$[m^3/s/m]$	Maximum discharge exceeded by x % of the incident waves
R_c	$[m]$	Free board
R^*	$[-]$	Dimensionless free board
$R_{u2\%}$	$[m]$	Wave run-up height exceeded by 2% of the incoming waves
s	$[-]$	Wave steepness
$s_{m-1,0}$	$[-]$	Fictitious deep water wave steepness based on $T_{m-1,0}$
s_{om}	$[-]$	Fictitious deep water wave steepness based on T_m
s_{op}	$[-]$	Fictitious deep water wave steepness based on T_p
S	$[-]$	Damage level
t or t_{storm}	$[s]$	Duration of a storm
T_m	$[s]$	Mean wave period based on the time series
T_p	$[s]$	Peak wave period
$T_{m-1,0}$	$[s]$	Spectral wave period based on the first negative moment of the energy spectrum
$u_{x\%}$	$[m/s]$	Maximum velocity exceeded by x % of the incident waves
u_i	$[m/s]$	Velocity of overtopping plunge at location of impact
u	$[m/s]$	flow velocity
V_i	$[l/m/wave]$	Overtopping volume of an individual wave
V_{max}	$[l/m/wave]$	Maximum overtopping volume of an individual wave
$V_{x\%}$	$[l/m]$	Maximum volume exceeded by x % of the incident waves

Continued on next page

Symbol	Unit	Description
W	$[kg]$	Weight
W_c	$[m]$	Crest width
x	$[m]$	Coordinate along the crest
z	$[m]$	Coordinate along the front slope
α	$[-]$	Front slope angle
α_i	$[-]$	Angle of plunge impact
α_J	$[-]$	Constant that relates to the wind speed and fetch length in JONSWAP-Spectrum
β_J	$[-]$	A shape factor in JONSWAP-Spectrum (default value = 1.25)
γ_J	$[-]$	The peak enhancement factor in JONSWAP-Spectrum. (default value = 3.3)
γ_b	$[-]$	Influence factor for a berm
γ_f	$[-]$	Influence factor for roughness elements on a slope
γ_{f-C}	$[-]$	Influence factor for roughness elements on the crest
γ_β	$[-]$	Influence factor for oblique wave attack
Δ	$[-]$	Relative density
θ_{rear} or φ	$[-]$	Rear slope angle
μ	$[-]$	Mean value
$\xi_{m-1,0}$	$[-]$	Breaker parameter
ρ_c	$[kg/m^3]$	Density of concrete
ρ_r	$[kg/m^3]$	Density of rock
σ	$[-]$	Standard deviation
σ_J	$[-]$	Width of the peak
ϕ	$[N/m^2]$	Pressure on a single cube

1 | Introduction

The topic of this research will be introduced in this chapter. In the course of the chapter the topic will become more specific, while the corresponding research framework will be presented in the end.

1.1 General introduction

Breakwaters are coastal structures with the main function of providing a sheltered area from wave action. The subsequently reduced wave climate allows vessels to berth into a port and port facilities to be operational. Another important application of breakwaters is to counteract erosion in coastal areas. In this case, the wave action reduction leads to less sediment transport along the coast. Besides the protection against wave action, breakwaters are used to limit the currents in a certain area. For example, the siltation in a navigation channel could be reduced by a breakwater.

There is a great variety in breakwater structures that can fulfill these functions. The most common breakwater types are:

- Conventional Rubble Mound Breakwater: loose, non-cohesive material
- Monolithic Breakwater: one solid block
- Composite caisson/rock Breakwater: combination of loose material and a solid block

In this research, the conventional rubble mound breakwater is considered. This breakwater consists of a core, filter/underlayers, an armour layer (e.g. rock or concrete units) and a toe. These elements are shown in figure 1.1. The armour layer is made up of armour units that are able to withstand the wave loads. The core is built up by small stones. One or more underlayers should be applied to avoid the washing out of core material through the armour layer. The toe prevents the armour units from sliding.

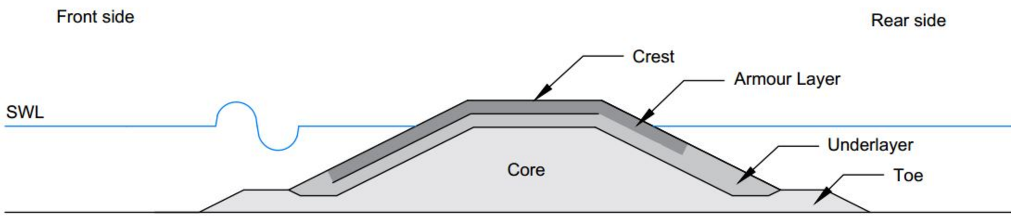

Figure 1.1: Cross section of a rubble mound breakwater [Setz and Finnegan, 2010]

A breakwater has several failure mechanisms, for example: instability of the armour layer, instability of the toe, settlement of the subsoil, erosion of the toe and slip circles (see figure 1.2). In this study, the focus is on the (in)stability of the armour layer with single layer concrete cubes at the rear side.

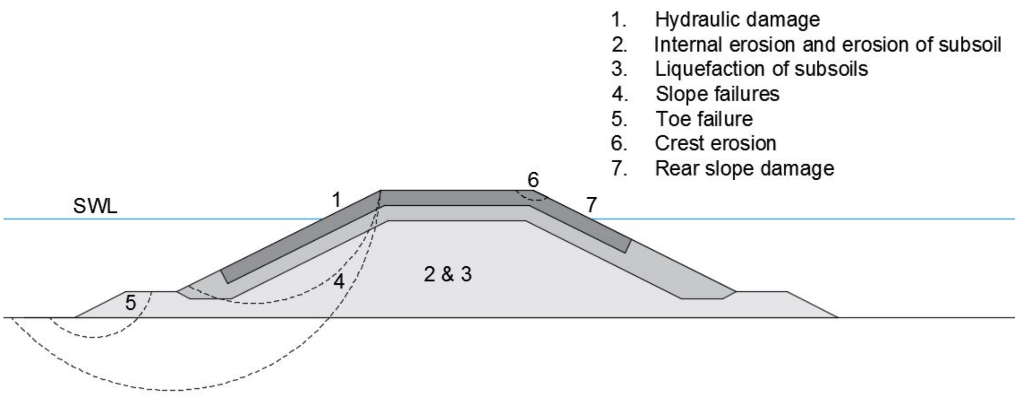

Figure 1.2: Failure mechanism of a rubble mound breakwater [CIRIA, 2007]

The armour layer gains its stability by the weight of the armour units. The loads on the armour layer are different at the front and rear slope. The front slope is directly loaded with waves, while the rear slope is loaded with the hydraulic response of the waves: overtopping waves. The overtopping waves can jeopardise the stability of the rear side armour layer, which eventually can lead to the failure of the rear slope. This phenomenon is even of a greater importance for low crested breakwaters.

1.2 Research framework

Despite the large amount of scientific literature about breakwaters, there is still lack of knowledge on the subject of the rear slope stability. This study focusses on the stability of a single layer of cubes on the rear side. The following paragraphs will clarify the problem and the research objectives.

1.2.1 Problem Description

The design methods of concrete units, e.g. Xbloc, Accropode, Coreloc or cubes do not cover the rear side stability of breakwaters. The current design method for interlocking elements (e.g. Xbloc and Accropode) prescribes that equal unit dimensions should be applied on the rear side as on the front side of low crested breakwaters. This design method is also used for single layer of cubes and this assumption is made due to the lack of knowledge on the stability of the rear side. It is expected that the dimensions of the cubes at the rear side could be smaller than at the front side. The rear slope is indirectly attacked by wave overtopping, while the front slope armour has to withstand the direct impact of the waves. The loads on the rear side are expected to be smaller and therefore the dimensions of the cubes might be smaller. Currently, the cubes are probably overdimensioned and therefore the design might be suboptimal. The current approach could lead to economically unattractive and environmentally unfriendly designs.

The problem definition can be stated in a single line:

> *The lack of knowledge on the dimensioning of cube armour units at the rear slope of a low crested rubble mound breakwater could lead to an overdimensioned design.*

1.2.2 Research objective

The main objective of this research is to develop an empirical expression for the rear slope stability of a breakwater armoured with single layer cubes. This expression can be used for future designs and might lead to more optimal solutions for breakwater designs.

1.2.3 Research questions

The main research question is:

> *What is the stability of a single layer of cubes at the rear side of a low crested breakwater, expressed as a stability number at the start of damage?*

Additional sub research questions are established in order to answer the main research question stepwise.

1. *What is the influence of various hydraulic (e.g. wave characteristics) and structural parameters (e.g. packing density of the rear slope) on the rear slope stability ?*
2. *What is the relation between individual wave overtopping volumes and wave front velocities on the stability of single layer cubes on the rear side?*
3. *What is the minimum level below mean sea level over which an armour layer should be extended?*

1.2.4 Research methodology

In order to answer the research question experiments are carried out. These tests are required due to involving complex phenomena (e.g. wave transmission and overtopping) [Frostick et al., 2011]. The physical model tests include different breakwater configurations and varying hydraulic conditions. The output of the tests is the amount of damage of the rear slope. A complete description of the experiments can be found in chapter 3.

The next step in this research is the analysis of the obtained data. The goal of this analysis is to find a relation between the input data (hydraulic and structural parameters) and the output data (damage at the rear slope). The results are presented in stability curves.

1.3 Outline of report

This report describes every part of the conducted research. This is been divided over the chapters below:

Chapter 2 "Theoretical background" gives the theoretical background of this research. This chapter focusses on the hydraulic and structural responses. The theory is used to set up and carry out a suitable test programme.

Chapter 3 "Experiments" explains every detail of the tests which are conducted.

Firstly, the general approach and the assumptions are discussed. Secondly, the complete model including the breakwater model and measuring equipment is described.

Chapter 4 "Results" summarizes the gathered data and gives an explanation of various data processing methods. An overview of the data can be found in appendix E.

Chapter 5 "Analysis" presents the analysis of the obtained data in several stability curves.

In chapter 6 "Conclusions" the research questions are answered, leading to various conclusions.

This study finishes with some recommendations for future research in chapter 7 "Recommendations".

The appendices present more detailed information and complete overview of the results.

2 | Theoretical background

The theory that is used within this study is presented in this chapter. Firstly, the hydraulic responses are described. Secondly, the structural strength is treated.

2.1 Run-up height

The run-up height is an important parameter for the overtopping calculation. The run-up height is the vertical difference between the highest point of the wave run-up and the still water level see figure 2.1. In general, the term $R_{u2\%}$ is used. This is the wave run-up height that is exceeded by 2% of the number of incoming waves.

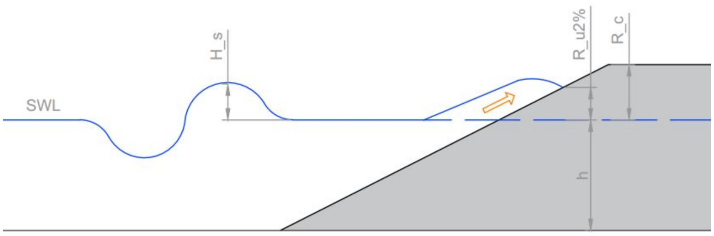

Figure 2.1: *Definition of the wave Run-up Height [Pullen et al., 2007]*

As advised in the Overtopping Manual [Pullen et al., 2007], the run-up height is described best by the empirical formula of TAW [2002] for open armoured slopes and mounds. This formula is based on smooth slopes, but is also applicable for rough slopes if a reduction factor is incorporated. The expression for the 2% mean wave run-up height for rock or rough slopes is:

$$\frac{R_{u2\%}}{H_{m_0}} = A \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \xi_{m-1,0}$$

With a maximum of:

$$\frac{R_{u2\%}}{H_{m_0}} = 1.00 \cdot \gamma_b \cdot \gamma_{f surging} \cdot \gamma_\beta \cdot \left(B - \frac{C}{\sqrt{\xi_{m-1,0}}}\right) \text{(impermeable slope)}$$

$$\frac{R_{u2\%}}{H_{m0}} = 1.97 \text{ (permeable slope)}$$

where:

$$\xi_{m-1,0} = \frac{\tan\alpha}{\left(s_{m-1,0}\right)^{0.5}} \quad (2.1)$$

The coefficients A, B and C in equation 2.1 are determined in a empirical way with and without safety margins. The values are presented in table 2.1. In a probabilistic approach, a normal distribution with a standard deviation of $\sigma = \mu \cdot 0.07$ can be assumed.

Table 2.1: *Coefficients of equation 2.1 [CIRIA, 2007]*

	Values with safety margin (Deterministic approach)	**Values without safety margin (Probabilistic approach)**
A	1.75	1.65
B	4.3	4.0
C	1.6	1.5

Reduction factor - Roughness elements

Some important values of the roughness reduction factor are shown in table 2.2. These values are only applicable for $\xi_{m-1,0} < 1.8$. For larger values this factor increases linearly up to 1 for $\xi_{m-1,0} = 10$. For $\xi_{m-1,0} > 10$ it remains 1.

Table 2.2: *Reduction factor for permeable structures of some armour types [CIRIA, 2007]*

Armour type	**Number of layers**	**Reduction factor γ_f**
Rock	2	0.4
Cube	2	0.47
Cube	1	0.5
Tetrapod	2	0.38
Accropode	1	0.46
Xbloc	1	0.45

2.2 Overtopping

The overtopping wave is the main load on the rear slope of a breakwater. In order to understand the overtopping loading on the rear slope, the mechanism is sketched and various overtopping parameters are described.

2.2.1 Overtopping discharges

The overtopping wave is sketched in figure 2.2. The wave can be divided in sub discharges, that acting on different parts of the breakwater [Verhagen et al., 2003]. This research focusses on the rear slope and therefore discharges q4, q5 and q6 are the main subject. Since little is known about the magnitude of the discharges acting on the rear slope, the well-known overtopping discharge at the rear side of the crest (q3) will be used.

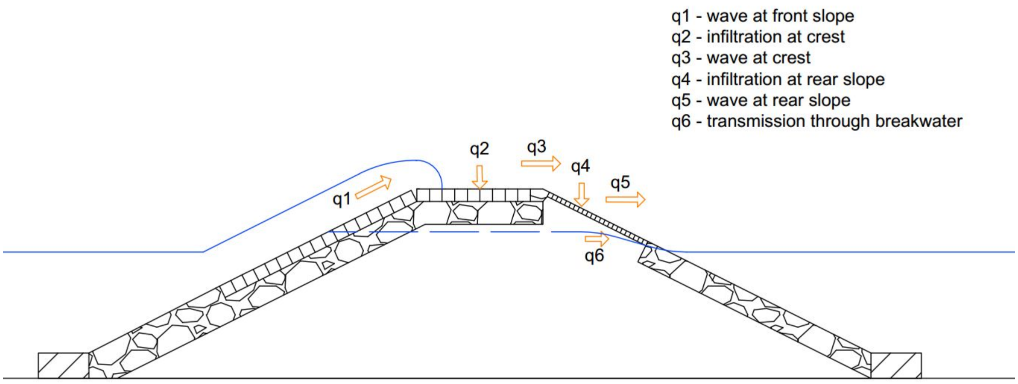

Figure 2.2: *Overtopping wave divided in six components*

2.2.2 Impact on rear slope

The impact of an overtopping wave on the rear slope is described by Kudale and Kobayashi [1996]. This study considers a jet of water impinging the rear slope above and below the water level. The velocity of the water jet is related to the velocity on the crest (corresponding to discharge q3).

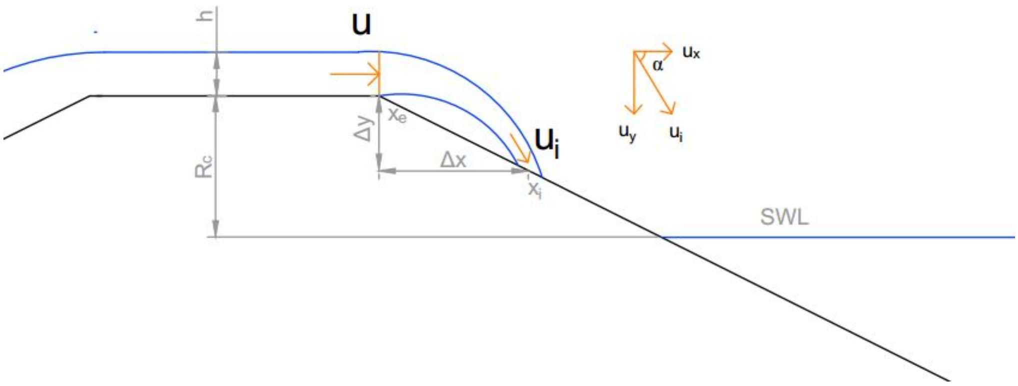

Figure 2.3: Overtopping water jet impinging the rear slope

At the edge of the crest (x_e) the horizontal velocity is equal to u and the vertical velocity is zero. Kudale and Kobayashi [1996] assumed that from this point the water falls due to gravity. The air friction is neglected. The flow is accelerated with the gravitational acceleration g until the water jet reach the rear slope. The impact velocity (u_i) is determined in the following way:

$$u_x = u \tag{2.2}$$

$$\Delta x = \frac{u^2 \cdot \tan\theta_{rear} + \sqrt{u^4 \cdot \tan^2\theta_{rear} + ghu^2}}{g} \tag{2.3}$$

$$\Delta y = \Delta x \cdot \tan\theta_{rear} + \frac{h}{2} \tag{2.4}$$

$$u_y = \frac{g\Delta x}{u} \tag{2.5}$$

$$u_i = \sqrt{u_x^2 + u_y^2} \tag{2.6}$$

$$\alpha_i = \tan^{-1}\frac{u_y}{u_x} \tag{2.7}$$

This expression changes when the water jet plunges into the water level and then strikes the rear slope. After entering the water, the jet is not falling freely due to the gravity. To simplify this situation, Kudale and Kobayashi [1996] approximated the velocity by assuming the jet penetrates straight into the water with the same velocity as at the free surface. This is reasonable for a short penetration distance. In case of a long penetration distance this simplification overestimate the velocity.

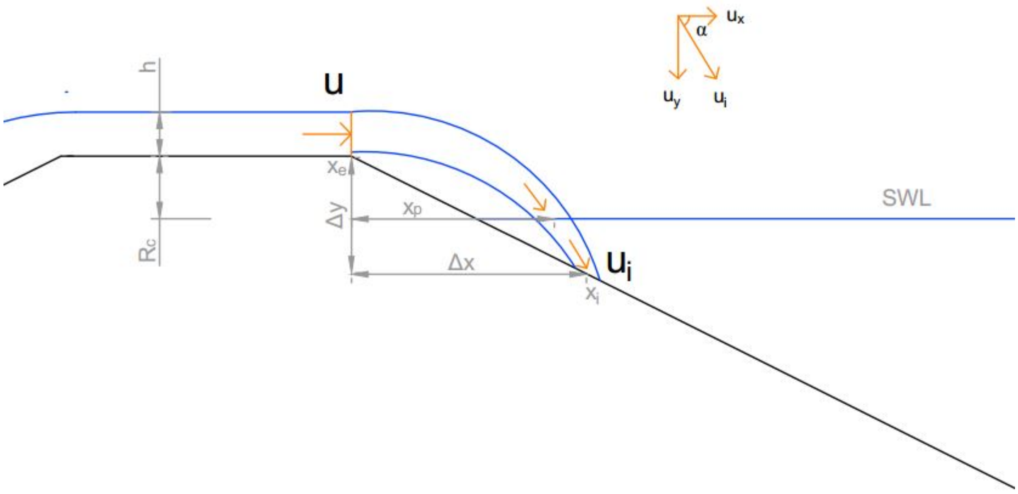

Figure 2.4: *Overtopping water jet impinging the rear slope under the free surface*

The derived equations for this situation are:

$$\Delta x = x_p + \frac{x_p \cdot \tan\theta_{rear} - R_c}{\tan\alpha_i - tan\theta_{rear}} \tag{2.8}$$

where the horizontal velocity of the free fall is:

$$x_p = u\sqrt{\frac{2\,(R_c + h/2)}{g}} \tag{2.9}$$

The velocity at the point of impact is equal to the velocity at the free surface:

$$u_y = \frac{g \cdot x_p}{u} \tag{2.10}$$

2.2.3 Overtopping parameters

Overtopping events are described with the following parameters:

- Average overtopping discharge (q)
- Extreme water layer thickness ($h_{2\%}$)
- Extreme overtopping velocity ($u_{2\%}$)
- Extreme individual overtopping wave volume ($V_{2\%}$)
- Extreme overtopping discharge ($q_{2\%}$)
- Probability of overtopping (P_{ov})

2.2.4 Average overtopping discharge

Owen [Owen, 1980] and Van der Meer [TAW, 2002] introduced the most common overtopping formulas. The main difference is the application range. Owen [1980] is only valid in the ranges of:

$$0.035 < s_{om} < 0.055$$

and

$$0.05 < R^* < 0.60$$

where

$$R^* = \frac{R_c}{H_s \sqrt{s_{om}/2\pi}} \tag{2.11}$$

The disadvantage of the overtopping formula of Owen [1980] is the application range for the dimensionless free board. As one can see, the method is not valid for a small or zero free board. Therefore, this method is not ideal for this research. The overtopping formula of van der Meer is applicable in a very wide range of wave conditions. This makes this formula more favourable. It is used in the calculation of the average wave overtopping discharge [CIRIA, 2007].

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = \frac{A}{\sqrt{\tan\alpha}} \cdot \gamma_b \cdot \xi_{m-1,0} \cdot \exp\left[-\left(B \cdot \frac{R_c}{H_{m0}} \cdot \frac{1}{\xi_{m-1,0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta} \right)^{1.3} \right] \tag{2.12}$$

With a maximum of:

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = C \exp\left[-\left(D \cdot \frac{R_c}{H_{m0}} \cdot \frac{1}{\gamma_f \cdot \gamma_\beta} \right)^{1.3} \right] \tag{2.13}$$

The reduction factors used in these equations are the same as in the TAW run-up height equations. The coefficients A, B, C and D are updated recently and presented in table 2.3.

Table 2.3: *Coefficients of equation 2.12 [van der Meer et al., 2013]*

	Values
A	0.023
B	2.7
C	0.09
D	1.5

2.2.5 Extreme overtopping parameters

Wave overtopping is a random process and this aspect is not covered in the average overtopping discharge q. The irregular and dynamic overtopping can be described, by parameters that include the probability of exceedance of a certain value. Furthermore, it is expected that the highest overtopping loads contribute most to a possible failure of the rear slope. Therefore, four additional overtopping parameters are defined:

- Maximum water layer thickness exceeded by x% of the incident waves ($h_{x\%}$)
- Maximum velocity exceeded by x% of the incident waves ($u_{x\%}$)
- Maximum discharge exceeded by x% of the incident waves ($q_{x\%}$)
- Volume exceeded by x% of the incident waves ($V_{x\%}$)

The two main researches in the field of extreme overtopping parameters are that of van Gent and Schrüttrumpf [Schüttrumpf and van Gent, 2004]. Different relations are valid for the crest, front and rear slope of a dike. However, the formulas are also applicable for breakwaters according to the Rock Manual.

The front slope:

$$\frac{h_{2\%}}{H_s} = c'_{a,h}\left(\frac{R_{u2\%} - z}{\gamma_f H_s}\right) \tag{2.14}$$

$$\frac{u_{2\%}}{\sqrt{gH_s}} = c'_{a,u}\left(\frac{R_{u2\%} - z}{\gamma_f H_s}\right)^{0.5} \tag{2.15}$$

The crest:

$$\frac{h_{2\%}}{H_s} = c'_{c,h}\left(\frac{R_{u2\%} - R_c}{\gamma_f H_s}\right) \cdot \exp\left(-c''_{c,h} \cdot x/W_c\right) \tag{2.16}$$

$$\frac{u_{2\%}}{\sqrt{gH_s}} = c'_{c,u}\left(\frac{R_{u2\%} - R_c}{\gamma_f H_s}\right)^{0.5} \cdot \exp\left(-c''_{c,u} \cdot x \cdot f_c/h_{2\%}\right) \tag{2.17}$$

The rear slope:

$$h = h_0 u_0 / \left(\frac{\alpha}{\beta} + \mu \exp\left(-3\alpha\beta^2 s\right)\right) \tag{2.18}$$

$$u = \left(\frac{\alpha}{\beta} + \mu \exp\left(-3\alpha\beta^2 s\right)\right) \tag{2.19}$$

With $\alpha = \sqrt[3]{g \sin\varphi}$, $\beta = \sqrt[3]{1/2 f_L/(h_0 u_o)}$, $\mu = u_0 - \alpha/\beta$, s is the co-ordinate along the landward slope, f_L is the friction factor along the rear slope and φ the slope angle of the landward slope.

In order to use these extreme overtopping formulas, another run-up height equation should be defined. This formula is used in the calculation process of van Gent and Schrüttrumpf:

$$\text{for } \xi_{m-1,0} \leq p:$$

$$\frac{R_{u2\%}}{H_s} = c_0 \cdot \xi_{m-1,0} \tag{2.20}$$

$$\text{for } \xi_{m-1,0} \geq p:$$

$$\frac{R_{u2\%}}{H_s} = c_1 - \frac{c_2}{\xi_{m-1,0}} \tag{2.21}$$

Table 2.4: *Coefficients for wave run-up predictions*

	Schrüttrumpf (2002)	**Van Gent (2002)**
c_0	1.25	1.35
c_1	-	4.0
c_2	$c_2 = 0.25\frac{c_1^2}{c_0}$	
p	$p = 0.5\frac{c_1}{c_0}$	

Additional tests are carried out by van Gent to determine the extreme overtopping discharge:

$$q_{2\%} = c_q' \cdot \sqrt{g}\frac{(R_{u2\%} - R_c)^{1.5}}{1 + c_q''\frac{W_c}{H_s}} \tag{2.22}$$

The following formula can be used to predict the extreme volume ($V_{2\%}$) within an overtopping wave:

$$V_{2\%} = c_V' \, (R_{u2\%} - R_c)^2 \tag{2.23}$$

Table 2.5: Values of the coefficients in equations 2.14 to 2.23

	Front slope				Crest			
	Van Gent		Schüttrumpf		Van Gent		Schüttrumpf	
Parameter	c'	c''	c'	c''	c'	c''	c'	c''
$h_{2\%}$	0.15	-	0.33	-	0.15	0.4	0.33	0.89
$u_{2\%}$	1.30	-	1.37	-	1.30	0.5	1.37	0.50
$q_{2\%}$	0.20	0	-	-	0.17	0.1	-	-
$V_{2\%}$	-	-	-	-	1.0	-	-	-

Schüttrumpf and Van Gent apply different coefficients in there calculations. The variations are caused by different model set-ups and test programs. The formulas presented above are valid within the following ranges:

$$R_{u2\%} \geq R_c$$
$$0 < \frac{(R_{u2\%} - R_c)}{\gamma_f \cdot H_s} < 1.0$$
$$1 < \frac{W_c}{H_s} < 7.5$$

2.2.6 Probability of overtopping

The overtopping waves have all a certain overtopping volume of water, which can be described with a Weibull distribution. If the number of overtopping waves N_{ow} and the overtopping discharge q are known, the exceedance probability P_v of an overtopping volume per wave can be calculated with the following formula [Pullen et al., 2007]:

$$P_V = P\left(\underline{V} \leq V\right) = 1 - exp\left[-\left(\frac{V}{a}\right)^b\right] \quad (2.24)$$

This equation has a shape factor b defining the extend of the tail and a dimensional scale factor a, which normalizes the distribution. The value of the shape factor is generally within a range of $0.6 \leq b \leq 0.9$. The curves for these values only differ significant in the extreme values. The mean value of $b = 0.75$ is commonly used. The value of the scale factor a can be quantified with:

$$a = 0.84 \cdot T_m \cdot \frac{q}{P_{ov}} = 0.84 \cdot T_m \cdot q \cdot N_w / N_{ow} = 0.84 \cdot q \cdot t / N_{ow} \quad (2.25)$$

The number of overtopping waves N_{ow} can be calculated with the probability of overtopping equation (2.26), where N_w is the number of waves in a storm. Pullen et al.

[2007] assumed that the run-up distribution conforms to the Rayleigh distribution in this equation.

$$P_{ov} = \frac{N_{ow}}{N_w} = exp\left[-\left(\sqrt{-\ln 0.02}\cdot\frac{R_C}{R_{u,2\%}}\right)^2\right] \tag{2.26}$$

Equation 2.24 can be rewritten:

$$V = a\cdot[-\ln(1-P_V)]^{4/3} \tag{2.27}$$

The maximum overtopping volume in a storm can be determined by filling in the number of overtopping waves N_{ow}.

$$V_{max} = a\cdot[-\ln(N_{ow})]^{4/3} \tag{2.28}$$

2.3 Rear slope stability

In practise some engineers faced a problem concerning the design of the rear slope stability with concrete elements. In order to define this problem, a literature study is conducted into the topic of rear slope stability. Within this study, the result of thirteen papers are taken into account. The complete overview of the study can be found in appendix A.

2.3.1 Conclusions literature study

The ten out of thirteen studied papers give quite a good impression of the rear slope stability of different types of breakwaters with a rock armour layer. For a conventional breakwater design with a rock armour layer, the formulas of Van Gent are applicable [van Gent and Pozueta, 2004]. In practice these formulas have proven to be on the safe side and may overestimate the actual maximum diameter of the rear slope rock armour. However, it can be concluded that there is enough knowledge available about this subject.

Only three papers can be found on the subject of rear slope stability of a breakwater with an armour layer of concrete units. Only some design guidelines are available for placed block revetments, an armour layer of Tetrapods and Xblocs.

Besides the conclusions about the available knowledge of rear slope stability, it can be concluded that several parameters influence the rear slope stability. Most studies include the parameters: armour unit dimensions, significant wave height, crest height, relative density and wave steepness. The most recent stability relations consider also the parameters: number of waves, rear slope angle and overtopping front velocity.

2.4 Cube armour units

There is a great variety in types of concrete units that are suitable for the armour layer of a rubble mound breakwater. Since not for all units a rear slope stability relation can be found due to a limit in time and money, a selection of one concrete unit is made. The most common used concrete units are shown in figure 2.5.

<table>
<tr><th rowspan="2">Placement pattern</th><th rowspan="2">Number of layers</th><th rowspan="2">Shape</th><th colspan="3">Stability factor (main contribution)</th></tr>
<tr><th>Own weight</th><th>Interlocking</th><th>Friction</th></tr>
<tr><td rowspan="5">Random</td><td rowspan="3">Double layer</td><td rowspan="2">Simple</td><td>Cube, Antifer Cube, Modified Cube</td><td></td><td></td></tr>
<tr><td colspan="2">Tetrapod, Akmon, Tripod</td><td></td></tr>
<tr><td>Complex</td><td></td><td>Stabit, Dolos</td><td></td></tr>
<tr><td rowspan="2">Single layer</td><td>Simple</td><td>Cube</td><td></td><td>Cube</td></tr>
<tr><td>Complex</td><td></td><td>Stabit, Accropode, Core-loc, Xbloc</td><td></td></tr>
<tr><td rowspan="2">Uniform</td><td rowspan="2">Single layer</td><td>Simple</td><td>Haro</td><td></td><td>Seabee, Haro</td></tr>
<tr><td>Complex</td><td></td><td></td><td>Cob, Shed, Tribar, Diode</td></tr>
</table>

Figure 2.5: *Classification of concrete armour units [CIRIA, 2007]*

A simple shape of a concrete unit is the cube. This unit can be placed regular or irregular either in a single or double layer. Due to its simple shape, it gains stability by its own weight (and friction). The downside to this stability mechanism is the large amount of concrete. Compared to other units, cubes have a relative large concrete volume, making them more expensive. On the other hand this unit has no patent, while for using other more complex units generally a fee has to be paid. Also, the placement and production cost less for cubes due to its simple shape. Besides the lower costs, the construction and maintenance of a breakwater with cubes is less complicated [van Gent and Luis, 2013]. These advantages lead to the decision to select the cube as the armour unit for the rear slope in this study.

2.4.1 Placing pattern and packing density

The cube can be applied in a single or double layer and can be placed either regular or irregular placed. The cubes are placed flat on the underlayer in both placement patterns. (see figure 2.6) This research considers a single armour layer of regular placed cubes for two reasons. Firstly, regular placement is more stable than irregular placement and secondly, a single layer of cubes contains less concrete than a double layer.

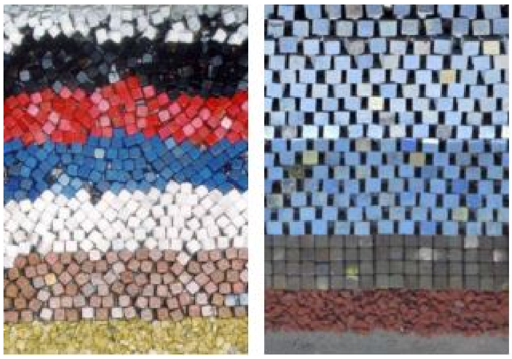

Figure 2.6: *Placement patterns, left: irregular placement, right: regular placement [van Gent et al., 1999]*

According to van Gent and Luis [2013], a packing density between 70% and 75% (porosity of n=0.25 - 0.3) is most appropriate. A packing density of 75% is preferred, since the amount of settlement within the armour layer is reduced.

2.5 Stability of the front side single armour layer of cubes

The Rock Manual [CIRIA, 2007] gives a design criteria for single layer of cubes for the front side, namely:

$$\textbf{Start of damage } N_{od} = 0: \quad \frac{H_s}{\Delta D_n} = 2.9 - 3.0 \tag{2.29}$$

$$\textbf{Failure } N_{od} = 0.2: \quad \frac{H_s}{\Delta D_n} = 3.5 - 3.75 \tag{2.30}$$

Also, CIRIA [2007] advices to use a safety factor, because the difference between start of damage and failure is very small. Because there is no reserve in the form of a second layer, in this system. Which means, damage of the amour layer will immediately result in exposure of the underlayer. A safety factor of 1.5 is recommended. The value of the stability number including the safety factor has almost the same value as a double layer of cubes (see figure 2.7).

$$\textbf{Design value:} \qquad \frac{H_s}{\Delta D_n} = 2.33 - 2.5 \tag{2.31}$$

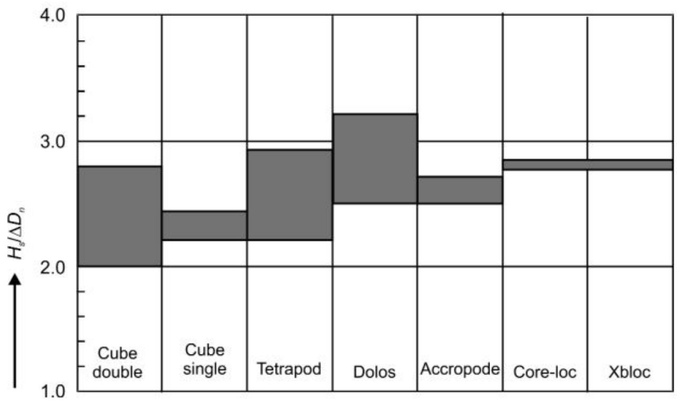

Figure 2.7: *Stability number for conceptual design of concrete units [CIRIA, 2007]*

These stability numbers for a single layer of cubes are applicable for a packing density between 70% and 75%. The Rock Manual makes no distinction between irregular and regular placements. Since these stability numbers are also valid for the less stable irregular placed armour layer, it is expected that the real stability number of the regular placed cube is larger.

2.6 Qualitative assessment of the cube stability

The assessment on the cube stability is done on two loading types; flow perpendicular to and plunges impinging the rear slope. Since such a assessment is not carried out for a single layer of cubes, a comparison is made with other armour units.

2.6.1 Flow perpendicular to the rear slope

An armour layer of single layer of cubes can be compared with a placed blocks revetment, only with larger porosity. A qualitative assessment of the rear side stability of a placed block revetment by [Kuiper et al., 2006] is used.

The overtopping wave results in a hydraulic load on the rear slope, namely a flow along the rear slope. These flow effects can affect the cube stability due to an uplift force at the cube. This uplift force is caused by an uneven surface.

In reality, the surface of the single layer of cubes is never completely flat. For example, irregularities can occur due during the construction of the breakwater or after a storm. A protruding cube is shown in 2.8. The uplift force is the result of the curved streamlines and the high pressure upstream of the cube.

Due to the angular shape of the cube, the streamlines will be curved around the cube. This results in eddies at the front, top and rear side of the cube. More important, the curved streamlines lead to a decrease of pressure on the cube, which results in an uplift force at the cube. The high pressure at the upstream side of the cube is the result of the blocked flow. The high pressure penetrates into the filter. This increases the uplift force even more.

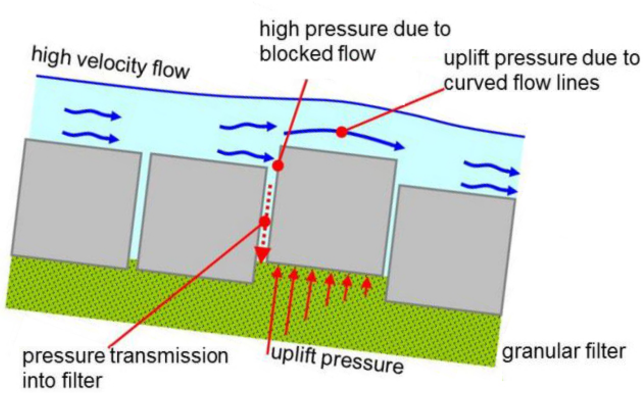

Figure 2.8: *Protruding cube with curved streamlines causing uplift pressure [Klein Breteler et al., 2014]*

The resulting forces are shown in figure 2.9. The uplift pressure in the underlayer is generally discounted in the uplift pressure caused by the underpressure on the armour layer. The fact that the force under the cubes act on a larger length is neglected. This simplification leads to the uplift force on a single cube as is shown in figure 2.9 as F_{op}. Also the forces belonging to the cube's weight and the contact with the underlying cube are displayed. These forces are used to find the critical value for which the cube starts to move.

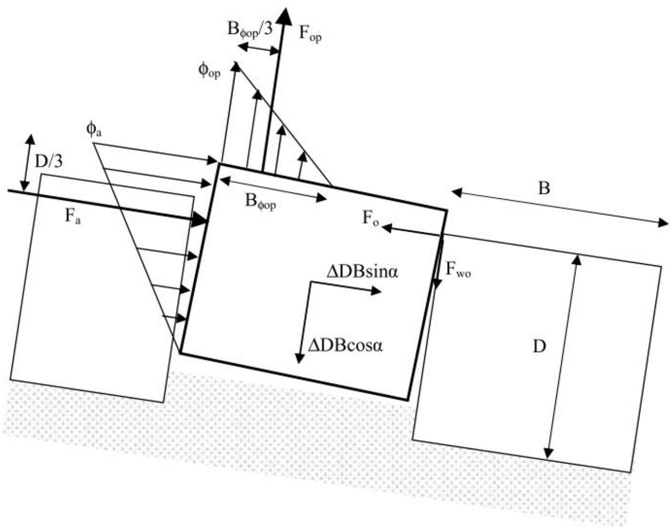

Figure 2.9: *Forces on a single cube [Kuiper et al., 2006]*

Forces along the slope are:

$$F_a + \rho g \Delta D_n^2 \sin\alpha - F_o = 0 \tag{2.32}$$

$$F_o = \rho g D_n \phi_a / 2 + \rho g \Delta D_n 2^2 \sin\alpha \tag{2.33}$$

Forces perpendicular to the slope are:

$$\rho g \Delta D_n^2 \cos\alpha + F_{wo} - F_{op} = 0 \tag{2.34}$$

For $F_{wo} = f \cdot F_o$, this leads to:

$$\rho g \Delta D_n^2 \cos\alpha + f\left(\rho D_n \phi_a/2 + \rho g \Delta D_n^2 \sin\alpha\right) - \rho g B_{\phi op}\phi_{op} = 0 \tag{2.35}$$

Applying $\phi_{op} = C_L \phi_a$ results in:

For $C_L \cdot B_{\phi op} \geq f \cdot D_n$

$$\phi_{a,max} < \frac{2\Delta D_n^2(\cos\alpha + f \cdot \sin\alpha)}{C_L\left(2 - D_n/B_{\phi op}\right)D_n - f \cdot D_n} \tag{2.36}$$

For $C_L \cdot B_{\phi op} < f \cdot D_n$ the cube is always stable.

The maximum pressure ϕ_a for which no movement occurs can be translated to a maximum flow velocity, with:

$$\phi_{a,max} = 0.9 \cdot u_{max}^2 / (2 \cdot g) \tag{2.37}$$

This theoretical value for flow velocity will be compared with the measured overtopping wave front velocity. In this way, the theory can be compared with the results from the experiments. See D for the complete calculation.

It should be mentioned that the this assessment is only valid for a placed block revetment. The porosity is higher for a single armour layer of cubes. This leads to higher impact loads on the side of the cube, but the pressure build-up in the underlayer is smaller.

2.6.2 Plunge impact at the rear slope

Kudale and Kobayashi [1996] studied the reaction forces of the plunges acting on the rear slope with an armour layer of rocks. Despite the different armour unit, the same forcing pattern can be used. Figure 2.10 shows the forces on a cube that is loaded with a overtopping plunge.

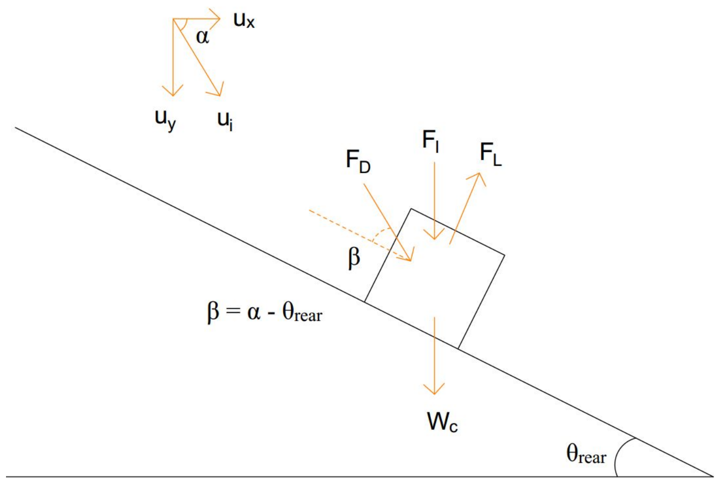

Figure 2.10: *Forces acting on a cube loaded with a plunge*

Subsequently, a force balance can be composed.

2.7 Damage criteria

The amount of the rear slope is expressed in the number of displaced cubes within a strip of rear slope of width D_n. This value represents the amount of displaced units in one column and its symbol is N_{od}.

According to the Rock Manual, the start of damage occurs within the range $N_{od} = 0.2 - 0.5$. Intermediate damage and failure have respectively a damage number of $N_{od} = 1$ and $N_{od} = 2$ [CIRIA, 2007]. Since a single layer behaves brittle, the sequential damage phases follow up quickly. Therefore, the start of damage is the target value and a value of $N_{od} = 0.2$ is defined as the damage criteria for single layer cubes.

A cube is considered as damaged if it is displaced a certain distance. The displacements are divided into three classes:

$\leq 0.2 \cdot d_n$: no displacement
$0.2 \cdot d_n - 0.3 \cdot d_n$: small displacement
$0.3 \cdot d_n - 1.5 \cdot d_n$: large displacement
$\geq 1.5 \cdot d_n$: cube removed from slope

A cube with a large displacement ($\geq 0.3 \cdot d_n$) is considered as damaged. The number of cubes with a large displacements are counted in order to find the damage number N_{od}.

3 | Experiments

This chapter gives an overall description of the experiment set-up and the testing procedure. The objective of the experiments is to find accurate measurements that give answers to the research questions.

3.1 General approach

The experiment focusses on six different input parameters, which have the greatest expected influence. The selection of the parameters is based on the previous studies of rear slope stability (see figure 3.1). The main objective of the experiments is to correlate these parameters to the structural response of the rear slope which is expressed in a rear slope damage number.

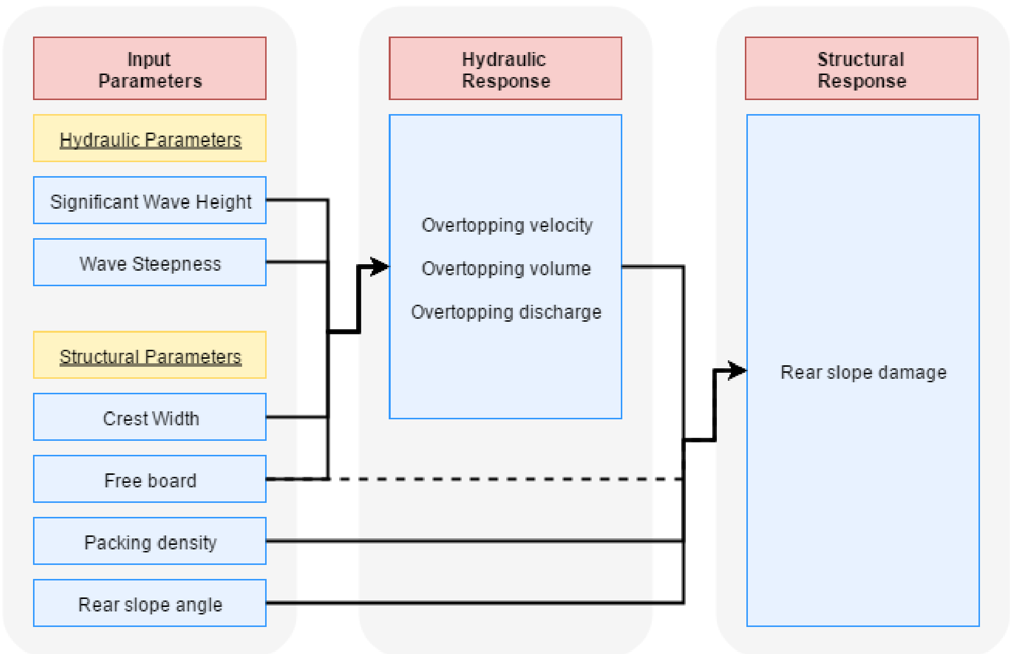

Figure 3.1: *General approach of the experiment*

As presented in the chapter 2, the structural response of the rear slope armour layer is a result of overtopping wave loads and the strength itself. Also, empirical expressions for the overtopping volume, overtopping velocity and overtopping discharge are presented. Besides linking the input parameters to the rear slope damage, an attempt is made to correlate these overtopping characteristics with the rear slope damage. The significant wave height, wave steepness, crest width and free board can be replaced by the overtopping characteristics. This operation could make the calculated relation applicable in a greater variety of breakwater designs than tested in this experiment. The placing density and rear slope angle are properties of the structural strength of the rear slope and should be correlated directly to the rear slope damage. The free board of the breakwater is a structural property of both the front and a the rear side. Possibly, it is insufficient to include the free board only in the overtopping characteristic, because of its additional influence on the rear slope. For that reason, a dotted connection is made between the free board and the rear slope damage in figure 3.1.

3.2 Assumptions

The most important assumptions made in the model are presented in terms of the selected parameters and scaling effects. Some other assumptions are mentioned in the last paragraph.

3.2.1 Variables

The influence could not be studied for all parameters, due to limiting time. A selection of hydraulic and structural parameters is made, based on the literature study (see table 3.1). It is assumed that these parameters have the largest influence on the rear slope stability and that the contribution of other factors can be neglected.

Table 3.1: *Parameters varied in the experiment*

Structural parameters	Hydraulic parameters
Free board (R_c)	Significant wave height (H_s)
Crest Width (Wc)	Wave steepness (s)
Rear Slope Angle (φ)	
Packing Density (n_p)	

The free board is varied by changing the water depth. It is assumed that the influence of the varying water depth on the hydraulic conditions is negligible.

3.2.2 Scaling

The scaling factors and dimensions of the model are determined according to Frostick et al. [2011].

Besides geometric scaling between the prototype and model, there are various scaling numbers, which are dimensionless numbers. These should have similar values for the model as for the prototype. The three relevant numbers for dynamic similarity in case of a breakwater model are Froude (Fr), Reynolds (Re) and Weber (We). However it is not possible to come up with a model that fulfill these three laws and the geometric scale. Below it is explained how to deal with this clash.

The geometric scaling is achieved by applying a certain scaling factor to all structural dimensions. The flow hydrodynamics should fulfill the Froude law, which means that the Froude value for the model should be the same as for the prototype. To accomplish this, the scaling factors in table 3.2 should be applied.

In order to neglect similarity in the Reynolds number, turbulent flow conditions have to exist throughout the primary armour layer in the model. This is the case for values of $Re > 30,000$ [Dai and Kamel, 1969].

The dimensions of the model should be as large as possible to reduce the scaling effects and to be able to neglect the Weber similitude. The Weber number describes the surface tension of the flow, which is in most cases negligible in the prototype. This is also the case for the models that satisfy: $L >> 0.02m, T > 0.35s, h > 0.02m$.

Scaling of the core material. Transmission

Table 3.2: *Scaling relationships expressed in the length scale factor n_L*

	Unit	**Scaling relationship**
Distance	$[m]$	n_L
Time	$[s]$	$n_T = n_L^{0.5}$
Velocity	$[m/s]$	$n_u = n_L^{0.5}$
Acceleration	$[m/s^2]$	$n_a = 1$
Mass	$[kg]$	$n_M = n_\rho \cdot n_L^3$
Discharge	$[m^3/s]$	$n_Q = n_L^{2.5}$
Specific discharge	$[l/s/m]$	$n_q = n_L^{1.5}$

It should be mentioned that model scales are applied. The results are all in model dimensions and not scaled to prototype dimensions.

3.2.3 Other assumption

In the wave flume of Fluid Mechanics Laboratory only two dimensions are taken into account. Three dimensional effects are not considered.

Currents (for example: tidal and density currents) are not included in the experiments. The hydraulic force is dominated by waves.

3.3 Model Set-up

This section describes the complete set up; the flume and the model.

3.3.1 Wave Flume

The wave flume ("Lange Speurwerk Goot"), located at the water lab of CEG faculty, is sketched in the figure 3.5. The flume's length, width and height are respectively 42, 0.8 and 1.0 metre. The sides of the flume are made of glass with in between steel bars. The location of these bars is taken in to account when placing the model in the flume to avoid disturbance of the view.

3.3.2 Wave generator

The wave generator (see figure 3.2) installed in the wave flume is driven electro-mechanically and can be controlled by a personal computer with the software "Wave-generator Control" (Developed by Deltares). The program is used to generate a variety of wave conditions, which are defined in an steering file. This file specifies the requested wave height, wave period, wave spectrum, spectral parameters and duration of the test.

The wave generator is equipped with an Active Reflection Compensator (ARC) that measures reflected waves and corrects the motion of the wave generator accordingly. This system avoids waves to be reflected from the paddle. However, the reflections from the breakwater model are in the flume. These waves are filtered in the data analysis in order to define only the incoming wave.

In this research irregular waves according to a JONSWAP-spectrum (see appendix B) are generated in a range of $0.06 < H_s < 0.20$ and $0.02 < s < 0.04$.

3.3.3 Configurations

The values of the parameters that are considered in the experiment are presented in table 3.3. As one can see, there are 11 different configurations, where in every experiment one parameter is varied.

The parameters to be studied, are varied in three different values, with the exception of the rear slope angle and packing density. The value of three is chosen as a balance between the number of tests and the accuracy of the relation.

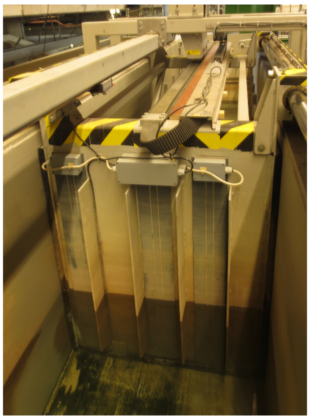

Figure 3.2: *Wave generator*

Free Board

A low crested breakwater model is chosen. The test programme consists of tests with a relative free board of $0.4 < \frac{R_c}{H_s} < 1.3$. The corresponding free board values are $R_c = 5, 10$ and $15\ cm$.

Crest Width

A wide range of relative crest width is chosen, namely $1.1 < \frac{W_c}{H_s} < 6.3$. The corresponding values for the crest width are $W_c = 15, 30$ and $50\ cm$. The integer number of cubes on the crest have been taken into account. The number of cubes on the crest are respectively 3, 6 and 10. (The diameter of the cube is determined in section 3.3.4)

Rear Slope Angle

Only two configurations are used to study the influence of the rear slope angle. A third configuration is not used, because the slope angle is commonly between 1:2 and 1:1.5. Also, it is expected that a third configuration constructed rear slope angle within this range would not lead to significant more or less damage.

Packing Density

As stated in section 2.4.1, a packing density between $n_p = 70\%$ and 75% is most appropriate. Two values within this range were selected.

Table 3.3: Test programme without wave conditions

	Freeboard	Crest width	Rear slope angle	Packing Density	Wave Steepness
	R_c $[m]$	W_c $[m]$	φ $[-]$	$n_p[-]$	$s[-]$
1	**0.15**	0.5	1:2	0.73	0.027
2	**0.10**	0.5	1:2	0.73	0.027
3	**0.05**	0.5	1:2	0.73	0.027
4	0.10	0.5	1:2	0.73	**0.039**
5	0.10	0.5	1:2	0.73	**0.015**
6	0.10	**0.3**	1:2	0.73	0.027
7	0.10	0.3	1:2	**0.69**	0.027
8	0.10	**0.15**	1:2	0.73	0.027
9	0.10	0.15	1:2	**0.69**	0.027
10	0.10	0.15	**1:1.5**	0.73	0.027
11	0.10	0.15	1:1.5	**0.69**	0.027

Wave Steepness

The steepness of the waves is chosen within a range of $0.015 < s < 0.040$, because these are commonly measured values. Again, three values are chosen within this range.

3.3.4 Breakwater model

The figure below shows the breakwater model of the first configuration. The front slope, the underlayer and the core are the same in all configurations. The crest and rear slope angle are varied in the other configurations.

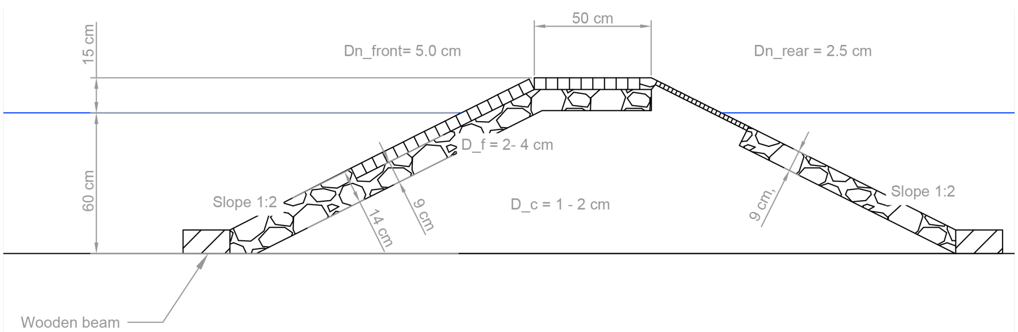

Figure 3.3: Cross section of the configuration 1 of the physical breakwater model

The part of interest is the rear slope with a single layer of cubes. The other parts of the breakwater are dummy and are designed in such way, no failure or displacements occurs at these parts. The wooden beam is one of these parts and represents the toe of the breakwater.

In the next paragraphs the determination of the various materials in the breakwater is explained.

Armour layer

Rear slope

The breakwater is armoured with cubes at the front slope, crest and rear slope. The diameter of the cubes of the rear slope are estimated with the formula of van Gent and Pozueta [2004]. This formula is meant for randomly placed armour rock, therefore a correction is done by using the difference in stability between rock and cubes for seaward slopes. The calculation of the damage level of a certain cube diameter is shown in appendix C.

The estimation of the rear slope damage is performed for all eleven configurations and wave conditions within the application range of the wave generator. The resulting diameter of the rear slope is determined iterative, namely $D_n = 0.035m$. For this value, the damage is large enough for every configuration ($N_{od} > 1$) if it is loaded with the largest wave ($H_s = 0.18m$). However, from practise it is found that the van Gent and Pozueta [2004] formula is quite conservative. Therefore, a smaller cube diameter is selected, which is also already available for the experiment, namely $D_n = 0.031m$. In a first experiment, this cube has proven to be too large. In most tests no damage was observed at the rear slope. In a second experiment, a smaller cube is used, namely $D_n = 0.019m$ ($W_c = 0.014kg$ and $\rho = 2120kg/m^3$), which leaded to a damaged rear slope in all tests. The results of this second experiment are used in this study.

The rear slope armour layer of cubes is placed in 23 rows. This is the minimum amount of rows to maintain the minimum of 5 rows below the free surface for every configuration. More than 23 rows could lead to larger displacements due to settlements.

Below the armour layer of cubes, a armour layer with rocks is placed. Also, this part is dummy and the selected nominal diameter of the rocks is such that it is stable in all tests. A value of $d_{n50} = 3cm$ is used and this armour layer has proven to be a stable.

The transition between the armour layer of cubes and rocks is constructed with an steep strip. This strip is used to create a stable base for the cube armour layer. This is important since small deviations in the bottom row cause less accurate placements and therefore a less stable armour layer. This strip does not affect the flow over the structure since it is placed in the armour layer. Also, the strip is placed deep into the water in order to avoid the strip having influence on the amount of damage. The damage occurs at higher levels. For this reasons, it is assumed that the effect of the steel strip can be ignored.

Front slope and crest

The cubes on the front slope and the crest are dummy sections. This means that these sections have not been analysed with regard to stability. The size of the cubes on the front slope and crest are selected in such way that these block are stable under all conditions. The dimensions of the cubes are determined according to the formulas in the rock manual. Within this formula, conservative values are chosen to be sure the units will not move or rock during the tests.

$$\frac{H_s}{\Delta \cdot D_n} = 2.33 \tag{3.1}$$

This results in a cube diameter of $D_n = 0.050m$, which is applied on both the front slope and the crest. To be sure no damage occurs, a high density cube is used. The two sections are important for the run-up and wave overtopping effects. Since larger cubes are selected than should be used in reality, the roughness of the layer is expected to be some what larger. The increased roughness is caused by a thicker boundary layer. The roughness reduction factor as is presented in the Rock Manual is $\gamma_f = 0.5$ for a single armour layer of cubes. However, the comparison between the measured and the calculated overtopping velocities (see section 5.2.1) leaded to a more suitable roughness reduction factor of $\gamma_f = 0.47$.

Filter & Core

A geometrically closed filter is applied to avoid erosion of the filter and core material. van Gent [2001] derived a relation between the diameter of the armour and the filter material:

$$\frac{D_{cube}}{D_{n50f}} = 1.8 \tag{3.2}$$

This results in a front slope and rear slope filter diameter of respectively $d_{n50} = 3cm$ and $d_{n50} = 1.1cm$. Suitable material for both filters are:
- Front slope filter: Mica rose split 20-40 mm
- Rear slope filter: Marne jaune split 10-20 mm

The permeability of the filter and core leads to a flow through the pores. In the model and the prototype, this flow velocity should have the same magnitude in relation to the other dimension. This has as consequence, that the filter and core are made generally more porous in the model than in the prototype. Therefore, the core material is chosen as large as possible. Namely, a core with the same material as the rear slope underlayer is selected:
- Core: Marne jaune split 10-20 mm

It should be mentioned that a underlayer with larger material at the front slope of the physical model is necessary because of the relative large areas between the cubes. If the same material as in the core should be used, the material would erode through the porous between the cubes.

The filter stability requirements should be checked for the front slope in order to be sure this filter is stable [Schiereck]. It is assumed that the lower and upper value of the founded rock classes are respectively the d_{n15} and d_{n85}.

Stability rule:

$$\frac{D_{15f}}{D_{85c}} \leq 5 \Rightarrow \frac{0.02}{0.02} = 1 < 5 \tag{3.3}$$

Internal stability:

$$\frac{D_{60}}{D_{10}} \leq 10 \Rightarrow \frac{0.033}{0.019} = 1.5 < 10 \tag{3.4}$$

Permeability:

$$\frac{D_{15f}}{D_{15c}} > 5 \Rightarrow \frac{0.02}{0.01} = 2 \not> 5 \tag{3.5}$$

The permeability rule is not met for the underlayer. However, no problems are expected since a high permeability of the armour layer ($n = 0.30$) and core will avoid pressure build up.

3.4 Hydraulic conditions

The different configurations are subjected to increasing wave loads until failure of the rear slope occurs. During the tests, the significant wave height and peak period are stepwise increased. This is performed until failure of the rear slope armour layer is observed or the wave generator's highest or longest wave is reached. The values of the increasing wave conditions are shown in table 3.4 for the first configuration. The other configurations have slightly different values for the wave peak period because of a varying water depth and equal wave steepness values.

Table 3.4: *Wave conditions for configuration 1 ($R_c = 15cm$ and $h = 60cm$)*

	1	2	3	4	5	6	7
$s = 0.015$	$H_s = 0.06$	$H_s = 0.08$	$H_s = 0.10$	$H_s = 0.12$	$H_s = 0.14$	$H_s = 0.16$	$H_s = 0.18$
	$T_p = 1.50$	$T_p = 1.87$	$T_p = 2.24$	$T_p = 2.63$	$T_p = 3.02$	$T_p = 3.42$	$T_p = 3.82$
$s = 0.027$	$H_s = 0.06$	$H_s = 0.08$	$H_s = 0.10$	$H_s = 0.12$	$H_s = 0.14$	$H_s = 0.16$	$H_s = 0.18$
	$T_p = 1.16$	$T_p = 1.39$	$T_p = 1.62$	$T_p = 1.87$	$T_p = 2.11$	$T_p = 2.37$	$T_p = 2.63$
$s = 0.039$	$H_s = 0.06$	$H_s = 0.08$	$H_s = 0.10$	$H_s = 0.12$	$H_s = 0.14$	$H_s = 0.16$	$H_s = 0.18$
	$T_p = 0.99$	$T_p = 1.16$	$T_p = 1.33$	$T_p = 1.50$	$T_p = 1.68$	$T_p = 1.87$	$T_p = 2.05$

Water level

During the tests, large amounts of water are overtopping the structure. This leads to a water level difference between the front and the rear side of the breakwater. Due to the permeability of the breakwater, the water can flow from the rear to the front side. However, this flow is not fast enough, which leads to water level differences mostly of the time. Equalizing the water level is accelerated by means of a pump (figure 3.4). The pump starts transporting the water from the rear to the front side of the breakwater when the water level increases. The outflow of the pump is far away from the breakwater in order to avoid undesired currents.

Number of waves

In order to have the complete range of wave conditions according to the JONSWAP-spectrum, a minimum number of waves is defined. Namely, every test should have at least contain 1000 waves.

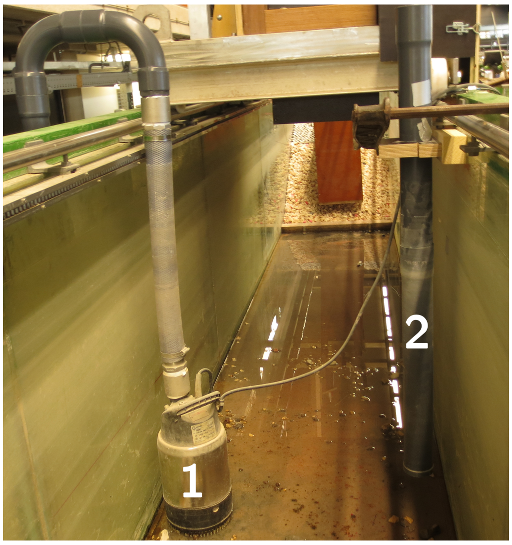

Figure 3.4: *Pumping system: pump (1) and tube with water level sensor (2)*

3.5 Measurements

In a first test series, the overtopping velocity and the damage at the rear slope are measured, see figure 3.5. In a second experiment with the same test and wave conditions, the overtopping volumes per wave are measured. The photo camera is removed and an overtopping box is installed. A description of these measurements is given in the next paragraphs.

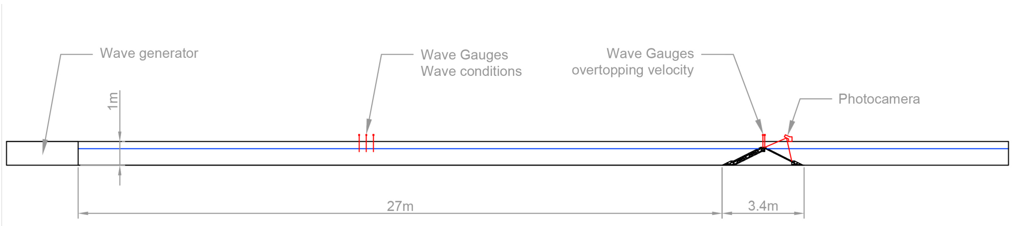

Figure 3.5: *Cross section of the wave flume with the measurement equipment of the first test series*

3.5.1 Wave condition measurements

The waves generated by the paddle transform in the first meters of the flume. At that location, the wave has a constant shape until it reaches the structure. The wave is measured with three wave gauges. This wave consists of the incoming and a reflecting wave originated from the breakwater. During the data processing, these waves are decomposed and the significant incoming wave height (H_s) and wave period

($T_{m-1,0}$) are derived with an existing Matlab routine based on Mansard and Funke [1980].

The location of the three wave gauges at which they are used frequently in this flume is shown in 3.5. This distance is large enough for the wave transforming from the shape generated by the paddle into a constant shape.

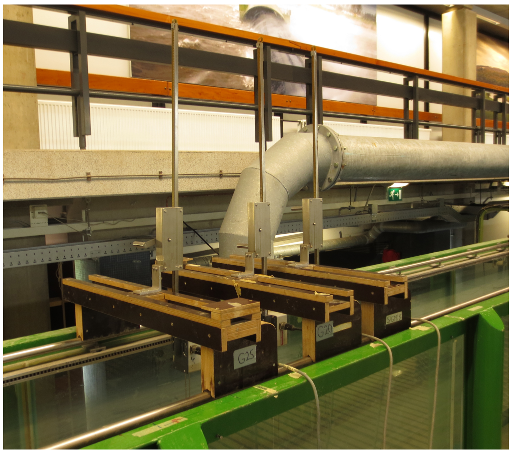

Figure 3.6: *Wave gauges*

The wave gauge (figure 3.6) obtains the water level by using a electric circuit. A voltage difference between two conducting metal bars which stick into the water is generated. This results in a current flow through the bars. At the water surface, the current can short-circuit from one bar to the other. This leads to less resistance and a higher voltage. The resistance decreases even more for increasing water levels. The measured voltage of the wave gauge can be translated to wave heights. Obviously, the wave gauges should be calibrated before every test. This is done by adjusting the depth of the gauge in the water and measure the voltage per metre. The analysis has been performed on the incident waves.

3.5.2 Rear slope damage measurement

The damage of the rear slope is determined by comparing the image taken at the start and at the end of the test. To avoid irregularities in and between the pictures, the flume is emptied before taking the image. The contract between the pores and the cubes in enhanced by two lights at the sides of the flume. The photo camera is installed parallel to the rear slope. The frame on which the camera is mounted is shown in figure 3.7 (number 1).

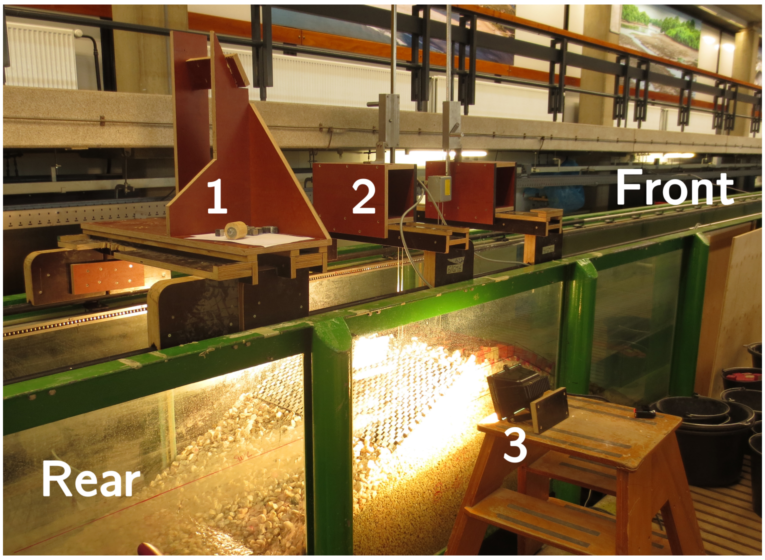

Figure 3.7: Equipment around the model: frame for the photo camera (1), wave gauges on the crest (2) and lights to enhance the contrast (3)

3.5.3 Overtopping wave velocity measurement

The measurement of the overtopping wave front velocity is carried out by two wave gauges on the crest (see figure 3.7, number 2). One gauge is placed at front side and one at the rear side of the crest. The distance in between the two gauges is almost equal to the crest width. The gauges are placed approximately 1 centimetre within the armour layer, such that also small overtopping amounts are recorded. The two gauges record the time difference between waves passing the first and the second wave gauge. The distance between the two gauges divided by the time differences results in the front velocity of the overtopping wave.

Besides this method, also Particle Image Velocimetry (PIV) measurements are carried out by Roberta Coticone for one configuration of the breakwater model [Coticone, 2015]. The obtained values can not be compared since other wave conditions are applied.

3.5.4 Overtopping volume per wave measurement

The total momentum of the overtopping wave is a product of the velocity and the volume. Besides the wave overtopping front velocity over the crest, also the volume of an overtopping wave could be correlated to the damage. In another experiment the overtopping volume per wave is determined. The overtopping waves are collected in a box located behind the breakwater (figure 3.8). This box is equipped with a water level gauge, which can measure the volume per overtopping wave. The gauge is placed in a cylinder with a small hole in order to avoid the turbulence of the overtopping wave influence the volume measurements. Before the experiment, the gauge is calibrated by filling the box with a known volume of water. In this way, the measure voltage are translated in the overtopping volume. The mean overtopping volume is determined by dividing the total volume of overtopping water by the test duration.

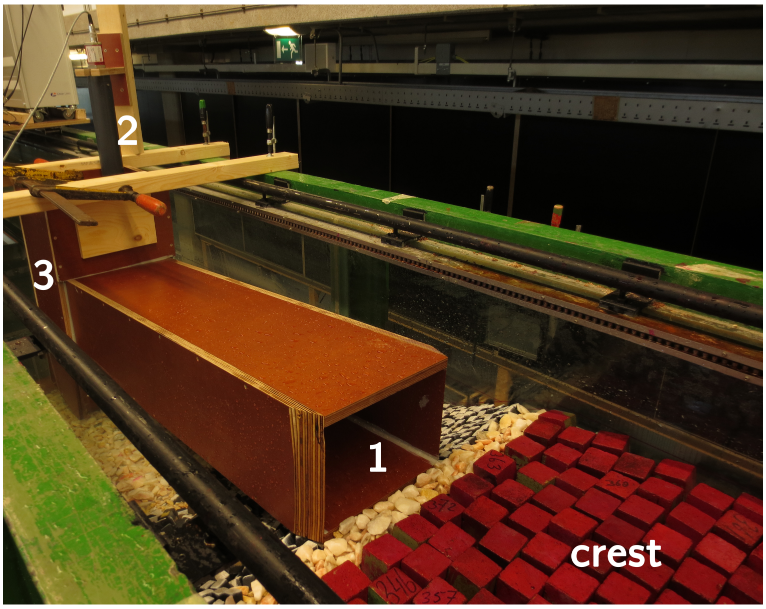

Figure 3.8: *Overtopping box: water inlet (1), water level gauge (2) and box (3)*

4 | Results

Appendix E displays all gathered and processed data in one table. This chapter consists of the visual observations during the tests and a summary of the used processing methods. Subsequently, the processed data are presented in stability curves in section 4.3.

4.1 Experiment execution

The research work is divided into three sub-experiments. The objective of the first two sub-experiments is to determine the rear slope damage for different configurations and the last sub-experiment is conducted in order to get the overtopping volume per wave. The following sections describe the three experiments.

4.1.1 Experiment 1 - Rear slope damage of $D_n = 0.03m$

From the dimension estimation of the rear slope armour units, a diameter of the cubes of $D_n = 0.03m$ seemed to be appropriate (see appendix C). Initially, this diameter was used. The test programme was composed in a way that the rear slope should fail in the first three configurations. However, this was not the case. The rear slope with cubes of $D_n = 0.03m$ proved to be stable in 2 of 3 configurations. Therefore, the remaining tests were not carried out and a smaller cube is selected.

The first experiment was not complete useless, because there were some interesting observations, which are described below.

Cube placement

The quality of the cube placement has a large influence of the stability. It is essential that the underlayer is very smooth and the first row of cubes (lower boundary) is placed precisely. A smooth underlayer can be achieved by selected the small filter material and to apply an uniform pressure to the layer. The first row of cubes are placed stably against a steel strip, in order to construct a solid base row. In reality this bar should be replaced with a toe.

Crest transition

Since one is dealing with an integer number of cubes within the armour layer, the design of the transition from the crest to the rear slope needs some attention. Initially, the cubes on the crest were connected directly with the last (highest) row of rear slope cubes. This resulted in a gap between the crest and rear slope due to small deviations in the rear slope placement. Therefore, the space between the crest and the highest row of the rear slope is filled with rocks. This crest transition is more smooth and there is no gap visible between the two sections. In reality, the difference in cube diameter is much smaller and a smooth transition can be designed without the rock fill. This transition is used in the second experiment for all tests (see figure 4.1).

Figure 4.1: *Transition from crest to rear slope filled with rock*

Damage recording

During the first experiment, the processing method of the damage images is improved. Initially, the different rows were distinguished by two different colours. Since cube displacements were limited, the different colours were unnecessary. Instead, the contrast between the pores and the cubes is enhanced by colouring the cubes black at the sides and white at the top in the second experiment (see section 4.2.2).

Free board variations

The performed tests consisted of three configurations with a varying free board. It is noteworthy that almost no cube displacement was visible with the smallest and largest free board ($R_c = 0.05m$ and $0.15m$), while several cubes moved during the test with the average free board ($R_c = 0.10m$). This is in contrast with the expectation that a larger free board would lead to less displacement of the cubes. In the second experiment, this is also observed. This aspect is treated in more detail in the analysis (see appendix G)

4.1.2 Experiment 2 - Rear slope damage of $D_n = 0.019m$

All configurations with the cube of $D_n = 0.019m$ have failed in the second experiment. Per configuration 2 to 4 tests were conducted before the rear slope failed. The next table gives an overview of all performed tests. Just like the first experiment, the crest transition and cube placement were important aspects. Some other important visual observations are described in the next paragraphs.

Underlayer wash-out

With the selected underlayer material, no wash-out is observed in all the tests and it was possible to make the rear slope smooth enough such that the cubes could be accurate placed. This indicates that a suitable underlayer material is used.

Location of initial damage

The initial damage is located 1 to 4 rows below the water level in most tests. After displacements in this region, one or more cubes are moved out. Subsequently, the cubes in the upper rows have no support anymore and tend to displace shortly after the initial damage.

Rocking during experiment

The first 4-5 rows of cubes are subjected to rocking motions during the tests. However, these cubes are not the first to move out of their place. Only damage in this region is observed, when the underlying regions fails. Initial damage within this region could occur in case the rocking leads to damage to the cubes. This subject is not considered in this study.

Table 4.1: Test programme of experiment 2 (rear slope damage experiment)

	CX		Free board $R_c[m]$	Crest Width $W_c[m]$	Rear Slope Angle $1/tan(\phi)$	Packing Density n_P	Wave Steepness s	Wave Height $H_s[m]$
1	C	1	0.15	0.50	2	0.75	0.03	0.12
2	C	1	0.15	0.50	2	0.75	0.03	0.14
3	C	1	0.15	0.50	2	0.75	0.03	0.16
4	C	2	0.10	0.50	2	0.75	0.03	0.10
5	C	2	0.10	0.50	2	0.75	0.03	0.12
6	C	2	0.10	0.50	2	0.75	0.03	0.14
7	C	2	0.10	0.50	2	0.75	0.03	0.16
8	C	3	0.05	0.50	2	0.75	0.03	0.08
9	C	3	0.05	0.50	2	0.75	0.03	0.10
10	C	3	0.05	0.50	2	0.75	0.03	0.12
11	C	3	0.05	0.50	2	0.75	0.03	0.14
12	C	4	0.10	0.50	2	0.75	0.04	0.10
13	C	4	0.10	0.50	2	0.75	0.04	0.12
14	C	4	0.10	0.50	2	0.75	0.04	0.14
15	C	4	0.10	0.50	2	0.75	0.04	0.16
16	C	5	0.10	0.50	2	0.75	0.02	0.10
17	C	5	0.10	0.50	2	0.75	0.02	0.12
18	C	5	0.10	0.50	2	0.75	0.02	0.14
19	C	6	0.10	0.30	2	0.75	0.03	0.10
20	C	6	0.10	0.30	2	0.75	0.03	0.12
21	C	6	0.10	0.30	2	0.75	0.03	0.14
22	C	6	0.10	0.30	2	0.75	0.03	0.16
23	C	7	0.10	0.30	2	0.70	0.03	0.10
24	C	7	0.10	0.30	2	0.70	0.03	0.12
25	C	8	0.10	0.15	2	0.75	0.03	0.10
26	C	8	0.10	0.15	2	0.75	0.03	0.12
27	C	8	0.10	0.15	2	0.75	0.03	0.14
28	C	9	0.10	0.15	2	0.70	0.03	0.08
29	C	9	0.10	0.15	2	0.70	0.03	0.10
30	C	9	0.10	0.15	2	0.70	0.03	0.12
31	C	10	0.10	0.15	1.5	0.75	0.03	0.10
32	C	10	0.10	0.15	1.5	0.75	0.03	0.12
33	C	10	0.10	0.15	1.5	0.75	0.03	0.14
34	C	11	0.10	0.15	1.5	0.70	0.03	0.08
35	C	11	0.10	0.15	1.5	0.70	0.03	0.10
36	C	11	0.10	0.15	1.5	0.70	0.03	0.12

4.1.3 Experiment 3 - Overtopping volume

The final experiment is intended to measure the associated overtopping volume per configuration. The test programme is shown in table 4.2.

Total volume

During this experiment, the box, collecting the overtopping water, proved to be too small. The box should be large enough to collect overtopping water during the whole test duration. In some tests this was not possible. Therefore, two measures were applied; emptying the box during the test and apply less waves. This first measure had no influence on the measured volume per wave. Only, the processing of the data became more complicated since the emptying of the box time period should not be considered in the processing method. The second measure only could be used if the wave spectrum is the same as in the second experiment. After comparing the wave spectra of both experiments, it can be concluded this is true for all tests. Therefore, the resulting overtopping wave volumes from this overtopping box can be used in the remaining of this study.

Table 4.2: Test programme of experiment 3 (overtopping volume experiment)

	CX		Free board $R_c[m]$	Crest Width $W_c[m]$	Rear Slope Angle $1/tan(\phi)$	Packing Density n_P	Wave Steepness s	Wave Height $H_s[m]$
1	C	1	0.15	0.50	2	0.75	0.03	0.12
2	C	1	0.15	0.50	2	0.75	0.03	0.14
3	C	1	0.15	0.50	2	0.75	0.03	0.16
4	C	2	0.10	0.50	2	0.75	0.03	0.10
5	C	2	0.10	0.50	2	0.75	0.03	0.12
6	C	2	0.10	0.50	2	0.75	0.03	0.14
8	C	3	0.05	0.50	2	0.75	0.03	0.08
9	C	3	0.05	0.50	2	0.75	0.03	0.10
10	C	3	0.05	0.50	2	0.75	0.03	0.12
12	C	4	0.10	0.50	2	0.75	0.04	0.10
13	C	4	0.10	0.50	2	0.75	0.04	0.12
14	C	4	0.10	0.50	2	0.75	0.04	0.14
15	C	4	0.10	0.50	2	0.75	0.04	0.16
16	C	5	0.10	0.50	2	0.75	0.02	0.10
17	C	5	0.10	0.50	2	0.75	0.02	0.12
18	C	5	0.10	0.50	2	0.75	0.02	0.14
19	C	6	0.10	0.30	2	0.75	0.03	0.10
20	C	6	0.10	0.30	2	0.75	0.03	0.12
21	C	6	0.10	0.30	2	0.75	0.03	0.14
25	C	8	0.10	0.15	2	0.75	0.03	0.10
26	C	8	0.10	0.15	2	0.75	0.03	0.12
27	C	8	0.10	0.15	2	0.75	0.03	0.14

4.2 Data processing

In order to find the desired parameters, several data processing routines are used. An overview of the data processing methods is shown in table 4.3. The output columns shows the resulted data from the experiments. The data from experiment 2 and 3 is only used. The processing routines outcomes are several parameters (see last column). The next paragraphs give a summary of the processing methods and the related routines can be found in the appendices.

Table 4.3: *Overview of output data, processing method and resulting parameters of experiment 2 and 3*

Exp.	Output	Number of tests	Processing method	Outcome		
2	Wave gauge data	36	'decomp.m' Appendix F	H_s	$[m]$	Significant wave height
				$T_{m-1,0}$	$[s]$	Wave period
				s	$[-]$	Wave steepness
				N	$[-]$	Number of waves
2	Damage photos	36	Appendix G	N_{od}	$[-]$	Number of damaged cubes
				N_{om}	$[-]$	Number of moved cubes
2	Overtopping velocity data	36	Appendix H	u	$[m/s]$	Overtopping wave front velocity
				N_{ow}	$[-]$	Number of overtopping waves
3	Wave gauge data	22	'decomp.m' Appendix F	H_s	$[m]$	Significant wave height
				$T_{m-1,0}$	$[s]$	Wave period
				s	$[-]$	Wave steepness
				N	$[-]$	Number of waves
3	Overtopping volume data	22	Appendix I	V	$[l/m]$	Volume of an individual wave
				q	$[l/m/s]$	Average overtopping discharge
				N_{ow}	$[-]$	Number of overtopping waves

4.2.1 Wave conditions

The three wave gauges in the flume measure the sum of the incoming and reflecting wave in voltages. The relevant parameters that are obtained from this data set are the incident significant wave height of the incoming waves (H_{m0}), the wave period based on the first negative moment of the energy spectrum of the incoming waves ($T_{m-1,0}$) and the number of waves (N_w). The first two parameters are easily found by using an existing routine called 'Decomp.m'. This routine is especially made for experiments in the TU Delft wave flume. Another routine is used to determine the number of waves, presented in appendix F.

4.2.2 Rear slope damage

After the experiments, the damage at the rear slope is determined by means of a Matlab routine. The routine calculates the distance of a displaced unit. The structural damage is the number of displaced units of the rear slope. A description of this analysis method is given in appendix G.

4.2.3 Overtopping wave front velocity

The overtopping wave front velocity at the crest results from two wave gauges recording overtopping waves. The time difference between the overtopping wave passing the first and the second wave gauge is divided by the distance between the wave gauges. This results in the overtopping wave front velocity. In this process, waves that arrive only at the first wave gauge are taken into account. The used routine is presented in appendix H.

4.2.4 Overtopping volume per wave

The measured voltage in the overtopping box is translated into the volume per individual wave. First, the data is filtered by removing oscillations, leading to a smoothed line. Second, the start and end of an overtopping wave is manual selected. The difference in voltages is translated in volumes. Subsequently, the distribution of the volumes per wave are plotted. A detailed description and the used Matlab routine are shown in appendix I.

4.3 Stability curves

The output of the data processing can be displayed best by stability curves. These curves show the amount of displacement (N_{od}) as function of the stability number ($\frac{H_s}{\Delta \cdot D_n}$). The stability curves are shown for the different structural and hydraulic parameters and for overtopping characteristics. In this section the curves are presented and in the next chapter the damage criteria and the calculated values are added to the curves.

4.3.1 Structural and hydraulic parameters

The next figures present the stability curves of the free board, wave steepness, crest width, rear slope angle and packing density. In these curves, the influence of the five parameters can be determined. The analysis of these graphs is presented in chapter 5. The curve of the second configuration is the reference situation in the first four graphs. The packing density is varied in two values over three configurations, therefore the influence of packing density is presented in three graphs.

Free Board

The next figure shows the stability curve of the free board. At first sight, it is already visible that the curve of the second configuration ($R_c = 0.10m$) shows to be most stable. This is in contrast to the observations of the first experiment, where the same tests are carried out with smaller cubes. Namely, the most damage was observed with the second configuration in the first experiment. This may implies some other effects play a role regarding the rear slope stability.

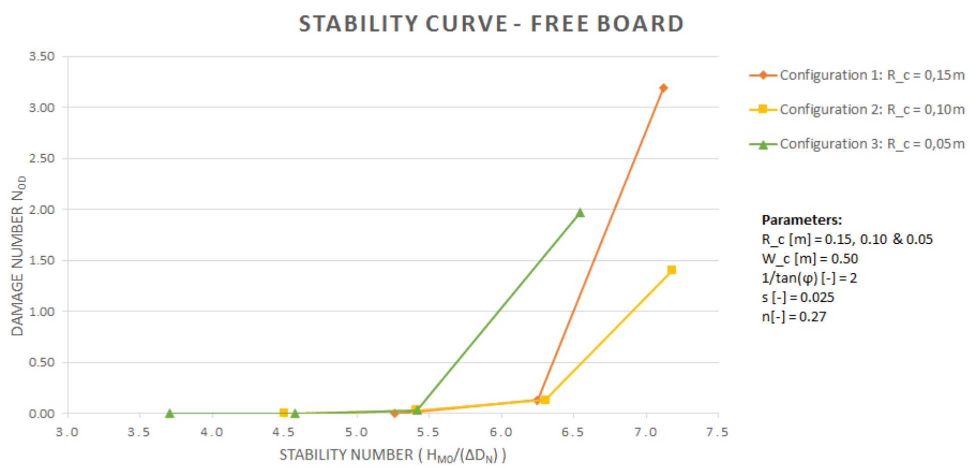

Figure 4.2: Stability curves of a varying free board

Wave steepness

The wave steepness influence is tested by keeping the wave height constant and varying the wave period. From the graph below, can already concluded that long waves cause more damage than the shorter waves.

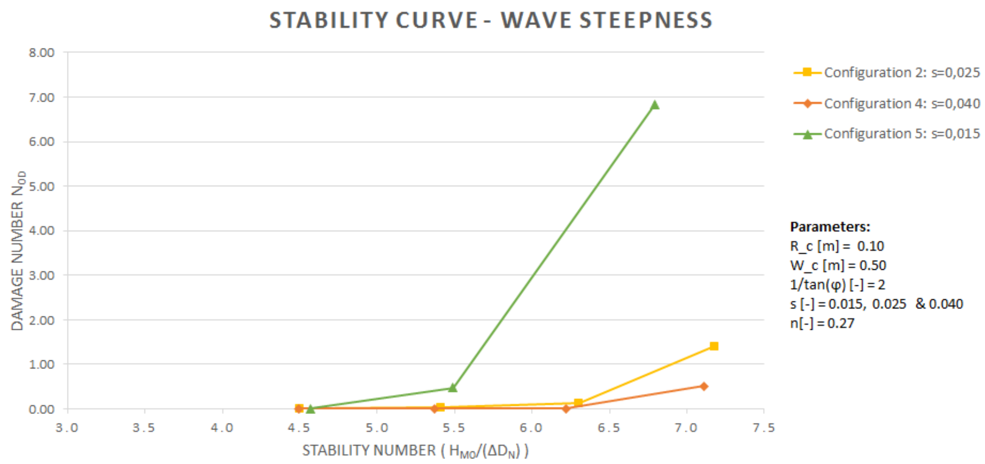

Figure 4.3: *Stability curves of a varying wave steepness*

Crest width

Three crest width variations are considered and the resulting stability curves are presented in figure 4.4. The distinctive last value in the curve of configuration 6 is caused by complete failure of the rear slope. In a short period, almost the whole rear slope was damaged. This proves the sudden behaviour of a single layer of cubes.

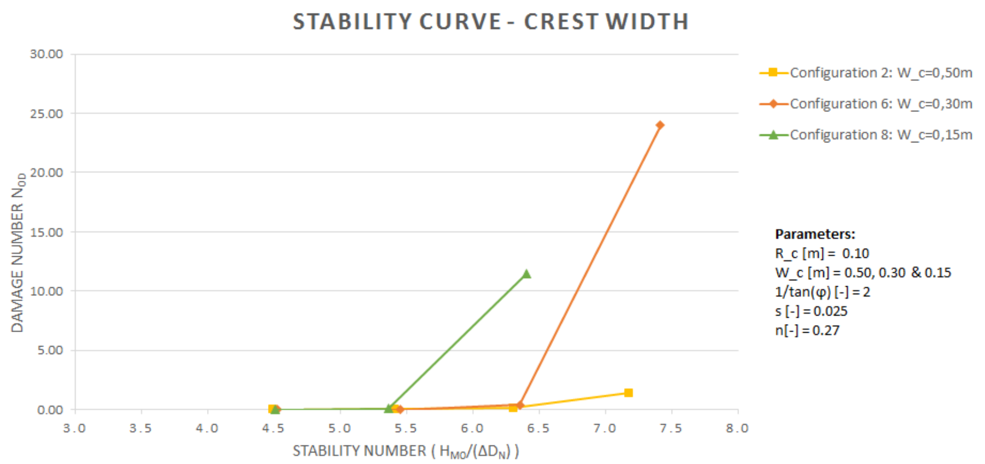

Figure 4.4: *Stability curves of a varying crest width*

Rear slope angle

The rear slope angle seems to have not much influence on the rear slope damage, since both curves in figure 4.5 are close to each other.

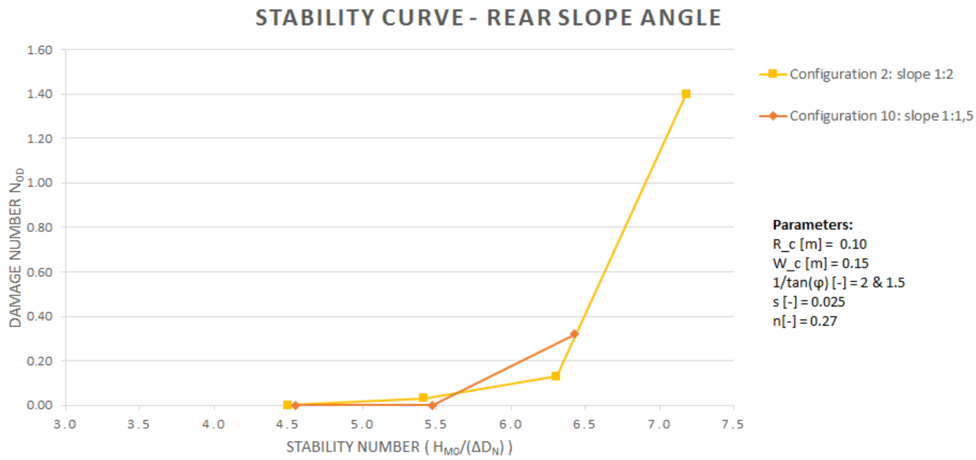

Figure 4.5: Stability curves of a varying rear slope angle

Packing density

Two packing densities are compared with three different configurations. A packing density of $n = 0.31$ is used in the previous configurations. For three configurations a packing density of $n = 0.27$ is applied and this resulted in three stability curves. At first glance, it can already be concluded that this parameter has a large influence on the rear slope stability.

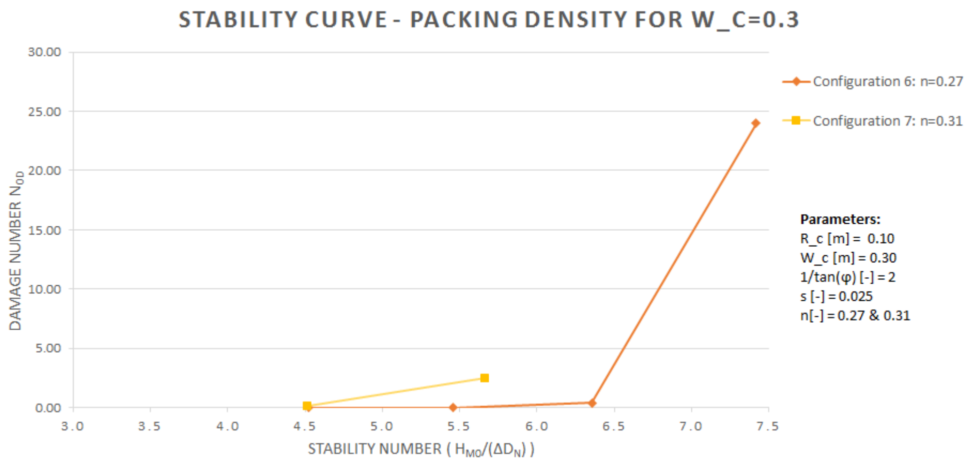

Figure 4.6: Stability curves of a varying packing density

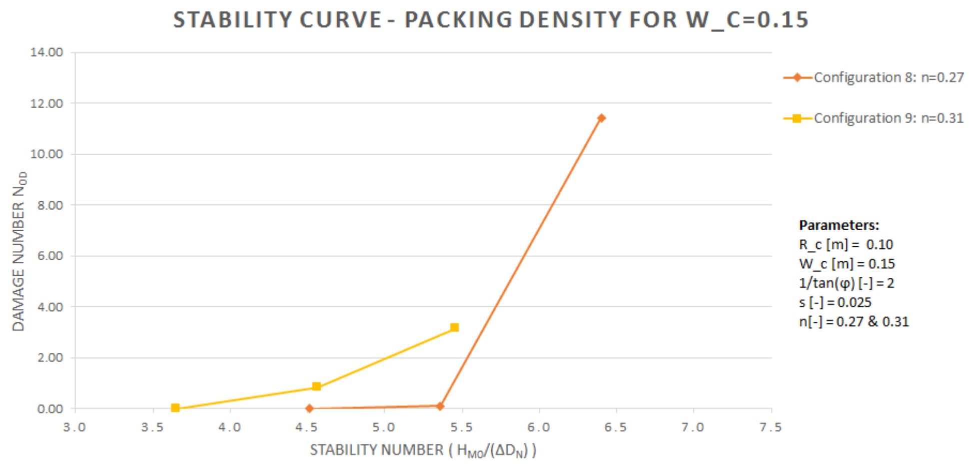

Figure 4.7: *Stability curves of a varying packing density*

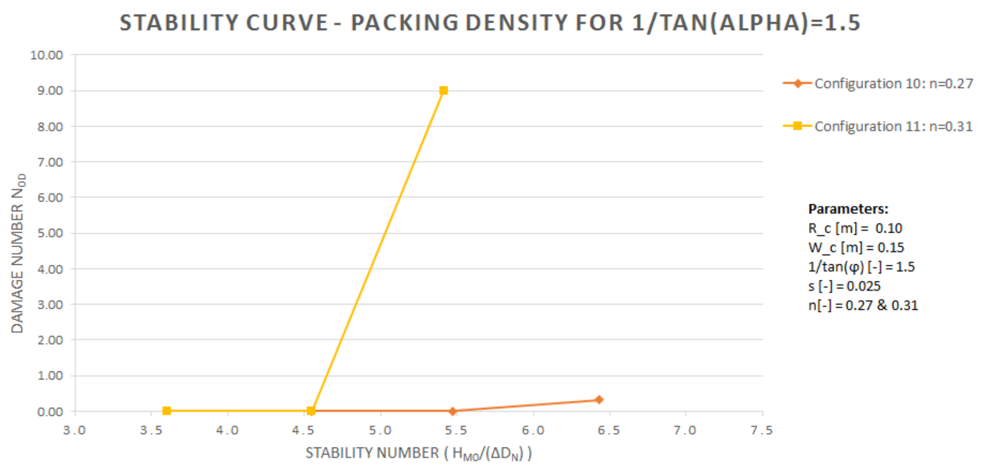

Figure 4.8: *Stability curves of a varying packing density*

4.3.2 Overtopping characteristics

After the data processing, two overtopping parameters are defined and will be used in the analysis; the overtopping front velocity and the volume per individual overtopping wave. In total 22 values per parameter are obtained and plotted against the damage observed at the rear slope. The resulting graphs are shown below. In the next chapter, the graphs are treated in more detail.

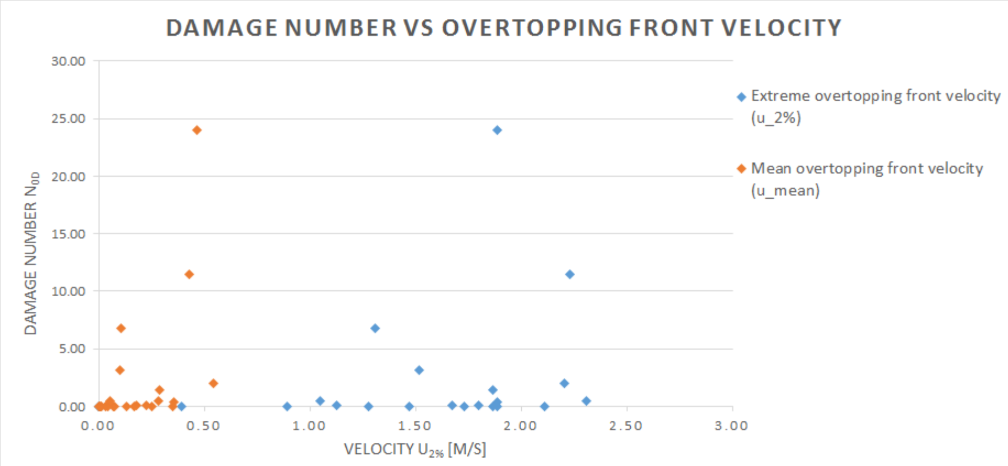

Figure 4.9: *Stability curves of the overtopping front velocity (u [m/s])*

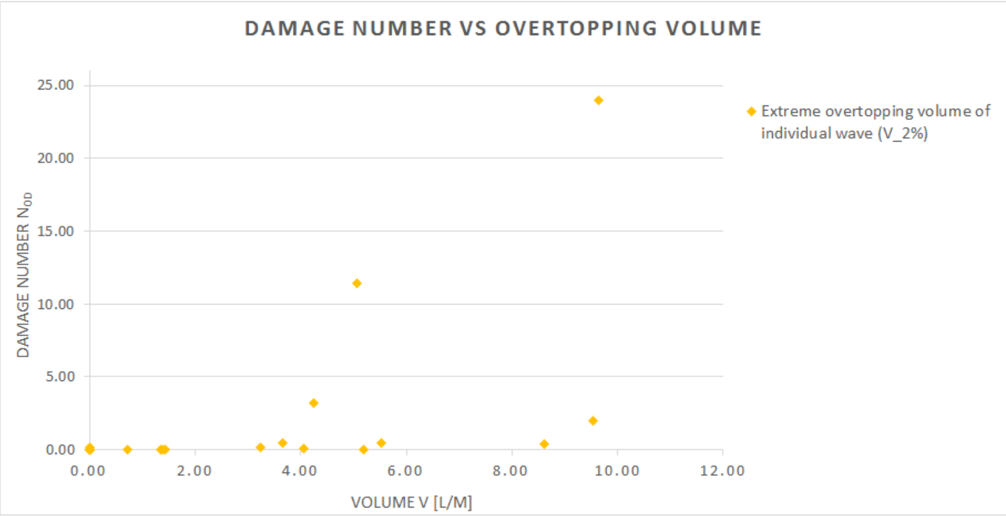

Figure 4.10: *Stability curves of volume per individual overtopping wave (V [l/m/wave])*

5 | Analysis

The analysis of the obtained data is divided in two parts; the analysis of the stability curves and of the overtopping characteristics. Most of the acquired results are supported by the theory elaborated in chapter 2.

5.1 Analysis of stability curves

The number of damaged cubes is plotted against the stability number in graph 4.2 to 4.5. The key findings in these graphs will be highlighted in the next paragraphs.

5.1.1 Cube Dimension

An estimation of the expected damaged is made with the commonly used rear slope formula of van Gent and Pozueta [2004] for randomly placed rocks. The assumptions and calculation procedure are presented in appendix C. A comparison of the measured values and the calculated values are presented in figure 5.1 and an overview of all data is shown in appendix E. It is easy to see that the rear slope is much more stable than was predicted. Most test results show a smaller damage number than is calculated. Especially, the start of damage should occur much later according to the calculated damage numbers. For larger values of the damage number, the difference between the calculated and measured values are smaller. It must be mentioned that the calculated damage is only a rough estimation and the influence of the packing density is not taken into account.

In order to obtain a better fit between the calculated and measured values, the stability number of the single layer cubes is changed relative to the value used in the estimation of the cube dimension. As described in appendix C, a value of $N_{s,cube} = 3$ is used, however a value of $N_{s,cube} = 2.85$ has a better fit with the measured data. This number is used in the analysis of the curves.

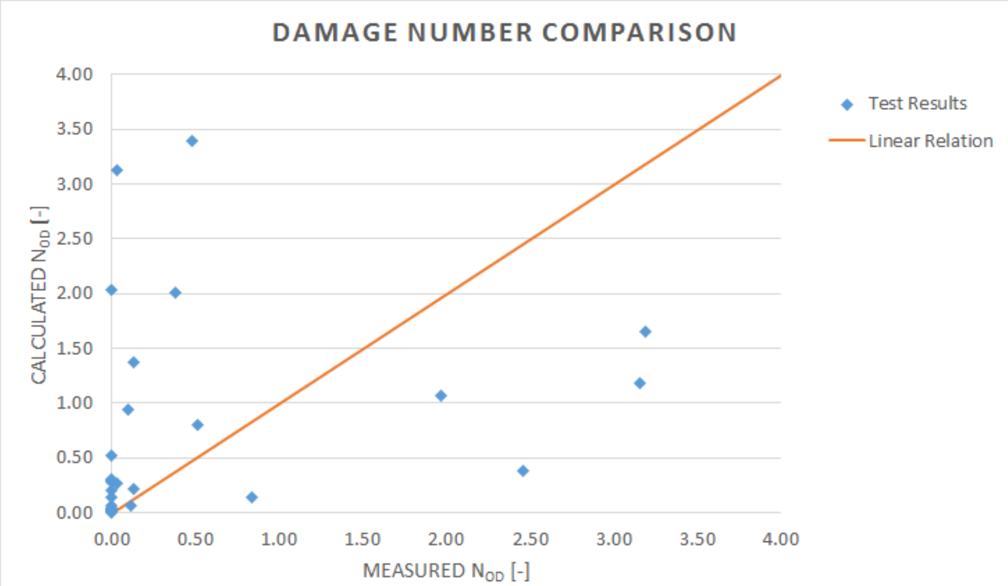

Figure 5.1: *Comparison of the measured and calculated damage number*

5.1.2 Sudden failure

The stability graphs of all tests show a very sudden failure of the rear slope. The rear slope already fails by a small increase in wave height after a test where some displacements were observed. This phenomenon is expected since a sudden failure is a well-known property of single armour layers. However, this has led to small amount of damage measurements, which results in a less accurate stability curves.

The sudden failure is expressed in lesser extent in the calculated stability curves (see figure 5.2 to 5.5). This can be explained by the fact that these theoretical values are based on a rear slope rock armour layer. It is known that multiple armour layers with random placed rock units are behaving less brittle than a single layer of concrete units.

5.1.3 Influence of the various parameters

The obtained stability curves in chapter 4 are analysed. Due to a lack of data, no fitting relation can be constructed for the all curves. A linear relation is assumed between the points of the stability curves. This assumption is on the conservative side, since the trend of the curve probably is exponential because the slope steepens for increasing values.

The moment of failure is indicated with a red dot. This point is the intersection of the damage number $N_{od} = 0.2$ (see section 2.7) and the stability curve.

The expected damage as it is calculated in appendix C are shown as stripped graphs.

It should be mentioned, that the resulting stability curves are based on one experiment where no tests are repeated. Some scatter around the points is expected.

Free board

The free board has influence on the rear slope stability in two ways. Firstly, a smaller free board causes larger overtopping waves, which leads to a higher load on the rear slope. Secondly, a smaller free board at the rear side (same as at the front side) has a positive effect on the rear stability due to a smaller load on the slope. The water at the rear side dampens the overtopping wave. Which of those two aspects has the greatest influence on the stability was not clear in the beginning of the study. From this study it can be concluded that a greater free board is favourable for the rear slope stability. As is shown in figure 5.2, a breakwater with a free board of $R_c = 0.05m$ fails for a lower stability number than for the higher two free board values. However, the critical stability number of the two largest free board values are almost the same. This suggests the free board has less influence for larger values. This is not visible in the calculated stability curves, where higher free board values lead to less damage.

Transmission was not taken into account in this research and could be of a large influence. It could explain the almost equal stability graphs of the configuration 1 and 2 in figure 5.2. The transmission for the smaller free board (configuration 2) is larger and could cause more damage at the rear slope.

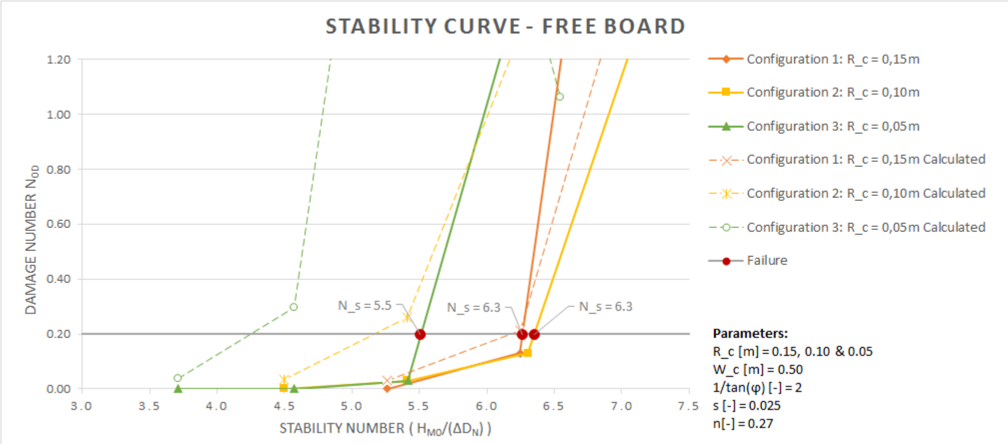

Figure 5.2: *Stability curves of measured and calculated damage numbers for three free board values*

Wave steepness

The wave steepness affects the rear slope stability in an expected manner. Namely, the steeper the wave, the less damage it causes. The longer waves (swell) induce a higher load on the breakwater front slope and cause more damage [Verhagen and D'Angremond, 2001]. This is valid for surging waves. The almost all applied wave conditions meet the surging wave criterion. From this study can also be concluded that long waves cause more damage on the rear slope cube armour layer.

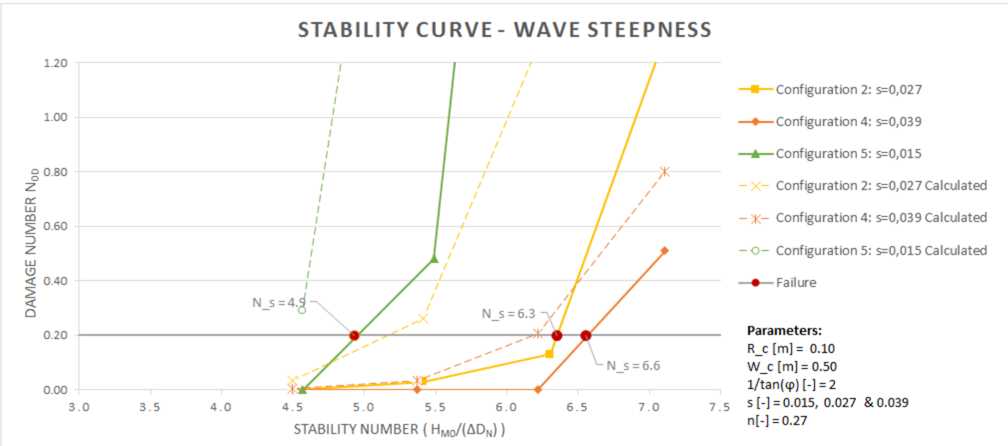

Figure 5.3: *Stability curves of measured and calculated damage numbers for three wave steepness values*

Crest Width

The width of the crest influences the overtopping velocity and volume. The overtopping velocity over the crest decreases when passing the crest due to friction. The volume of the overtopping wave drops by the infiltration into the crest. These two load reductions cause a smaller load on the rear slope. This is in line with the outcome: significant more damage is observed in case of a smaller crest width.

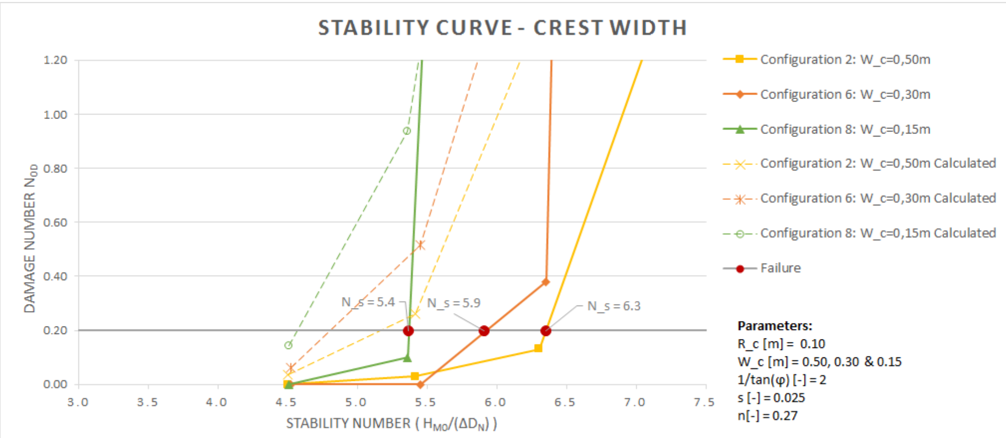

Figure 5.4: *Stability curves of measured and calculated damage numbers for three crest width values*

Rear slope angle

It can be concluded that both stability curves correspond. This implies that the rear slope angle has only little influence on the rear slope damage within the range of $1:2-1:1.5$. The calculated theoretical values are not in line with the measured values. This can be explained by the origin of the obtained theoretical value, namely the used formula is intended for randomly placed rock. In contrast to this armour layer, a single layer of regular placed cubes obtains its stability partially from friction between the cubes. This friction force increases when the slope becomes steeper. The armour layer of cubes behaves more like a placed block revetment in case of this steeper slope. This explains that the two stability curves are in line with each other. Despite of the steeper rear slope, which reduces the friction on the underlayer, the armour layer maintains its stability by the increased friction force.

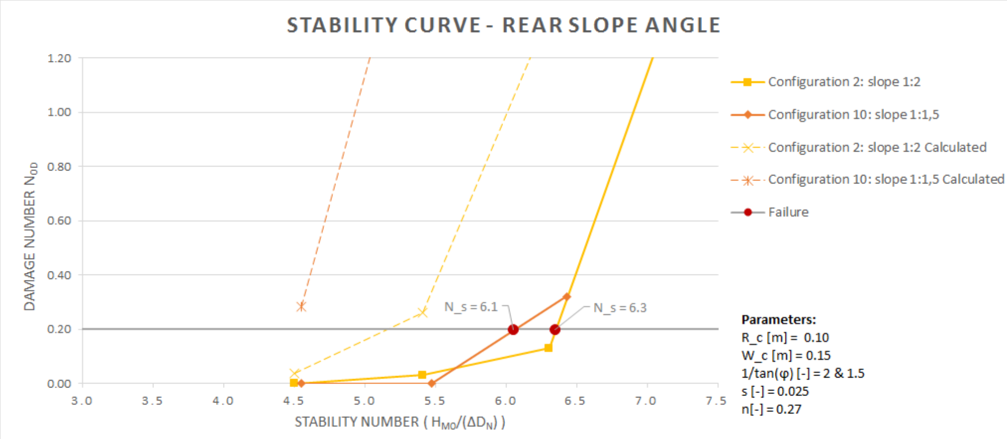

Figure 5.5: *Stability curves of measured and calculated damage numbers for two rear slope angles*

Packing Density

The influence of the packing density is clearly visible in the next three graphs. A higher packing density (the smaller the porosity n) implies a more stable armour layer. This parameter is varied in two values for three different configurations. The calculated damage does not consist of a packing density parameter, therefore the acquired curves can not be compared with two theoretical curves. However, one theoretical curve is plotted, which can be suitable for both packing densities. Notably, the critical damage number of the low packing density ($n = 0.31$) is almost the same as the critical damage number of the theoretical curve (see figure 5.6). In the other graphs, this similarity does not exist. However, it may imply that the calculated values correspond more to a smaller packing density. This can not be concluded from these three stability curves.

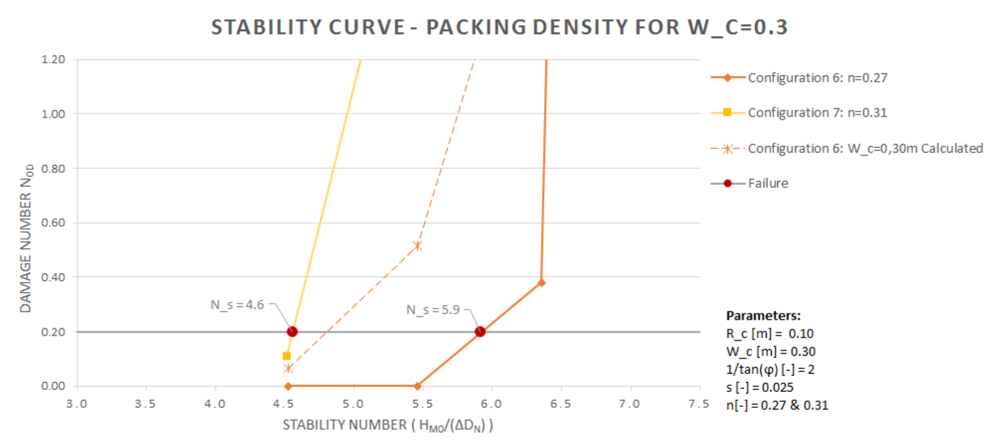

Figure 5.6: *Stability curves of measured and calculated damage numbers for two packing densities*

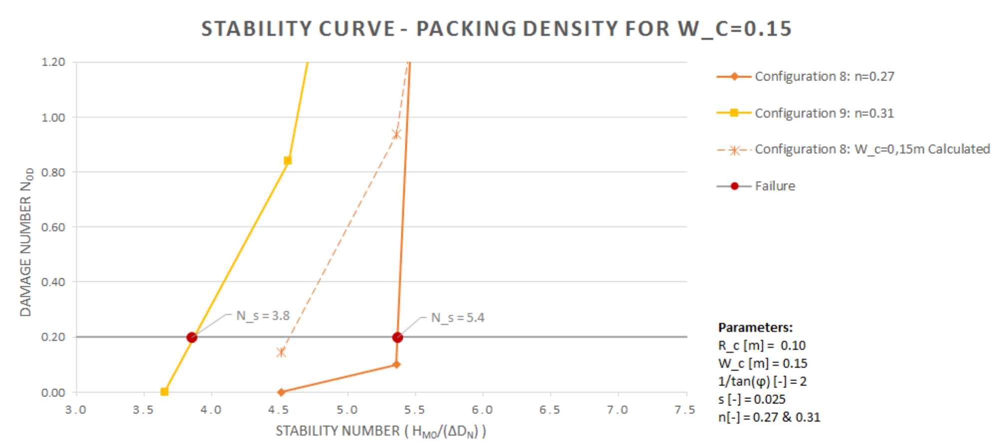

Figure 5.7: *Stability curves of measured and calculated damage numbers for two packing densities*

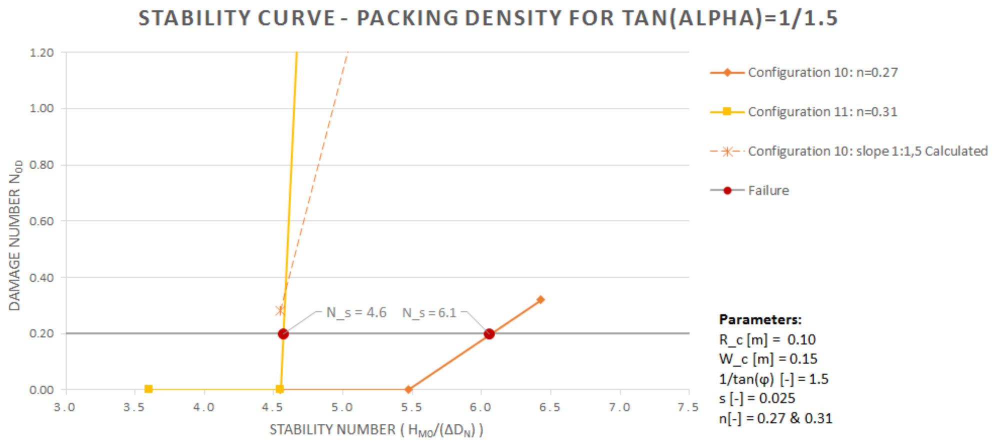

Figure 5.8: *Stability curves of measured and calculated damage numbers for two packing densities*

5.2 Overtopping characteristics

One of the objectives of this study is to correlate the overtopping characteristics with the rear slope damage. The purpose of this correlation is to replace the wave steepness and the crest width by one or more general known overtopping parameters. In order the do, the possible relation between rear slope damage and two overtopping parameters is determined. The rear slope angle, the placing density and the free board can not be replaced by this hydraulic response because these parameters influence the rear slope strength.

5.2.1 Overtopping front velocity $u_{2\%}$

The overtopping front velocity is calculated and elaborated in appendix H per test. The obtained overtopping velocity parameters are: the average overtopping velocity (u_m) and the extreme overtopping velocity ($u_{2\%}$). It is expected that the highest overtopping velocities contribute most to the rear slope damage. As a result, it is most likely to find a relation between the extreme overtopping front velocity and the rear slope damage. From the four most often used extreme overtopping front velocities (maximum, 1%, 2% and 5%), the percentage of 2% is chosen. Possible errors in the maximum measured velocity are not taken into account and still this parameter represents the extreme events.

Theoretical values

Firstly, the measured overtopping velocities are compared with the obtained theoretical values. The overtopping velocity is calculated with two different formulas; Schüttrumpf and Van Gent [Schüttrumpf and van Gent, 2004]. The formulas are quite similar, only different coefficients are used (see section 2.2.5). In order to compare the two formulas, they are plotted against the measured values (see figure 5.10 and 5.9). The least square method is used to find the formula which corresponds best to the measured data. The formula used in this method is:

$$Error\left(u_{2\%,c}, u_{2\%,m}\right) = \sum_{n=1}^{N}\left(u_{2\%,c} - u_{2\%,m}\right)^2 \tag{5.1}$$

where, $u_{2\%,c}$ and $u_{2\%,m}$ are respectively the calculated and measured extreme overtopping parameters.

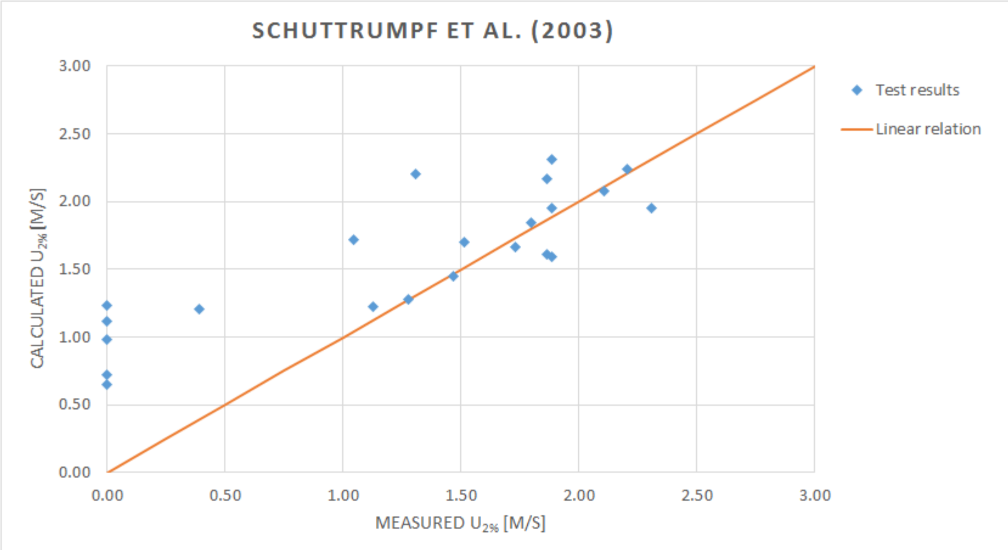

Figure 5.9: *Comparison between Schüttrumpf overtopping velocity and measured overtopping front velocity ($u_{2\%}$)*

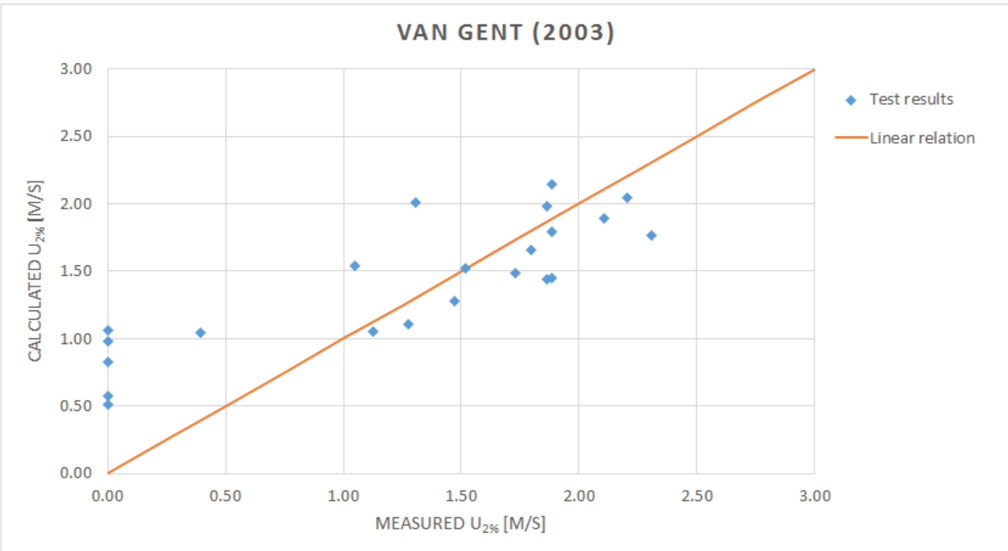

Figure 5.10: *Comparison between Van Gent overtopping velocity and measured overtopping front velocity ($u_{2\%}$)*

The least square method computed the smallest $\sum r^2$-value for the Van Gent-formula (see appendix E). Also, figure 5.9 shows the best fit with the measured velocity. The difference is probably caused by the measuring method. The extreme overtopping velocities formulas are also empirical relations, but the velocity is measured in a different way. The maximum velocity in an overtopping wave is measured by propellers in the previous studies. In this research the front velocity is determined by correlating the signals of two wave gauges. The difference is caused by a two aspects:

- Different measuring methods; correlating wave gauges and propellers
- Different overtopping parameter measurements; overtopping front velocity and maximum overtopping velocity

In general, the measured values are smaller than calculated with the formulas. Probably, this is caused by the fact that the front velocity is generally smaller than the maximum overtopping velocity.

The previous overtopping velocity formulas by van Gent and Schüttrumpf are also taken into account in this analysis. However, the $\sum r^2$-values were both larger than that of Van Gent and Schüttrumpf 2003 . For this reason, these formulas and results are not treated in detail.

Correlation with the rear slope damage

Figure 5.11 shows extreme overtopping velocity plotted against the slope damage in yellow. The critical extreme overtopping front velocity (red dots) are determined by linear regression between two data points. These dots are within a range of $1.05 \leq u_{2\%} \leq 2.12 m/s$. Due to the scattering and the small number of data results, no clear relation can be found between the critical extreme overtopping front velocity and the rear slope damage. Also, from the theoretical values in orange ($u_{2\%}$ according to Van Gent 2003) do not show a clear relation with the observed damage.

The along slope velocity for which cubes start to move is calculated with a formula of Kuiper et al. [2006] (see appendix D). This velocity is indicated with a blue dot. According to the theory, initial damage occurs for velocities just above $u = 1.61 m/s$. From the graph can be seen that this is the case for 5 of the 7 tested configurations. This velocity gives an estimation of the velocity for which initial damage occurs, however it is not that accurate.

The velocity of the plunge is not calculated since generally the flow does not detach the breakwater model (see section 5.4).

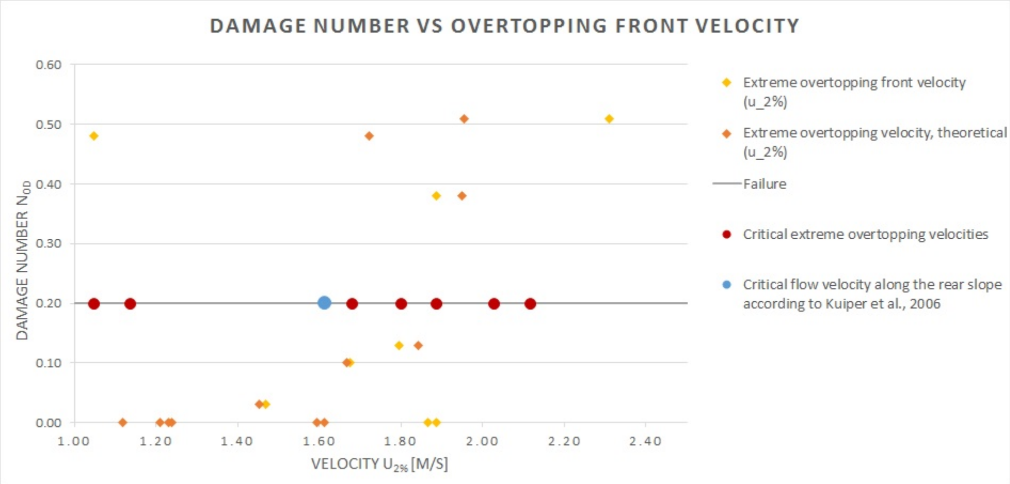

Figure 5.11: *Relation between the overtopping velocity and rear slope damage for the measured values (yellow) and calculated values (orange)*

5.2.2 The individual overtopping wave volume

Besides the velocity, a relation between the overtopping volumes and rear slope damage is expected. Also, the extreme values of this parameter have probably the most influence on the rear slope damage.

Theoretical values

The extreme individual overtopping wave volume is calculated with the Van Gent-formula as described in Schüttrumpf and van Gent [2004] with the same input values as measured in the tests. Again, the obtained values are plotted against the measured values. Clearly, the differences between those two values are very large. The measured volumes are significantly smaller than expected.

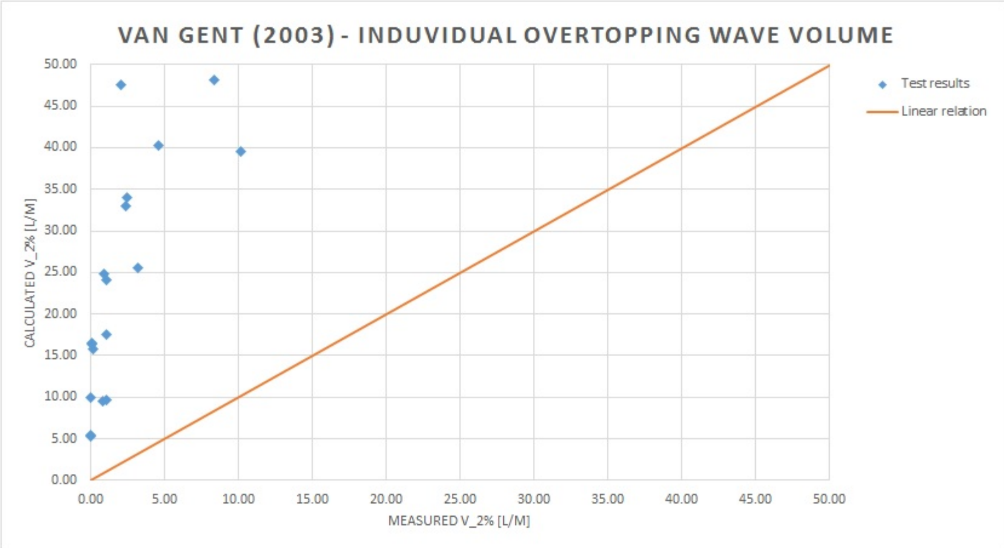

Figure 5.12: *Comparison between van Gent-formula and measured extreme individual overtopping wave volume ($V_{2\%}$)*

Correlation with the rear slope damage

The expected correlation between the rear slope damage and overtopping volumes is not visible. The next graphs show the obtained volumes with the corresponding damage. The red dots indicate the volume for which the rear slope failed. These points are calculated with linear interpolation. Also in this graph, the critical values are in a wide range and no fitting curve can be generated due to the lack and the large scattering of the data points. However, it was observed that large volumes of water cause more damage in the experiment. This is not visible in the graph, which may indicate that other mechanisms play a role.

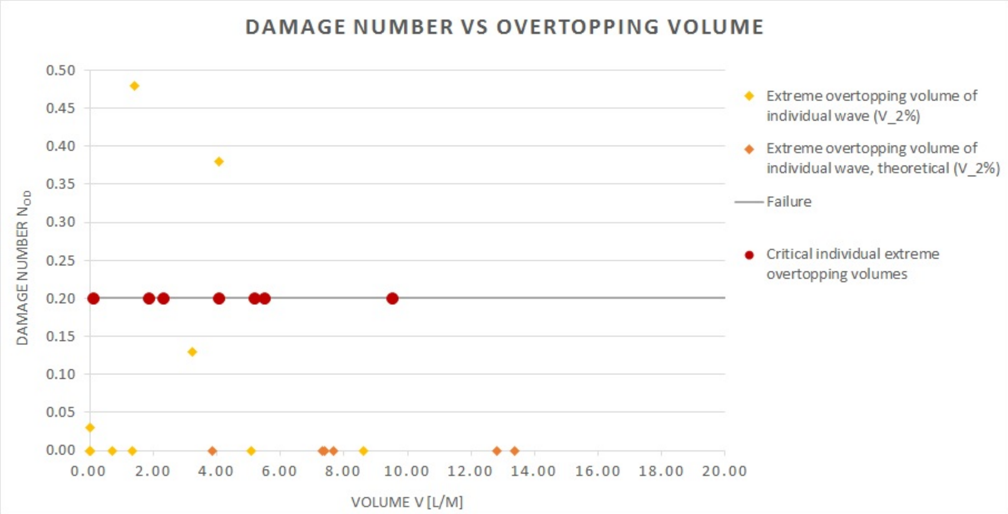

Figure 5.13: *Relation between the overtopping velocity and rear slope damage*

5.3 Location of initial damage

The location of initial damage is observed 1 - 4 rows of cubes below the free surface. This can be explained by the fact that the cubes have buoyancy and therefore a smaller force can cause them to move compared to the cubes above the free surface. Also, at this location the turbulence of the flow is higher than above the free surface due to the flow entering the water. Deeper in the water, the flow will be dampened more and thereby looses its energy.

5.4 Overtopping flow

Since the stability curves do not show a clear relation between the various parameters and the rear slope damage, an other aspect could have influence on the stability. The type of impact of the overtopping wave on the rear slope could scatter the obtained data.

In chapter 2, two types of overtopping flow at the rear slopes are described; the plunge impact and the flow parallel to the rear slope. From video analysis can be concluded that the overtopping waves are mainly causing a flow that follows the shape of the model. The flow does not detach the breakwater and therefore the plunge impact is not observed. Since, this is the case for all configurations, this aspect has probably not caused the scatter in the stability graphs. However, this aspect could be investigated in more detail by directly correlating the overtopping flow type with the observed damage.

This is also an important aspect in the design of a breakwater. Loads at the rear slope could be reduced when the impact of a plunge is avoided or the plunges impact the rear slope far under the free surface. This aspect could be further investigated.

6 | Conclusions

In the introduction, a number of research questions are stated. These questions are answered in the first part of this chapter. Additional conclusions are given in the second part.

6.1 Research questions

The first three sub-research questions are answered and form the base of the main research question.

What is the influence of various hydraulic (e.g. wave characteristics) and structural parameters (e.g. packing density of the rear slope) on the rear slope stability?

Five parameters are varied in order to find a relation with the rear slope stability. The results of the experiment are described in seven stability curves (figure 4.2 to 4.8). Due to insufficient test data, no expression could be found for each of the curves. However, the influence of the parameters can be visually predicted from the graphs.

The influence of the significant wave height, crest width and wave steepness on the rear slope stability is more or less as expected. From the results of the other parameters some conclusions can be drawn.

Free Board

A large free board affects the rear slope stability on the one hand by large overtopping waves and on the other hand by a larger submerged rear slope area. The first aspect causes larger loads on the rear slope while the second aspect reduces the loads on te cubes. The two largest free board values led to an almost equal damage number. This concludes that the second effect plays a larger role when the free board becomes larger. It should be mentioned that this conclusion is based on only three data points and therefore this relation is not decisive.

Rear slope angle

The rear slope angle is varied into two values during the experiment. Almost no difference in damage was observed between those two rear slope angle values. Probably, this parameter is not that influential.

Packing density

Variations in the packing density shows large differences in the damage numbers. Therefore it can be concluded that this parameter has a large effect on the rear slope damage.

What is the relation between individual wave overtopping volumes and wave front velocities on the stability of single layer cubes on the rear side?

An attempt is made to correlate the extreme overtopping front velocity and the extreme individual wave overtopping volumes with the rear slope damage. This relation has not be found. This suggests that the overtopping wave is a complex mechanism which can not be described in only two parameters. For both parameters a wide range in which the rear slope fails is obtained, which can be observed in figure 4.9 and 4.10.

What is the minimum level below mean sea level over which an armour layer should be extended?

The location of the initial damage is monitored in the experiment. In none of the tests the location is larger than 4 cube rows below the free surface. This implies that the minimum level below the mean sea level should be at least 4 times the cube diameter parallel to the slope ($\geq 4 \cdot D_n$)

What is the stability of a single layer of cubes at the rear side of a low crested breakwater, expressed as a stability number at the start of damage?

Due to the lack of accuracy in the obtained answers of the sub questions (which form the base of the answer of this main research question), it is hard to obtain a clear and quantifiable expression. However, the stability curves per parameter give an initial prediction of the rear slope damage. In this research, no formula that describes the stability curves per parameter has been found, which indicates other aspects play a role.

6.2 Additional conclusions

Besides the answers to the research questions, some other conclusions can be drawn.

6.2.1 Cube dimension

At first, a cube diameter of $d_n = 3.0cm$ is selected on the base of previous rear slope studies for a rock armour layer. In the first experiment, no damage occurred at the rear slope when applying the largest waves. Therefore, a second experiment is conducted with a smaller cube, $d_n = 1.9cm$. In the second experiment, failure of the rear slope is observed for every test within the range of the wave generator. The cube diameter is reduced with 37% between these two experiments. It can be concluded that the rear slope cube dimensions can be designed smaller than is predicted from the rear slope stability studies for rock armour layers.

6.2.2 Cube placement

Selection of the suitable underlayer material is of great importance for the placement of the cubes. Irregularities in the underlayer cause more protruding cubes. These cubes are more likely to displace during a storm. Secondly, the placement of the cubes is more difficult on an irregular underlayer.

7 | Recommendations

This study raised some new questions about the rear slope stability. Further research could be carried out in the following subjects.

7.1 Rear slope stability formula

This study gives a first impression of the rear slope stability with single layer cubes. The lack of data results did not lead to a clear relation between various parameters and rear slope stability. Another experiment with more tests could be carried out to attempted to define a design formula. This experiment should contain smaller subsequent steps between significant wave height values and more variations of parameters should be applied. Both improvements will lead to more indications of the start of damage, which makes the relations more clear. Not so much attention should be paid to the rear slope angle, since this parameter has almost no influence on the rear slope stability. Also, other aspects should be taken into account; for example the transmission and the type of impact on the rear slope.

7.2 Transmission

Transmission through the breakwater model is not taken into account. This aspect could have cause the discrepancy in the relation between the overtopping characteristics and rear slope damage. The combination of the flow through the breakwater and the overtopping flow could lead to a relation with the rear slope damage.

7.3 Complex mechanism

It is not clear if more data points will lead to a relation between the rear slope stability and the various parameters. The overtopping process is a complex mechanism where more aspects play a role. Further research into the type of overtopping flow and impact on the rear slope could lead to a better understanding of the rear slope stability.

7.4 Crest transition

The transition from the crest to the rear slope is an important design aspect. In some initial tests, the rear slope failed due to erosion at this transition. Also, a rear slope positioned in the shadow of the crest seems to increase the slope stability. The tests revealed that the impact of the plunges appeared below the water level. This caused damping of the plunge in the water and therefore a smaller load on the cubes. On the other hand, the cubes under the water level have a smaller relative density due to buoyancy, which makes them easier to move. The influence of the crest transition to the rear slope stability could be a subject for future research.

7.5 Construction costs analysis

It is proven that the rear slope armour cubes can be smaller than the cubes at the front slope. This results in less concrete volume. However, the rear slope should be armoured with more units to cover the whole surface. A larger amount of cubes leads to more deviations from the correct position of the cube, which makes the placement more difficult. Besides, the smaller cubes also deviate more due to irregularities of the underlayer. Summarized, smaller cubes use less material but are more difficult to place. It would be valuable to find out when the cube dimensions should be increased in order to save money during the construction of the breakwater.

Bibliography

O. H. Andersen, J. Juhl, and P. Sloth. Rear Side Stability of Berm Breakwaters. *23rd International Coastal Engineering Conference*, pages 1020–1029, 1992.

T. L. Andersen. *Hydraulic Response of Rubble Mound Breakwaters Scale Effects - Berm Breakwaters*. PhD thesis, Aalborg University, 2006.

CIRIA. *The Rock Manual*. 2007.

R. Coticone. Reconstruction of flow characteristics over the crest of a breakwater with piv technique. 2015.

Y.B. Dai and A.M. Kamel. Scale effect tests for rubble-mound breakwaters: Hydraulic model investigation. Technical report, US Army Engineer Waterways Experiment Station, 1969.

R.J de Jong. Wave transmission at low-crested structures - Stability of tetrapods at front, crest and rear of a low-crested breakwater. 1996.

Delta Marine Consultants. Guidelines for Xbloc Concept Designs. Technical report, 2014.

L. E. Frostick, S. J. McLelland, and T. G. Mercer. Users Guide to Physical Modelling and Experimentation. *IAHR Design Manual Series, CRC Press/Balkema, Leiden, The Netherlands*, 2011.

L. H. Holthuijsen. *Waves in oceanic and coastal waters*. 2007.

M. Klein Breteler, G. Mourik, and Y. Provoost. Stability of placed block revetments in the wave run-up zone. *Coastal Engineering*, 2014.

M. D. Kudale and N. Kobayashi. Hydraulic Stability Analysis of Leeside Slopes of Overtopped Breakwaters. *Coastal Engineering Proceedings*, pages 1721–1734, 1996.

C. Kuiper, M. Klein Breteler, W. Eysink, and L.N. Booster. Stabiliteit van gezette steenbekledingen op havendammen - Afleiding van een verbeterde toetsmethode van de toplaag. Technical report, 2006.

E.P.D. Mansard and E.R. Funke. The measurement of incident and reflected spectra using a least squares method. *Coastal Engineering Proceedings*, 1(17), 1980.

M.W. Owen. Design of sea walls allowing for wave overtopping. *Rep. EX924, HR Wallingford.*, 1980.

T. Pullen, N.W.H. Allsop, T. Bruce, A. Kortenhaus, H. Schüttrumpf, and J.W. van der Meer. *EurOtop - Wave Overtopping of Sea Defences and Related Structures : Assessment Manual*. Number August. 2007.

G. Schiereck. *Bed, Bank and Shore Protection*.

H. Schüttrumpf and M.R.A. van Gent. Wave Overtopping at Seadikes. *Coastal Structures 2003*, 2004.

M. Setz and M. Finnegan. University Wimadison Breakwater, 2010. URL `http://universitywimadisonbreakwater.weebly.com`.

TAW. *Wave Run-up and Wave Overtopping at Dikes*. 2002.

J.W. van der Meer. Stability of breakwater armour layers (design formula), 1987. URL `http://www.sciencedirect.com/science/article/`.

J.W. van der Meer and K.W. Pilarczyk. Stability of low-crested and reef breakwaters. *Coastal Engineering*, pages 1375–1388, 1990.

J.W. van der Meer and J.J. Veldman. Singular points at berm breakwaters: scale effects, rear, round head and longshore transport. *Coastal Engineering*, 17:153–171, 1992.

J.W. van der Meer, T. Bruce, W. Allsop, L. Franco, A. Kortenhaus, T. Pullen, and H. Schüttrumpf. EurOtop revisited. Part 1 : sloping structures. *Proceedings of the ICE, Coasts, Marine Structures and Breakwaters*, 1, 2013.

B. van Dijk. The rear slope stability of rubble mound breakwaters. (December), 2001.

M.R.A. van Gent. Rubble mound breakwaters: Single armour layers and high-density concrete units. 2001.

M.R.A. van Gent. Rear-side stability of rubble mound structures with crest elements. Technical report, 2007.

M.R.A. van Gent and L. Luis. Application of Cubes in a Single Layer. pages 1–10, 2013.

M.R.A. van Gent and B. Pozueta. Rear-side stability of rubble mound structures. *Coastal Engineering Conference, ASCE*, 29-4(1):1–13, 2004.

M.R.A. van Gent, S. E. Plate, E. Berendsen, and J. W. van der Meer. Single-layer rubble mound breakwaters. *Proc. Coastal Structures*, 99, 1999.

H.J. Verhagen and K. D'Angremond. Breakwaters and Closure Dams, 2001.

H.J. Verhagen, B. van Dijk, and A. Nederpel. Riprap Stability on the Inner Slopes of Medium-Height Breakwaters. *Coastal Structures*, pages 213–222, 2003.

L. Via, T. Pullen, T. Stewart, and W. Allsop. Damage to rubble mound breakwaters - Extracting design guidance from old test data. 2013.

C. Vidal, M. A. Losada, and R. Medina. A universal analysis for the stability of both low-crested and submerged breakwaters. *Coastal Engineering Proceedings*, 23: 1679–1692, 1992.

J.R. Walker, R.Q. Palmer, and J.W. Dunham. Breakwater Back slope Stability. *Proceedings Civil Engineering in the Oceans*, 1976.

Appendices

A | Literature Study - Rear slope

This literature study is conducted in order to find the knowledge gap concerning the stability of the breakwater rear slope. The summary and conclusion of the literature study are presented in section 2.3. The study consists of two parts, namely the rear slope stability of rock armour layers and concrete armour layers.

A.1 Rock armour Layer

There have been several researches into the stability of low crested breakwaters and breakwater's rear slope armoured with rock. These are described in this section.

A.1.1 Walker et al. [1976]

Research

Walker et al. [1976] first described a rear stability experiment and its results. The relation between two dimensionless parameters was investigated, namely $\frac{R_c}{H}$, the freeboard divided by the wave height and $\frac{W_{front}}{W_{rear}}$, the front slope stone weight divided by the rear slope stone weight.

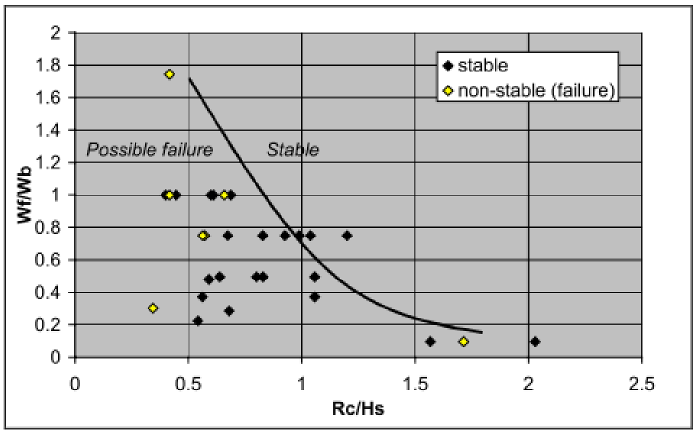

Figure A.1: *Results of the rear slope stability experiment by Walker et al. [1976]*

Conclusions
Three important results of this research are:

$\frac{R_c}{H} > 0.7$: armour units on the rear slope may be reduced relative to armour units on the front slope
$\frac{R_c}{H} < 0.7$: larger units or better placement may be required on the rear slope relative to armour units on the front slope
$\frac{R_c}{H} > 1.5$: only minor protection may be required on the rear slope.

Walker's conclusions are:

- The rear slope of low-crested breakwaters may be subjected to more damage than the front slope
- More research on rear slope design may lead to more economic breakwater designs in the future
- The design wave for the rear slope is not necessarily equal to the design wave for the front slope
- Waves that have the highest rate of overtopping and break just at the structure appear to damage the rear slope more severely.

The research was carried out with only a limiting number of variables. Therefore, the research gives a first approximation of the rear slope's rock dimensions. For example, the influence of the wave period and slope angle are not taken into account [van Dijk, 2001].

A.1.2 van der Meer and Pilarczyk [1990]

Research
van der Meer and Pilarczyk [1990] analysed data sets of the statistically stable low crested breakwater in order to come up with an estimation of the armour dimensions of the front slope.

Conclusions
The stability of a low-crested breakwater with the crest above sea water level is first established as being a non-overtopped structure. Stability formulas derived by van der Meer [1987] can be used. The required stone diameter for an overtopped breakwater can then be determined by multiplying the derived stone diameter for a non-overtopped structure with a reduction factor, which is presented in van der Meer and Pilarczyk [1990].

A.1.3 Vidal et al. [1992]

Research

Vidal et al. [1992] executed experiments with a low crested and submerged breakwater. The stability of the total section, front slope, crest and rear slope are considered independently, because of the diverse stability response to a certain sea state condition of the different parts.

The experiment resulted in stability curves for the four different sections. The curves show a relation between the free board, stability number, wave height and rock diameter.

Conclusions

Vidal main conclusions are:

- In order to determine the armour weight, the obtained stability curves should be determined for each section.
- The stability of low crested rubble-mound breakwaters mainly depends on the freeboard.
- More research should be done to determine the influence of other variables.

Again, not all parameters that might effect the stability are taken into account.

A.1.4 van der Meer and Veldman [1992]

Research

The research of van der Meer and Veldman [1992] includes experiments with the physical models with a different scale. Within this research, the following subjects of a Berm Breakwater were treated: scale effects, rear stability, round head and longshore transport.

The significant wave height at the toe of the structure, the peak period, the relative density, nominal diameter and the crest height relative to the still water level are included in the experiment. These parameters are used in a dimensionless form, namely: $\frac{R_c}{H_s}, \frac{H_s}{\Delta d_{n50}}, s = \frac{2\pi H_s}{g T_p^2}$.

Conclusions

The obtained relation for the rear side of a berm breakwater is as follows:

- start of damage: $\frac{R_c}{H_s} \cdot s_{op}^{1/3} = 0.25$

- moderate damage: $\frac{R_c}{H_s} \cdot s_{op}^{1/3} = 0.21$
- severe damage: $\frac{R_c}{H_s} \cdot s_{op}^{1/3} = 0.17$

A.1.5 Andersen et al. [1992]

Research

The Andersen et al. [1992] research consists of physical model tests and a parameter analysis for the rear slope stability of a Berm Breakwater. Both parts lead to a relation between physical parameters and the required rock dimension. In the parameter analysis, the stability of a single stone and surf similarity equations are used to come up with an expression for the rear slope stability.

In contrast to the other rear side stability researches, Andersen et al. [1992] emphasize on a large number of physical parameters, namely wave height and steepness, crest height, rear side slope, effective sea side slope, stone diameter, relative density and natural angle of response. These parameters are all included in the resulting parametrical expression.

Conclusions

The expression found in this experiment is:

$$\frac{R_c}{H_{m_0}}\sqrt{s_{02}} > \tan\alpha - \left(\frac{H_{m_0}}{\Delta D_{n50}}\frac{1}{\sqrt{s_{02}}}\right)^{-1}\frac{\mu\sin\beta - \sin\beta}{C_D + \mu C_L} \tag{A.1}$$

Andersen et al. [1992] main conclusions are:

- The measurements show that the rear side stability increases with a decreasing effecttive sea side slope. A decrease in the effective sea side slope can be obtained by increasing the berm area.

A.1.6 Kudale and Kobayashi [1996]

Research

The study of Kudale and Kobayashi [1996] was done with a numerical model for the stability of the rear slope of overtopped breakwaters. In the study, an overtopping jet of water impinging on the rear slope above or below the still water level is modelled. This jet causes drag, inertia and lift forces on the armour rock at the rear slope. The stability of rear slope armour units is expressed in terms of the stability number, N_s as a function of the impinging jet velocity and direction and the rear slope angle. The computed stability number is shown to be in line with the measured stability number for the initiation of damage presented by Vidal et al. [1992].

The stability model is then used to perform sensitivity analyses to gain insight into the mechanisms of the rear slope armour stability.

Conclusions

The study performed by Kudale and Kobayashi [1996] did not result in a general relation of the rear slope stability. However, the sensitivity analyses lead to the following unquantifiable conclusions:

- A flatter rear slope increases the rear stability.
- A flatter front slope increases the rear stability.
- The rear slope is more stable in deeper water.
- The rear slope stability of a breakwater with a crest near SWL increases by steepen the rear slope angle (for the shallower water depths)
- A wider crest increases the rear stability.

A.1.7 Verhagen et al. [2003]

Research

A special device is constructed in the labatory to determine the effect of a single overtopping wave on the stability of the rear slope. Within this experiment, only the discharge q5 is considered (see figure A.2).

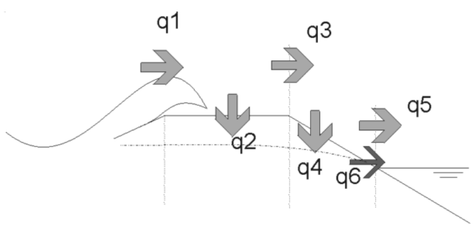

Figure A.2: *Discharges of overtopping waves [Verhagen et al., 2003]*

Opposite to previous studies, Verhagen et al. [2003] used the velocity of the overtopping waves instead of the wave height and period at the front side. The other variables taken into account are: the height of the crest, the number of waves, the angle of the slope and the approach angle of the wave on the slope.

Conclusions

The performed experiments have led to a relation between the velocity of the overtopping water and the stability of the armour units at the rear slope:

$$\Theta_{u_{\text{char}\|},R_c,\alpha,i} = \frac{(u_{char}\cos(\varphi-\alpha))^2}{\Delta g D_{n50}} \frac{R_c}{D_{n50}} \sin(\alpha)\sqrt{i} \tag{A.2}$$

Some important conclusions are:

- There is always damage visible above the waterline. This is caused by the effect of the direct impact of the wave on the stones above the waterline and the loss of support because of movement of stones in a lower position.
- Most damage occurs at the level of the waterline. Stones are fully subjected here to the impact force of the wave, but have less stability because of the buoyancy.
- Below the waterline the damage decreases rapidly.

A.1.8 van Gent and Pozueta [2004]

Research

The objective of van Gent and Pozueta [2004] was to find a formula that could predict the amount of erosion at the rear slope of a breakwater. In order to do so, they determined the following parameters in this order:

1. Wave run-up levels from the wave conditions at the toe of the structure.
2. Wave overtopping values from the wave run-up levels.
3. Amount of erosion at the rear slope from the wave overtopping parameters at the crest.

This approach is applied on three different structures:

- Rock at rear slope, a smooth crest and a smooth front slope
- Rock at rear slope, a smooth crest and a smooth front slope, with different rear side water levels
- Rubble mound structure with rock at rear slope, at crest and front slope

The considered variables are: the maximum velocity that is exceeded by 1% of the incident waves, the number of waves, the wave period, the rear slope angle and the rear side water level.

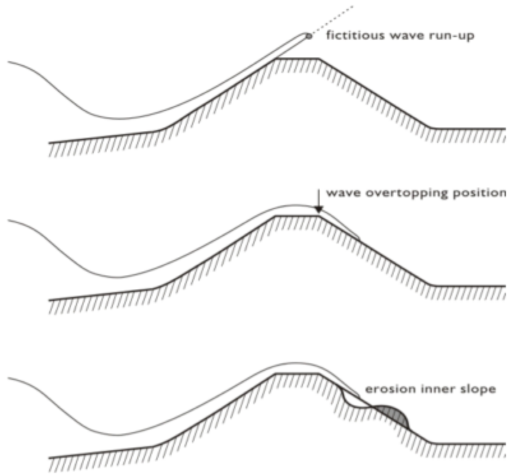

Figure A.3: *The three-step approach of van Gent and Pozueta [2004]*

Conclusions

The following rear stability formula is found:

$$D_{n50} = 0.008\left(\frac{S}{\sqrt{N}}\right)^{-1/6}\left(\frac{u_{1\%}T_{m-1,0}}{\Delta^{0.5}}\right)(\cot\varphi)^{-2.5/6}\left(1 + 10\cdot\exp\left(-R_{c_{rear}}/H_s\right)\right)^{1/6} \tag{A.3}$$

The main conclusions from this study:

- The size of stone material that can be applied at the rear slope is often smaller than the size of the material at the front slope. This reduction can be estimated for structures with a crest elevation higher than $\frac{R_c}{H_s} = 0.3$.
- The relative density of the rock material has not been varied and the number of incident waves per wave condition was lower than 4000 in the present test programme. It would be desirable to validate the obtained expression for a wider field of application.

A.1.9 Andersen [2006]

Research

Andersen [2006] did more extensive research into the stability of different parts of a berm breakwater. Also, the rear slope stability was treated, however the tests were carried out with less variables than in the research of Andersen et al. [1992]. On the other hand, he did corporate the amount of damage in this second research.

Conclusions

Only one configuration is applied, namely a rear slope of 1:1.25. This leads to the following formulas:

- No damage: $\frac{q}{\sqrt{g\cdot\Delta\cdot D_{n50}^3}} < 4\cdot 10^{-5}$
- Start of damage: $4\cdot 10^{-5} \leq \frac{q}{\sqrt{g\cdot\Delta\cdot D_{n50}^3}} < 3\cdot 10^{-4}$
- Moderate damage: $3\cdot 10^{-4} \leq \frac{q}{\sqrt{g\cdot\Delta\cdot D_{n50}^3}} < 7\cdot 10^{-4}$
- Severe damage: $7\cdot 10^{-4} \leq \frac{q}{\sqrt{g\cdot\Delta\cdot D_{n50}^3}}$

A.1.10 van Gent and Pozueta [2004]

Research

In addition to van Gent and Pozueta [2004], a study is carried out for the stability of the rear side of a breakwater with crest element. [van Gent, 2007] A same approach is applied in this research.

Conclusions

The corresponding equation is:

$$D_{n50} = 0.036\,(\cot\varphi)^{0.5}\cdot(R_{1\%}-R_c)^{0.8}\cdot R_c^{0.2}\cdot\left(1+5\frac{R_{c2-rear}}{R_c-R_{c2-rear}}\right)^{0.4}\cdot\left(1+\frac{R_{c2-front}}{H_s}\right)^{-0.4}\cdot\left(\frac{S}{\sqrt{N}}\right)^{-0.4} \tag{A.4}$$

van Gent [2007] also concluded: "The size of stone material that can be applied at the rear slope is often smaller than the size of the material at the front slope. This reduction can be estimated for structures with a crest elevation higher than $\frac{R_c}{H_s} = 0.5$."

A.2 Concrete armour layer

In contrast to the rock armour layer rear stability, not so much information is available about the rear stability of a breakwater with an armour layer of concrete units. The next three studies are about stability of rear slopes armoured with Tetrapods and placed blocks.

A.2.1 de Jong [1996]

Research
de Jong [1996] used two different data sets to find a relation for the stability of the front slope, crest and rear slope of a breakwater armoured with Tetrapods.

Conclusions
It was not possible to derive an empirical formula, however the relation can be shown in a graph, see figure A.4. Besides the wave parameters, de Jong incorporated the free board, relative density and the nominal diameter.

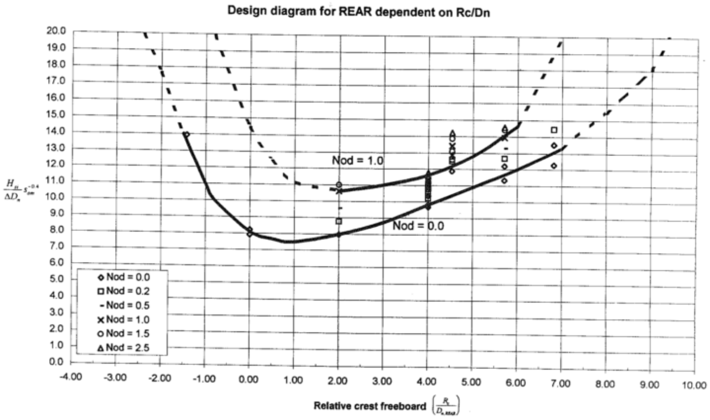

Figure A.4: Design diagram for the rear slope armoured with Tetrapods [de Jong, 1996]

A.2.2 Kuiper et al. [2006]

Research
This study contains a small scale physical model, "Zsteen" calculations and a large scale physical model for a breakwater covered with placed blocks. In this extensive research, different configurations and the stability of different sections of the breakwater are considered. The leakage length is an important adjustment to the old design guideline regarding the rear stability.

Conclusions
Kuiper et al. [2006] final result was a set of rear slope stability formulas that make a distinction between small and large leakages length.

A.2.3 Delta Marine Consultants [2014]

The 'Guidelines for Xbloc Concept Designs' recommend to design the rear slope of a low crested breakwater with the same Xbloc's as applied on the front slope (for

$R_c/H_s < 1.2$). Also, they emphasize that there is no generic design formula and physical model tests are required for a detailed rear armour design.

B | JONSWAP-Spectrum

The wave conditions that are applied in the experiments are according to a JONSWAP-Spectrum. This chapter gives some theoretical background about this spectrum.

There are various wave spectra, which are empirical relationships that define the distribution of energy with frequency within the ocean. A common used wave spectrum is the Pierson-Moskowitz spectrum. It is developed by assuming that the wind blows steadily for a long time over a large area and the waves reach a point of equilibrium with the wind. This is called a fully developed sea. The measurements are based on the North Atlantic during 1964. The JONSWAP-Spectrum (Joint North Sea Wave Observation Project) is based on the Pierson-Moskowitz spectrum. After analysing data, that is collected at the North sea, it is proven that the wave spectrum is not fully developed. Due to quadruplet wave-wave interactions, the wave spectrum can continue to develop. This can be observed in figure B.1, where this aspect is presented by an enhanced peak and the waves continue to grow in time. This spectrum is proven to be most relevant for an engineer, because the quadruplet wave-wave interactions tend to stabilise the shape of the spectrum to the JONSWAP shape [Holthuijsen, 2007].

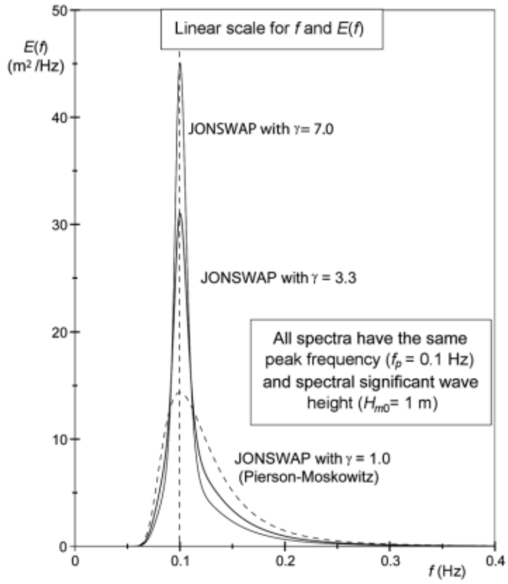

Figure B.1: *JONSWAP spectrum with different peak enhancement factors (γ_J)*

The expression of the JONSWAP-spectrum is:

$$E_{JONSWAP}(f) = \alpha_J g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)\right] {\gamma_J}^{exp\left[-\frac{1}{2}\left(\frac{f/f_p-1}{\sigma_J}\right)^2\right]} \tag{B.1}$$

This expression can also be written in terms of the significant wave height and the peak period [CIRIA, 2007].

$$E_J^{Goda}(f) = \beta_J \cdot H_s^2 \cdot f_p^4 \cdot f^{-5} \cdot \exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right] {\gamma_J}^{\delta} \tag{B.2}$$

$$\beta_J = \frac{0.0624}{0.230 + 0.0336\gamma_J - 0.185\,(1.9+\gamma_J)^{-1}}\,(1.094 - 0.01915\ln\gamma_J) \tag{B.3}$$

$$T_p = \frac{1}{f_p} \tag{B.4}$$

C | Rear slope damage estimation

Despite the lack of knowledge of the rear slope cube layer stability, an estimation of the cube dimension is made, using the rear slope formula for a rock armour layer of van Gent and Pozueta [2004]. Since this formula is not applicable for regular placed cubes a number of assumptions are made.

C.1 Approach and calculation

In order to use the rear slope stability formula for random placed rock in this study, a correction factor is applied, by translating the dimension of a cube into a nominal diameter of rock. Hereby, the differences in stability and density of the two armour units are taken into account. The assumption is that the stability number of both armour units is the same for the front and rear slope of a breakwater. The density of the nominal rock diameter is assumed to have an average value of 2600 $[kg/m^3]$.

Diameter of rock relative to Cube:

$$D_{n50r} = D_n \cdot \frac{N_{s,cube} \cdot \Delta_c}{N_{s,rock} \cdot \Delta_r} \tag{C.1}$$

The stability number of rock amour is determined with the original Hudson formula [CIRIA, 2007]. The stability number for regular placed cubes is $N_{s,cube} = 3.0$, as stated in section 2.5.

$$N_{s,rock} = (K_d \cdot \cot\phi)^{1/3}/1.27 = (4 \cdot 2)^{1/3}/1.27 = 1.57 \tag{C.2}$$

The next step is to use the method of van Gent and Pozueta [2004] and apply the calculated nominal diameter of rock.

Irribaren number:

$$\xi_{s-1,0} = \frac{\tan\alpha}{\sqrt{\frac{2\pi Hs}{\left(g \cdot T_{m-1,0}^2\right)}}} \tag{C.3}$$

The run-up height is calculated with $c_0 = 1.45$, $c_1 = 5.1$ and $\gamma_f = 0.6$.

$$c_2 = 0.25 \cdot \frac{c_1^2}{c_0} \tag{C.4}$$

$$p = 0.5 \cdot \frac{c_1}{c_0} \tag{C.5}$$

$$\text{for } \xi_{s-1,0} < p \text{ holds } R_{u1\%} = c_0 \cdot \xi_{s-1,0} \cdot \gamma_f \cdot H_s \tag{C.6}$$

$$\text{for } \xi_{s-1,0} \geq p \text{ holds } R_{u1\%} = \left(c_1 - \frac{c_2}{\xi_{s-1,0}}\right) \cdot \gamma_f \cdot H_s \tag{C.7}$$

Extreme overtopping velocity is calculated with the following formula, where $\gamma_{f-C} = 0.6$.

$$u_{1\%} = 1.7 \cdot \gamma_{f-C}^{0.5} \cdot \left(\frac{R_{u1\%} - R_c}{\gamma_f \cdot H_s}\right)^{0.5} \cdot \frac{1}{1 + 0.1 \cdot \frac{W_c}{H_s}} \cdot \sqrt{g \cdot H_s} \tag{C.8}$$

The relation between the damage number and number of displaced units [Via et al., 2013] is:

$$N_{od} \approx 0.7 \cdot S \tag{C.9}$$

Eventually the expected damage is:

$$N_{od} \approx 0.7 \cdot S = 0.7 \cdot \left(\frac{D_{n50r}}{0.008 \cdot \frac{u_{1\%} \cdot T_{m-1,0}}{\Delta_r^{0.5}} \cdot \cot\varphi^{-2.5/6} \cdot \left(1 + 10 \exp\left(-R_c/H_s\right)^{1/6}\right)}\right)^{-6} \cdot \sqrt{N} \tag{C.10}$$

The resulting values are shown in appendix E and figure 5.1.

D | Calculation critical along rear slope velocity

As described in chapter 2, a maximum velocity can be calculated for which a protruding cube starts to move [Kuiper et al., 2006]. In order to carry out this calculation, a number of assumptions should be made.

D.1 Assumptions

The used formula is applicable for a placed block revetment. It is assumed that this formula is also applicable for a single layer of cubes. The influence of the larger porosity is neglected.

Furthermore, it is assumed that the cubes protrude not more than 20% of there own diameter.

The values of the used parameters are $c = 0.9$, $f = 0.5$, $C_L = 0.9$ and $B_{\phi op} = 5 \cdot d_r$.

D.2 Calculation

First, the criteria of stability is checked, namely for $C_L \cdot B_{\phi op} < f \cdot D_n$ holds that the cube is always stable.

$$0.9 \cdot 5 \cdot 0.00372 > 0.05 \cdot 0.019 \tag{D.1}$$

Since the cube is not stable by definition, the following formula is used.

$$\phi_{a,max} < \frac{2\Delta D_n^2 (\cos\alpha + f \cdot \sin\alpha)}{C_L (2 - D_n/(5 \cdot d_r)) D_n - f \cdot D_n} \tag{D.2}$$

where:

$$\phi_{a,max} = \frac{0.9 \cdot u_{max}^2}{2g} \tag{D.3}$$

In this equation is u_{max} the critical velocity for which the cube starts to move.

The two equations combined leads to:

$$u_{max} = \sqrt{\frac{4 \cdot g \cdot \Delta \cdot D_n^2 (\cos\alpha + f \cdot \sin\alpha)}{c \cdot (C_L (2 - D_n / (5 \cdot d_r)) D_n - f \cdot D_n)}} \tag{D.4}$$

$$u_{max} = \sqrt{\frac{4 \cdot 9.81 \cdot 1.15 \cdot 0.019^2 (\cos 0.46 + 0.5 \cdot \sin 0.46)}{0.9 \cdot (0.9 (2 - 0.019/(5 \cdot 0.0037)) 0.019 - 0.5 \cdot 0.019)}} = 1.61 ms/s \tag{D.5}$$

This value is used in the analysis of the overtopping front velocity in section 5.2.1.

E | Test data overview

The tables on the next page give an overview of all performed tests with the gathered data. The first table presents the results of the experiment and the second the used values in the analysis. The first three columns of both tables show the number and the name of the test.

E.1 Results

The structural parameters have exactly the same values as was designed. The hydraulic parameters result from the wave data analysis and have almost the same value as was intended. The output parameters consist of rear slope damage values and overtopping characteristics (see appendix G, H and I). The dimensionless parameters are calculated with the values of the previous columns.

E.2 Analysis

The second table presents the theoretical values that are used in the analysis. The expected damage is calculated according to appendix C. The overtopping parameters are calculated in four different ways and for each the least-squares method is performed on the extreme overtopping velocity.

#	CODE	Steering files	Structural parameters: Free board R_c [m]	Crest Width W_c [m]	Slope angle 1/tan(φ) [-]	Packing density n [-]	Hydraulic parameters: Significant wave height H_m0 [m]	Wave period T_p [s]	Wave period T_m-1,0 [s]	Wave length L [m]	Wave steepness s [-]	Test duration t_test [s]	Test duration t_test [min]	Number of waves N_w [-]
1	C1 - **15** - 50 - 2 - 0,25 - 0,03 - 12	I601219	0.15	0.5	2	0.27	0.11	1.92	1.74	4.72	0.024	2040	34	1358
2	C1 - **15** - 50 - 2 - 0,25 - 0,03 - 14	I601421	0.15	0.5	2	0.27	0.13	2.07	1.87	5.48	0.024	1779	30	1061
3	C1 - **15** - 50 - 2 - 0,25 - 0,03 - 16	I601624	0.15	0.5	2	0.27	0.15	2.43	2.20	7.53	0.020	1845	31	981
4	C2 - **10** - 50 - 2 - 0,25 - 0,03 - 10	I651016	0.10	0.5	2	0.27	0.10	1.62	1.46	3.34	0.029	1676	28	1322
5	C2 - **10** - 50 - 2 - 0,25 - 0,03 - 12	I651218	0.10	0.5	2	0.27	0.12	1.82	1.65	4.23	0.027	1919	32	1319
6	C2 - **10** - 50 - 2 - 0,25 - 0,03 - 14	I651421	0.10	0.5	2	0.27	0.13	2.07	1.87	5.48	0.025	2140	36	1311
7	C2 - **10** - 50 - 2 - 0,25 - 0,03 - 16	I651623	0.10	0.5	2	0.27	0.15	2.33	2.10	6.91	0.022	2146	36	1169
8	C3 - **5** - 50 - 2 - 0,25 - 0,03 - 8	I700814	0.05	0.5	2	0.27	0.08	1.35	1.22	2.32	0.034	1276	21	1138
9	C3 - **5** - 50 - 2 - 0,25 - 0,03 - 10	I701016	0.05	0.5	2	0.27	0.10	1.58	1.43	3.18	0.031	1916	32	1514
10	C3 - **5** - 50 - 2 - 0,25 - 0,03 - 12	I701218	0.05	0.5	2	0.27	0.12	2.07	1.87	5.48	0.021	1546	26	1078
11	C3 - **5** - 50 - 2 - 0,25 - 0,03 - 14	I701420	0.05	0.5	2	0.27	0.14	1.78	1.61	4.03	0.035	917	15	579
12	C4 - 10 - 50 - 2 - 0,25 - **0,04** - 10	I651013	0.10	0.5	2	0.27	0.10	1.32	1.19	2.21	0.044	1270	21	1147
13	C4 - 10 - 50 - 2 - 0,25 - **0,04** - 12	I651215	0.10	0.5	2	0.27	0.11	1.48	1.34	2.80	0.041	1276	21	1037
14	C4 - 10 - 50 - 2 - 0,25 - **0,04** - 14	I651417	0.10	0.5	2	0.27	0.13	1.68	1.52	3.60	0.037	1562	26	1152
15	C4 - 10 - 50 - 2 - 0,25 - **0,04** - 16	I651618	0.10	0.5	2	0.27	0.15	1.87	1.69	4.46	0.034	1691	28	1149
16	C5 - 10 - 50 - 2 - 0,25 - **0,02** - 10	I651022	0.10	0.5	2	0.27	0.10	2.07	1.87	5.46	0.018	1827	30	1056
17	C5 - 10 - 50 - 2 - 0,25 - **0,02** - 12	I651225	0.10	0.5	2	0.27	0.12	2.53	2.29	8.16	0.014	2203	37	1097
18	C5 - 10 - 50 - 2 - 0,25 - **0,02** - 14	I651429	0.10	0.5	2	0.27	0.15	2.87	2.59	10.47	0.014	837	14	359
19	C6 - 10 - **30** - 2 - 0,25 - 0,03 - 10	I651016	0.10	0.3	2	0.27	0.10	1.58	1.43	3.18	0.030	1379	23	1076
20	C6 - 10 - **30** - 2 - 0,25 - 0,03 - 12	I651218	0.10	0.3	2	0.27	0.12	1.82	1.65	4.23	0.028	1505	25	1034
21	C6 - 10 - **30** - 2 - 0,25 - 0,03 - 14	I651421	0.10	0.3	2	0.27	0.14	2.02	1.83	5.22	0.026	1653	28	1010
22	C6 - 10 - **30** - 2 - 0,25 - 0,03 - 16	I651623	0.10	0.3	2	0.27	0.16	2.27	2.05	6.58	0.024	616	10	325
23	C7 - 10 - 30 - 2 - **0,30** - 0,03 - 10	I651016	0.10	0.3	2	0.31	0.10	1.58	1.43	3.18	0.030	1391	23	1088
24	C7 - 10 - 30 - 2 - **0,30** - 0,03 - 12	I651218	0.10	0.3	2	0.31	0.12	1.82	1.65	4.24	0.029	642	11	428
25	C8 - 10 - **15** - 2 - 0,25 - 0,03 - 10	I651016	0.10	0.15	2	0.27	0.10	1.58	1.43	3.18	0.030	1589	26	1251
26	C8 - 10 - **15** - 2 - 0,25 - 0,03 - 12	I651218	0.10	0.15	2	0.27	0.11	1.82	1.65	4.24	0.027	1534	26	1048
27	C8 - 10 - **15** - 2 - 0,25 - 0,03 - 14	I651421	0.10	0.15	2	0.27	0.14	2.07	1.87	5.48	0.025	1629	27	991
28	C9 - 10 - 15 - 2 - **0,30** - 0,03 - 8	I650814	0.10	0.15	2	0.31	0.08	1.38	1.25	2.43	0.032	1194	20	1077
29	C9 - 10 - 15 - 2 - **0,30** - 0,03 - 10	I651016	0.10	0.15	2	0.31	0.10	1.58	1.43	3.18	0.031	1368	23	1081
30	C9 - 10 - 15 - 2 - **0,30** - 0,03 - 12	I651218	0.10	0.15	2	0.31	0.12	1.87	1.69	4.46	0.026	1386	23	957
31	C10 - 10 - 15 - **1,5** - 0,25 - 0,03 - 10	I651016	0.10	0.15	1.5	0.27	0.10	1.58	1.43	3.18	0.031	1343	22	1057
32	C10 - 10 - 15 - **1,5** - 0,25 - 0,03 - 12	I651218	0.10	0.15	1.5	0.27	0.12	1.82	1.65	4.24	0.028	1487	25	1018
33	C10 - 10 - 15 - **1,5** - 0,25 - 0,03 - 14	I651421	0.10	0.15	1.5	0.27	0.14	2.02	1.83	5.22	0.026	1706	28	1038
34	C11 - 10 - 15 - 1,5 - **0,30** - 0,03 - 8	I650814	0.10	0.15	1.5	0.31	0.08	1.38	1.25	2.44	0.032	1336	22	1205
35	C11 - 10 - 15 - 1,5 - **0,30** - 0,03 - 10	I651016	0.10	0.15	1.5	0.31	0.10	1.58	1.43	3.18	0.031	1423	24	1234
36	C11 - 10 - 15 - 1,5 - **0,30** - 0,03 - 12	I651218	0.10	0.15	1.5	0.31	0.12	1.82	1.65	4.24	0.027	1359	23	938

#	Rear slope damage: Displaced units N_od [-]	Moved units N_om [-]	Overtopping characteristics – Video: Overtopping waves N_ow [-]	Probability of overtopping P_ow [-]	Overtopping velocity: u_2% [m/s]	Critical: u_2% [m/s]	u_mean [m/s]	Overtopping waves N_ow (velocity)	Probability of overtopping P_ow (velocity)
1	0.00				0.00	1.14	0.00	3	0%
2	0.13	0.98			1.13		0.04	30	3%
3	3.19	8.38			1.52		0.10	78	8%
4	0.00				0.00	1.80	0.01	5	0%
5	0.03	0.16			1.47		0.07	61	5%
6	0.13	0.38			1.80		0.18	175	13%
7	1.40	2.70	254	22%	1.87		0.29	251	21%
8	0.00				1.28	2.12	0.07	70	6%
9	0.00				1.73		0.17	189	12%
10	0.03	0.98			2.11		0.35	282	26%
11	1.97	2.79	245	42%	2.20		0.54	230	40%
12	0.00				0.00	2.03	0.01	11	1%
13	0.00				0.39		0.03	23	2%
14	0.00				1.87		0.13	105	9%
15	0.51	1.05	205	18%	2.31		0.28	218	19%
16	0.00				0.00	1.05	0.01	13	1%
17	0.48	2.54			1.05		0.05	84	8%
18	6.83	11.65	55	15%	1.31		0.11	61	17%
19	0.00				0.00	1.89	0.00	3	0%
20	0.00				1.89		0.25	228	22%
21	0.38	1.75			1.89		0.36	294	29%
22	24.00		125	38%	1.89		0.46	124	38%
23	0.11	0.46			1.43		0.07	54	5%
24	2.46	3.30	83	19%	2.04		0.23	84	20%
25	0.00				0.89	1.68	0.05	260	21%
26	0.10	0.38			1.68		0.23	246	23%
27	11.43	19.84	405	41%	2.23		0.43	392	40%
28	0.00				1.34		0.05	37	3%
29	0.84	5.44			1.68		0.13	123	11%
30	3.16	5.93	230	24%	1.91		0.28	248	26%
31	0.00				0.00		0.00	12	1%
32	0.00		~230		1.91		0.26	257	25%
33	0.32	1.49			2.23		0.45	431	42%
34	0.00				0.89		0.04	129	11%
35	0.00				1.91		0.19	196	16%
36	9.00		~230		2.23		0.29	253	27%

#	Overtopping volume: Number of waves N_w [-]	Overtopping waves N_ow (volume)	Probability of overtopping P_ow (volume)	Average discharge q [l/s/m]	N	Volume per wave: V_average [l/m/wave]	V_2% [l/m]		critical V_2% [l/m]
1	950	3	0%	0.001	1500	0.46	0.00	0.00	0.10
2	1041	10	1%	0.010	500	1.82	0.00	0.00	
3	340	11	3%	0.133	500	8.02	4.25	42.52	
4	928	0	0%	0.000	500	NaN	0.00	0.00	5.50
5	1141	20	2%	0.027	500	2.24	0.00	0.00	
6	225	12	5%	0.190	500	6.23	3.23	32.34	
7					x				
8	1066	15	1%	0.008	500	0.66	0.00	0.00	9.53
9	991	38	4%	0.073	500	2.39	1.42	14.23	
10	522	36	7%	0.254	500	5.36	5.18	51.84	
11	201	24	12%	0.477	150	6.75	9.53	95.26	
12	1029	2	0%	0.000	2000	0.13	0.00	0.00	1.86
13	1061	16	2%	0.011	500	0.92	0.00	0.00	
14	830	22	3%	0.056	500	2.82	0.71	7.08	
15	223	12	5%	0.207	500	6.07	3.65	36.46	
16	1027	7	1%	0.004	500	1.13	0.00	0.00	2.30
17	404	21	5%	0.137	500	5.46	5.53	55.27	
18					x				
19	1008	20	2%	0.033	500	2.10	0.00	0.00	5.19
20	412	14	3%	0.084	500	3.58	1.39	13.93	
21	297	20	7%	0.348	250	8.64	8.61	86.14	
22	183	18	10%	0.539	250	10.34	9.64	96.45	
23									
24									
25	991	29	3%	0.072	500	3.15	1.34	13.41	4.06
26	411	30	7%	0.190	250	3.76	4.05	40.49	
27	105	9	9%	0.480	250	9.45	5.07	50.68	
28									
29									
30									
31									
32									
33									
34									
35									
36									

#	Dimensionless parameters: Stability number N_s [-]	Stability number criteria (lineair) N_s [-]	Stability number criteria (exponential) N_s [-]	Relative freeboard R_c/H_m0 [-]	Relative crest width W_c/H_m0 [-]	Surf similarity parameter Ksi_(s-1) [-]
1	5.3	6.3	6.3	1.3	4.4	3.24
2	6.2			1.1	3.7	3.20
3	7.1			1.0	3.3	3.52
4	4.5	6.4	6.3	1.0	5.2	2.95
5	5.4			0.9	4.3	3.02
6	6.3			0.7	3.7	3.19
7	7.2			0.7	3.3	3.35
8	3.7	5.5	5.5	0.6	6.3	2.70
9	4.6			0.5	5.1	2.85
10	5.4			0.4	4.3	3.44
11	6.5			0.4	3.6	2.68
12	4.5	6.6	6.6	1.0	5.2	2.40
13	5.4			0.9	4.4	2.47
14	6.2			0.8	3.8	2.60
15	7.1			0.7	3.3	2.71
16	4.6	5.0	4.9	1.0	5.1	3.74
17	5.5			0.9	4.3	4.17
18	6.8			0.7	3.4	4.25
19	4.5	5.9	5.9	1.0	3.1	2.87
20	5.5			0.9	2.6	3.01
21	6.4			0.7	2.2	3.10
22	7.4			0.6	1.9	3.22
23	4.5	4.6	4.6	1.0	3.1	2.87
24	5.7			0.8	2.5	2.96
25	4.5	5.4	5.4	1.0	1.6	2.87
26	5.4			0.9	1.3	3.04
27	6.4			0.7	1.1	3.16
28	3.6	3.9	3.8	1.3	1.9	2.79
29	4.6			1.0	1.5	2.85
30	5.5			0.9	1.3	3.09
31	4.5	6.1	6.1	1.0	1.5	2.86
32	5.5			0.9	1.3	3.01
33	6.4			0.7	1.1	3.08
34	3.6	4.6	4.6	1.3	1.9	2.81
35	4.5			1.0	1.5	2.86
36	5.4			0.9	1.3	3.03

Table C.1: Data overview part 1

#	CODE	Steering files	Expected damage: Run-up height z_1% [m]	Extreme velocity u_1% [m/s]	Damage number Nod N_od [-]	Difference damage numbers Delta N_od [%]	Overtopping parameters – Pullen 2007: Run-up height R_u2% [m]	TAW: Average discharge q [l/s/m]
1	C1 - **15** - 50 - 2 - 0,25 - 0,03 - 12	I601219	0.20	0.76	0.03	100%	0.36	0.0006
2	C1 - **15** - 50 - 2 - 0,25 - 0,03 - 14	I601421	0.23	0.97	0.21	39%	0.42	0.0013
3	C1 - **15** - 50 - 2 - 0,25 - 0,03 - 16	I601624	0.27	1.15	1.66	-92%	0.53	0.0033
4	C2 - **10** - 50 - 2 - 0,25 - 0,03 - 10	I651016	0.16	0.90	0.04	100%	0.28	0.0007
5	C2 - **10** - 50 - 2 - 0,25 - 0,03 - 12	I651218	0.20	1.09	0.26	89%	0.35	0.0018
6	C2 - **10** - 50 - 2 - 0,25 - 0,03 - 14	I651421	0.23	1.24	1.37	90%	0.43	0.0037
7	C2 - **10** - 50 - 2 - 0,25 - 0,03 - 16	I651623	0.27	1.36	4.83	71%	0.51	0.0065
8	C3 - **5** - 50 - 2 - 0,25 - 0,03 - 8	I700814	0.13	1.04	0.04	100%	0.21	0.0014
9	C3 - **5** - 50 - 2 - 0,25 - 0,03 - 10	I701016	0.16	1.20	0.30	100%	0.28	0.0031
10	C3 - **5** - 50 - 2 - 0,25 - 0,03 - 12	I701218	0.21	1.38	3.13	99%	0.39	0.0072
11	C3 - **5** - 50 - 2 - 0,25 - 0,03 - 14	I701420	0.23	1.40	1.06	-85%	0.37	0.0071
12	C4 - 10 - 50 - 2 - 0,25 - **0,04** - 10	I651013	0.15	0.77	0.00	100%	0.23	0.0003
13	C4 - 10 - 50 - 2 - 0,25 - **0,04** - 12	I651215	0.18	0.97	0.03	100%	0.28	0.0008
14	C4 - 10 - 50 - 2 - 0,25 - **0,04** - 14	I651417	0.21	1.13	0.21	100%	0.34	0.0019
15	C4 - 10 - 50 - 2 - 0,25 - **0,04** - 16	I651618	0.25	1.25	0.80	36%	0.41	0.0035
16	C5 - 10 - 50 - 2 - 0,25 - **0,02** - 10	I651022	0.18	1.01	0.29	100%	0.36	0.0019
17	C5 - 10 - 50 - 2 - 0,25 - **0,02** - 12	I651225	0.22	1.22	3.40	86%	0.48	0.0050
18	C5 - 10 - 50 - 2 - 0,25 - **0,02** - 14	I651429	0.28	1.39	10.61	36%	0.61	0.0096
19	C6 - 10 - **30** - 2 - 0,25 - 0,03 - 10	I651016	0.16	1.03	0.06	100%	0.27	0.0007
20	C6 - 10 - **30** - 2 - 0,25 - 0,03 - 12	I651218	0.20	1.24	0.52	100%	0.35	0.0018
21	C6 - 10 - **30** - 2 - 0,25 - 0,03 - 14	I651421	0.23	1.38	2.01	81%	0.42	0.0035
22	C6 - 10 - **30** - 2 - 0,25 - 0,03 - 16	I651623	0.28	1.51	4.23	-467%	0.51	0.0065
23	C7 - 10 - 30 - 2 - **0,30** - 0,03 - 10	I651016	0.16	1.03	0.06	-74%	0.27	0.0007
24	C7 - 10 - 30 - 2 - **0,30** - 0,03 - 12	I651218	0.20	1.26	0.38	-544%	0.35	0.0020
25	C8 - 10 - **15** - 2 - 0,25 - 0,03 - 10	I651016	0.16	1.16	0.14	100%	0.27	0.0007
26	C8 - 10 - **15** - 2 - 0,25 - 0,03 - 12	I651218	0.20	1.37	0.94	89%	0.34	0.0018
27	C8 - 10 - **15** - 2 - 0,25 - 0,03 - 14	I651421	0.24	1.53	4.33	-164%	0.43	0.0039
28	C9 - 10 - 15 - 2 - **0,30** - 0,03 - 8	I650814	0.13	0.86	0.01	100%	0.22	0.0002
29	C9 - 10 - 15 - 2 - **0,30** - 0,03 - 10	I651016	0.16	1.17	0.14	-495%	0.28	0.0007
30	C9 - 10 - 15 - 2 - **0,30** - 0,03 - 12	I651218	0.20	1.40	1.18	-168%	0.36	0.0020
31	C10 - 10 - 15 - **1,5** - 0,25 - 0,03 - 10	I651016	0.16	1.17	0.28	100%	0.28	0.0007
32	C10 - 10 - 15 - **1,5** - 0,25 - 0,03 - 12	I651218	0.20	1.38	2.03	100%	0.35	0.0019
33	C10 - 10 - 15 - **1,5** - 0,25 - 0,03 - 14	I651421	0.24	1.52	7.57	96%	0.42	0.0036
34	C11 - 10 - 15 - 1,5 - **0,30** - 0,03 - 8	I650814	0.13	0.84	0.02	100%	0.21	0.0002
35	C11 - 10 - 15 - 1,5 - **0,30** - 0,03 - 10	I651016	0.16	1.17	0.31	100%	0.28	0.0007
36	C11 - 10 - 15 - 1,5 - **0,30** - 0,03 - 12	I651218	0.20	1.38	1.89	-376%	0.35	0.0018

#	Van Gent 2002: Run-up height z_2% [m]	Layer thickness h_2% [m]	Velocity u_2% [m/s]	Discharge q_2% [m^2/s]	Schüttrumpf 2001b: Run-up height z_2% [m]	Layer thickness h_2% [m]	Velocity u_2% [m/s]	RM - van Gent (2003): Layer thickness h_2% [m]	Velocity u_2% [m/s]	Discharge q_2% [m^2/s]	Wave volume V_2% [m^3/m]	Wave volume V_2% [l/m]	RM- Schuttrumpf et al (2003): Layer thickness h_2% [m]	Velocity u_2% [m/s]	R^2 method – Van Gent (2002): R-squared r^2 [-]	Schüttrumpf (2001b): R-squared r^2 [-]	RM - van Gent (2003): R-squared r^2 [-]	RM - Schuttrumpf et al (2003): R-squared r^2 [-]
1	0.18	0.01	0.66	0.00	0.15	0.00	0.00	0.01	0.51	0.00	0.00	3.15	0.01	0.65	0.4	0.0	0.3	0.4
2	0.21	0.01	0.99	0.01	0.18	0.00	0.22	0.01	1.06	0.01	0.01	13.10	0.02	1.22	0.0	0.8	0.0	0.0
3	0.25	0.02	1.29	0.03	0.21	0.01	0.53	0.02	1.52	0.02	0.03	33.01	0.03	1.70	0.1	1.0	0.0	0.0
4	0.15	0.01	0.78	0.01	0.13	0.00	0.19	0.01	0.83	0.00	0.01	7.68	0.01	0.99	0.6	0.0	0.7	1.0
5	0.18	0.02	1.07	0.02	0.16	0.01	0.50	0.02	1.28	0.01	0.02	20.93	0.02	1.45	0.2	0.9	0.0	0.0
6	0.22	0.02	1.33	0.03	0.18	0.01	0.76	0.02	1.66	0.03	0.04	42.19	0.03	1.84	0.2	1.1	0.0	0.0
7	0.25	0.03	1.56	0.05	0.21	0.01	0.99	0.03	1.98	0.04	0.07	70.94	0.04	2.17	0.1	0.8	0.0	0.1
8	0.12	0.01	0.86	0.01	0.11	0.01	0.48	0.01	1.11	0.01	0.01	14.71	0.02	1.28	0.2	0.6	0.0	0.0
9	0.15	0.02	1.11	0.02	0.13	0.01	0.74	0.02	1.49	0.02	0.03	31.10	0.03	1.67	0.4	1.0	0.1	0.0
10	0.19	0.03	1.40	0.04	0.16	0.01	0.98	0.03	1.89	0.04	0.06	61.84	0.04	2.08	0.5	1.3	0.0	0.0
11	0.21	0.03	1.56	0.05	0.19	0.02	1.17	0.03	2.04	0.05	0.08	78.35	0.05	2.24	0.4	1.1	0.0	0.0
12	0.14	0.01	0.66	0.00	0.12	0.00	0.12	0.01	0.57	0.00	0.00	3.85	0.01	0.72	0.4	0.0	0.3	0.5
13	0.16	0.01	0.94	0.01	0.15	0.01	0.41	0.01	1.05	0.01	0.01	12.80	0.02	1.21	0.3	0.0	0.4	0.7
14	0.20	0.02	1.20	0.02	0.18	0.01	0.68	0.02	1.44	0.02	0.03	28.27	0.03	1.61	0.4	1.4	0.2	0.1
15	0.23	0.03	1.43	0.04	0.20	0.01	0.92	0.03	1.77	0.03	0.05	50.79	0.04	1.95	0.8	1.9	0.3	0.1
16	0.17	0.01	0.90	0.01	0.14	0.00	0.26	0.01	1.07	0.01	0.01	13.36	0.02	1.23	0.8	0.1	1.1	1.5
17	0.21	0.02	1.21	0.03	0.16	0.01	0.57	0.02	1.54	0.02	0.03	34.34	0.03	1.72	0.0	0.2	0.2	0.5
18	0.26	0.03	1.56	0.05	0.20	0.01	0.92	0.03	2.01	0.04	0.07	74.62	0.04	2.20	0.1	0.1	0.5	0.8
19	0.15	0.01	0.90	0.01	0.13	0.00	0.33	0.01	0.98	0.01	0.01	7.39	0.01	1.12	0.8	0.1	1.0	1.2
20	0.18	0.02	1.22	0.02	0.16	0.01	0.68	0.02	1.45	0.01	0.02	21.52	0.02	1.59	0.4	1.5	0.2	0.1
21	0.22	0.02	1.49	0.04	0.18	0.01	0.93	0.02	1.79	0.03	0.04	41.71	0.03	1.95	0.2	0.9	0.0	0.0
22	0.26	0.03	1.77	0.06	0.22	0.01	1.19	0.03	2.14	0.04	0.08	75.23	0.04	2.31	0.0	0.5	0.1	0.2
23	0.15	0.01	0.90	0.01	0.13	0.00	0.32	0.01	0.98	0.01	0.01	7.35	0.01	1.12	0.3	1.2	0.2	0.1
24	0.19	0.02	1.27	0.02	0.16	0.01	0.73	0.02	1.51	0.02	0.02	24.52	0.03	1.66	0.6	1.7	0.3	0.1
25	0.15	0.01	1.02	0.01	0.13	0.00	0.49	0.01	1.13	0.01	0.01	7.31	0.01	1.24	0.0	0.2	0.1	0.1
26	0.18	0.02	1.34	0.02	0.16	0.01	0.81	0.02	1.55	0.01	0.02	20.23	0.02	1.67	0.1	0.7	0.0	0.0
27	0.22	0.03	1.66	0.04	0.19	0.01	1.10	0.03	1.93	0.03	0.04	44.14	0.03	2.07	0.3	1.3	0.1	0.0
28	0.12	0.00	0.61	0.00	0.10	0.00	0.02	0.00	0.56	0.00	0.00	1.09	0.01	0.65	0.5	1.8	0.6	0.5
29	0.15	0.01	1.03	0.01	0.13	0.00	0.51	0.01	1.15	0.01	0.01	7.73	0.01	1.26	0.4	1.4	0.3	0.2
30	0.19	0.02	1.38	0.02	0.16	0.01	0.84	0.02	1.60	0.02	0.02	22.52	0.02	1.72	0.3	1.1	0.1	0.0
31	0.15	0.01	1.03	0.01	0.13	0.00	0.50	0.01	1.15	0.01	0.01	7.61	0.01	1.25	1.1	0.3	1.3	1.6
32	0.18	0.02	1.37	0.02	0.16	0.01	0.84	0.02	1.58	0.02	0.02	21.77	0.02	1.70	0.3	1.2	0.1	0.0
33	0.22	0.03	1.65	0.04	0.19	0.01	1.10	0.03	1.92	0.03	0.04	43.19	0.03	2.06	0.3	1.3	0.1	0.0
34	0.12	0.00	0.59	0.00	0.10	0.00	0.01	0.00	0.53	0.00	0.00	0.96	0.01	0.62	0.1	0.8	0.1	0.1
35	0.15	0.01	1.03	0.01	0.13	0.00	0.50	0.01	1.15	0.01	0.01	7.62	0.01	1.25	0.8	2.0	0.6	0.4
36	0.18	0.02	1.35	0.02	0.16	0.01	0.82	0.02	1.56	0.01	0.02	20.97	0.02	1.68	0.8	2.0	0.4	0.3
															0.34	**0.76**	**0.25**	**0.31**
															0.37	**0.89**	**0.27**	**0.30**

Table C.2: Data overview part 2

F | Number of waves

The number of waves within a test is found by counting the number of zero-crossings and subsequently divide this value by two. The resulting value is the average of the number of waves of each wave gauge. The used Matlab routine is presented below.

```
clear all
close all
clc

%%  import data from file
filename = 'I601219.ASC';
delimiterIn = ';';
A = importdata(filename,delimiterIn);

t=A.data(:, 1);
H1=A.data(:, 4);
H2=A.data(:, 5);
H3=A.data(:, 6);

%% Test duration

dt=0.01;              %stepsize
t_test=size(t,1)*dt

%% Number of waves

% Hzerocross = dsp.ZeroCrossingDetector;
% NumZeroCross = step(Hzerocross,H)

ZeroCross1 = crossing(H1,t,mean(H1));
ZeroCross2 = crossing(H2,t,mean(H2));
ZeroCross3 = crossing(H3,t,mean(H3));

N_w1 = size(ZeroCross1,2)/2;
N_w2 = size(ZeroCross2,2)/2;
N_w3 = size(ZeroCross3,2)/2;

N_w=(N_w1+N_w2+N_w3)/3
```

G | Damage analysis

G.1 Method

The amount of damage at the rear slope is determined with an image analysis. This analysis compares the start image with the end image, where start is before and end is after a test. In order to do so, the coordinates of the cubes should be determined. This is carried out by selecting every single cube by hand in both images. An error is made in this manual task. This error is calculated by processing the same photograph two times. The calculated displacements that are smaller than the error are considered as no displacement.

The analysis consists of the following steps:

- Rescaling and shifting of the end photograph by selecting fixed points, resulting in two photographs with the same dimensions.
- Obtaining the distance per pixel value by selecting two points with a known distance from each other. This value is necessary to determine the displacements.
- Collecting the coordinates of the cubes for both photographs by manually selecting the upper left corners of the cubes.
- Calculating the distance between the coordinates of the start and end photograph.
- Selecting the threshold for start of moving, to include the error made by manual clicking the cubes.
- Calculating the number of displaced units

The complete routine is presented on the next pages.

The movements of the cubes are mapped for tests with severe displacements. In some tests, no displacements were observed. The images of these tests are not analysed. The other image analyses are presented in chapter G.2

Initially, the rear slope damage should have been determined automatically by object recognition. The image of the rear slope was transformed to a black and white image, where the cubes are white and pores are black. This transformation was possible due to the colours of the cubes; black at the sides and white at the top. The black and white image can be represented by a matrix of zeros (black) and ones (white). An attempt is made to recognize a matrix of ones (with the size of a cube) within the matrix of the image. However it was not possible to complete this routine within a foreseeable period, due to a large number of discontinuities. For example, not all cubes have the same size and some cubes rotated during the test.

```
clc
clear all
close all

%% ---------------------------------------------------------------
% Parameters
%-----------------------------------------------------------------

% global settings, configure these settings for every test
d = 18.6;                        % Diameter of cube in mm
out_of_place_factor = 1.5;       % Out of place relative to cube
disp_factor = 0.5;               % Displacement relative to cube
total_rows = 23;                 % number of rows
W_flume=800;                     % Width of the flume in mm

%% ---------------------------------------------------------------
% Load the images
%-----------------------------------------------------------------

B = imread('image_before.jpg');
A = imread('image_after.jpg');

%% ---------------------------------------------------------------
% Calibration: Obtain mm per pixel parameter
%-----------------------------------------------------------------

% Left point of flume
figure, imshow(B);
set(gcf, 'Position', get(0,'Screensize'));
disp(['Select fixed left point of flume'])
[x_c1, y_c1] = getpts;

% Right point of flume
figure, imshow(B);
set(gcf, 'Position', get(0,'Screensize'));
disp(['Select fixed right point of flume'])
[x_c2, y_c2] = getpts;

% Calculation of length in px
px_c = sqrt((x_c2-x_c1)^2+(y_c2-y_c1)^2);

% Calculation of mm/px
mm_per_px=W_flume/px_c

%% ---------------------------------------------------------------
% Transforming after image (A)
%-----------------------------------------------------------------

% Before image - Fixed point at left bottom (i1,j1)
figure, imshow(B);
set(gcf, 'Position', get(0,'Screensize'));
disp(['Select fixed point at bottom left (i1,j1)'])
[i1, j1] = getpts;

% Before image - Fixed point at upper right (i2,j2)
figure, imshow(B);
set(gcf, 'Position', get(0,'Screensize'));
disp(['Select fixed point at upper right (i2,j2)'])
[i2, j2] = getpts;
```

```
% After image - Fixed point at left bottom (x1,y1)
figure, imshow(A);
set(gcf, 'Position', get(0,'Screensize'));
disp(['Select fixed point at bottom left (x1,y1)'])
[x1, y1] = getpts;

% After image - Fixed point at upper right (x2,y2)
figure, imshow(A);
set(gcf, 'Position', get(0,'Screensize'));
disp(['Select fixed point at bottom left (x2,y2)'])
[x2, y2] = getpts;

% Obtain scaling and shifting parameters
scaling =(i1-i2)/(x1-x2);
shift_x = x1*scaling-i1;
shift_y = y1*scaling-j1;


%% ------------------------------------------------------------------
% Cube coordinates
%--------------------------------------------------------------------

% Start values
distances = [];
means_row = [];
N_disp = 0;
N_ofp = 0;

x_before_all=[];
y_before_all=[];

x_after_all=[];
y_after_all=[];

x_after_scaled_all=[];
y_after_scaled_all=[];

% Selecting the cubes

for row = 1:total_rows

    % Load before image
    disp(['Processing row ' num2str(row) ' before'])
    figure, imshow(B);
    set(gcf, 'Position', get(0,'Screensize'));
    [x_b, y_b] = getpts;

    % Load after image
    disp(['Processing row ' num2str(row) ' after'])
    figure, imshow(A);
    set(gcf, 'Position', get(0,'Screensize'));
    [x_a, y_a] = getpts;

    % Scale and shift of the after image
    x_a_scaled = x_a*scaling-shift_x;
    y_a_scaled = y_a*scaling-shift_y;

    % Calculate displacement of cubes
    distances_row = sqrt((x_a_scaled - x_b).^2 + (y_a_scaled - y_b).^2)...
        * mm_per_px / d;
```

```
    % Calculate number of out of place & displaced cubes
    distances_row(distances_row > out_of_place_factor) = out_of_place_factor;
    N_ofp = N_ofp + sum(distances_row(:) == out_of_place_factor);
    N_disp = N_disp + sum(distances(:) >= disp_factor);

    % Calculate mean value of row and add to mean matrix
    mean_row = mean(distances_row);
    means_row = [means_row; mean_row];

    % Translate distance_row, column->row
    distances_row = distances_row';

    % Add NaN to even rows, to give all rows the same dimension
    if mod(row, 2) == 0
        distances_row = [distances_row, NaN];
    end

    % add to total distances matrix
    distances = [distances; distances_row];

    % add NaN to even rows, to give all rows the same dimension
    if mod(row, 2) == 0
        x_b = [x_b; NaN];
        y_b = [y_b; NaN];
        x_a = [x_a; NaN];
        y_a = [y_a; NaN];
        x_a_scaled = [x_a_scaled; NaN];
        y_a_scaled = [y_a_scaled; NaN];
    end

    % Save coordinates
    x_before_all=[x_before_all, x_b];
    y_before_all=[y_before_all, y_b];
    x_after_all=[x_after_all, x_a];
    y_after_all=[y_after_all, y_a];
    x_after_scaled_all=[x_after_scaled_all, x_a_scaled];
    y_after_scaled_all=[y_after_scaled_all, y_a_scaled];

    close all
end

%% ----------------------------------------------------------------
% Output values
%-----------------------------------------------------------------

dlmwrite('x_before_all.csv', x_before_all, 'delimiter', ',');
dlmwrite('y_before_all.csv', y_before_all, 'delimiter', ',');
dlmwrite('x_after_all.csv', x_after_all, 'delimiter', ',');
dlmwrite('y_after_all.csv', y_after_all, 'delimiter', ',');
dlmwrite('x_after_scaled_all.csv', x_after_scaled_all, 'delimiter', ',');
dlmwrite('y_after_scaled_all.csv', y_after_scaled_all, 'delimiter', ',');
dlmwrite('distances.csv', distances, 'delimiter', ',');
```

G.2 Results

A table with the displacements is generated and shown in the next pages for all performed tests. The photos that are taken before and after the test and the corresponding damage table are shown per test on one page. Vital aspects of the damage table are explained below:

The even rows have one cube less due to the placing pattern, leaving the last column empty. In reality, the cubes in these rows are shifted a half cube to the right.

The amount of displacement is presented as the moved distance relative to the nominal diameter of the cubes. For example: a displacement of $0.3 \cdot d_n$ is equal to a distance of $0.3 \cdot 18.6 = 5.6$ mm. The movement of a cube is divided in three classes:

$\leq 0.2 \cdot d_n$: no displacement (green)
$0.2 \cdot d_n - 0.3 \cdot d_n$: small displacement (yellow)
$0.3 \cdot d_n - 1.5 \cdot d_n$: large displacement (red)
$\geq 1.5 \cdot d_n$: cube removed from slope (black)

Due to the possible errors in the data processing, a displacement of less than $0.2 \cdot d_n$ is considered as no displacement.

The average displacements of the cubes in the rows are summed up in the last column.

The water level is indicated with a horizontal blue line.

Since this study also focusses on the location of the initial damage, the cubes that moved out first are highlighted with a yellow line. This is especially important for damage patterns with large areas of damage, since it is not clear in the photographs which cube(s) triggered the severe damage.

G.3 Configuration 1

Test: C1-15-50-2-0.25-0.03-12 (I601219)

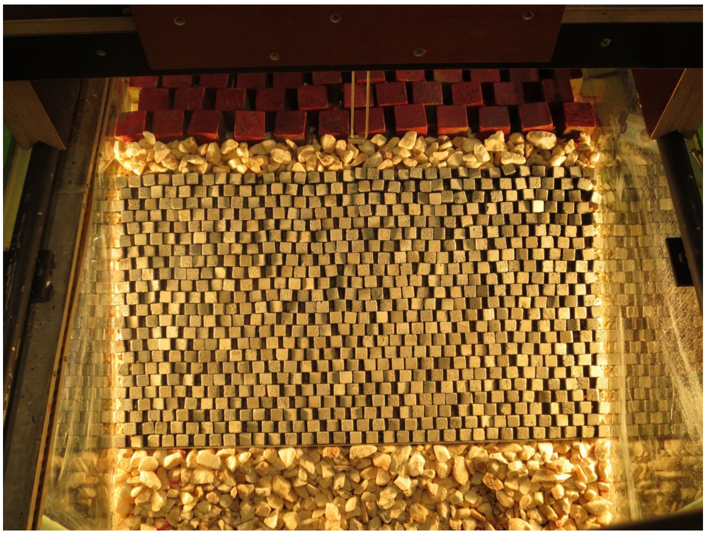

Figure G.1: Photo before the test

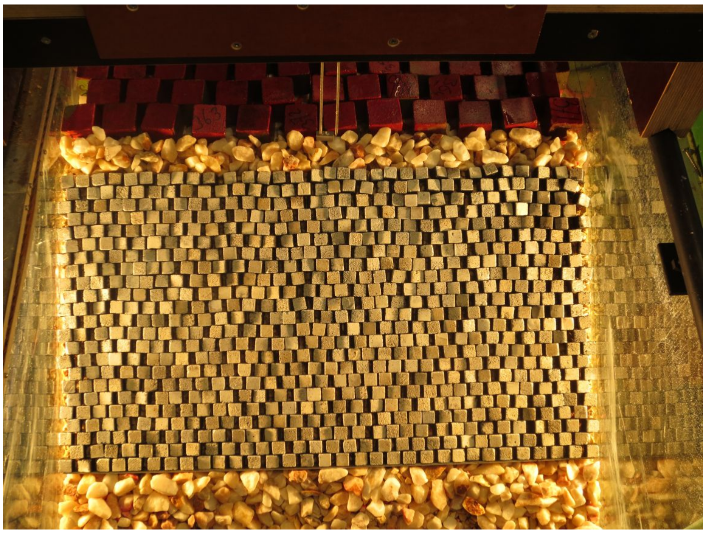

Figure G.2: Photo after the test

Test: C1-15-50-2-0.25-0.03-14 (I601421)

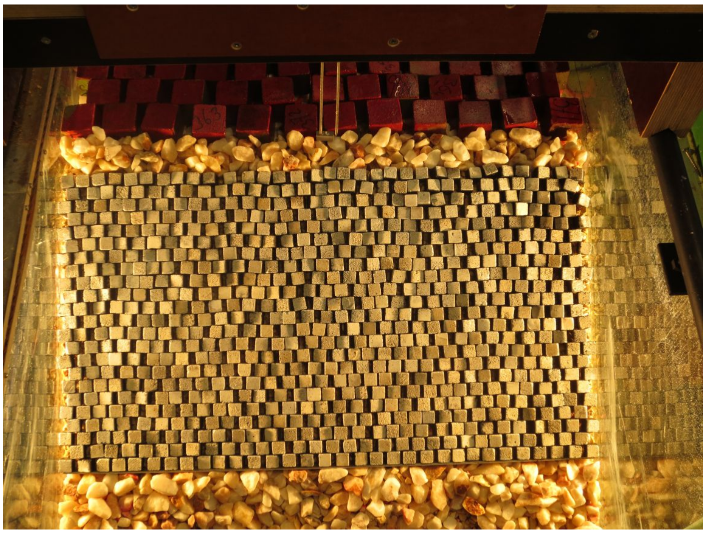

Figure G.3: *Photo before the test*

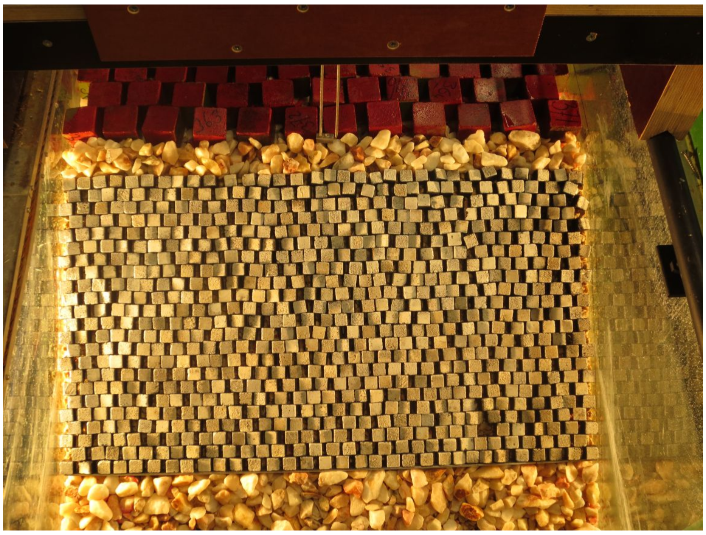

Figure G.4: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.09	0.09	0.14	0.18	0.18	0.17	0.25	0.10	0.18	0.16	0.19	0.14	0.17	0.16	0.29	0.17	0.17	0.13	0.09	0.16	0.13	0.16	0.13	0.14	0.06	0.14	0.15	0.17	0.13	0.14	0.09	0.09	0.15
2	0.17	0.22	0.13	0.11	0.17	0.12	0.08	0.12	0.16	0.14	0.12	0.11	0.10	0.10	0.09	0.13	0.16	0.11	0.14	0.05	0.12	0.08	0.13	0.12	0.09	0.11	0.06	0.09	0.12	0.12	0.16		0.12
3	0.14	0.13	0.18	0.25	0.19	0.09	0.20	0.17	0.19	0.18	0.17	0.21	0.15	0.06	0.07	0.02	0.07	0.14	0.07	0.11	0.11	0.12	0.11	0.12	0.09	0.06	0.13	0.12	0.15	0.12	0.15	0.14	0.13
4	0.09	0.14	0.19	0.16	0.09	0.10	0.02	0.06	0.09	0.02	0.06	0.09	0.15	0.08	0.10	0.06	0.06	0.14	0.11	0.12	0.11	0.16	0.07	0.12	0.08	0.07	0.06	0.16	0.07	0.11	0.12		0.10
5	0.23	0.21	0.25	0.19	0.18	0.06	0.11	0.04	0.09	0.02	0.10	0.19	0.03	0.16	0.16	0.06	0.08	0.05	0.08	0.11	0.10	0.05	0.09	0.10	0.20	0.10	0.06	0.10	0.14	0.10	0.10	0.12	0.11
6	0.11	0.19	0.18	0.04	0.08	0.10	0.09	0.20	0.17	0.10	0.21	0.23	0.19	0.13	0.06	0.04	0.10	0.04	0.05	0.19	0.10	0.05	0.11	0.07	0.31	0.13	0.10	0.15	0.15	0.05	0.05		0.12
7	0.23	0.22	0.18	0.11	0.08	0.15	0.14	0.06	0.11	0.11	0.03	0.07	0.14	0.19	0.03	0.15	0.02	0.10	0.09	0.19	0.14	0.05	0.08	0.07	0.08	0.01	0.12	0.07	0.09	0.10	0.10	0.09	0.11
8	0.12	0.30	0.11	0.20	0.07	0.14	0.09	0.17	0.06	0.11	0.08	0.06	0.10	0.05	0.02	0.09	0.20	0.01	0.19	0.06	0.05	0.05	0.11	0.03	0.08	0.08	0.13	0.08	0.07	0.11	0.07		0.10
9	0.12	0.12	0.14	0.10	0.16	0.19	0.15	0.09	0.23	0.06	0.17	0.07	0.10	0.14	0.08	0.06	0.06	0.02	0.04	0.12	0.07	0.04	0.02	0.06	0.07	0.08	0.10	0.10	0.10	0.08	0.14	0.06	0.10
10	0.09	0.23	0.18	0.21	0.19	0.06	0.09	0.16	0.07	0.10	0.12	0.07	0.10	0.09	0.10	0.09	0.03	0.08	0.03	0.03	0.04	0.05	0.02	0.07	0.12	0.11	0.03	0.05	0.07	0.09	0.12		0.09
11	0.20	0.07	0.21	0.06	0.08	0.04	0.13	0.05	0.04	0.12	0.13	0.03	0.15	0.10	0.06	0.08	0.06	0.06	0.09	0.05	0.04	0.09	0.01	0.02	0.13	0.01	0.15	0.08	0.00	0.10	0.08	0.09	0.08
12	0.04	0.20	0.06	0.12	0.03	0.18	0.17	0.04	0.11	0.05	0.08	0.15	0.06	0.01	0.09	0.06	0.07	0.08	0.11	0.03	0.09	0.01	0.03	0.05	0.03	0.15	0.06	0.01	0.06	0.08	0.16		0.08
13	0.24	0.20	0.18	0.21	0.15	0.14	0.02	0.08	0.07	0.08	0.13	0.12	0.06	0.02	0.10	0.07	0.06	0.09	0.09	0.06	0.09	0.04	0.07	0.03	0.11	0.02	0.07	0.11	0.05	0.07	0.04	0.11	0.09
14	0.16	0.14	0.05	0.05	0.15	0.15	0.05	0.08	0.10	0.10	0.04	0.07	0.09	0.05	0.11	0.10	0.09	0.08	0.09	0.10	0.14	0.02	0.14	0.05	0.07	0.04	0.10	0.05	0.02	0.12	0.08		0.09
15	0.22	0.15	0.13	0.21	0.15	0.10	0.05	0.08	0.07	0.07	0.08	0.07	0.07	0.14	0.12	0.05	0.05	0.04	0.11	0.10	0.04	0.08	0.04	0.10	0.05	0.09	0.06	0.06	0.01	0.07	0.09	0.04	0.09
16	0.08	0.19	0.13	0.17	0.11	0.14	0.04	0.07	0.02	0.13	0.06	0.15	0.10	0.08	0.11	0.19	0.04	0.09	0.05	0.05	0.06	0.06	0.11	0.01	0.04	0.03	0.01	0.08	0.09	0.02	0.12		0.08
17	0.13	0.15	0.18	0.09	0.15	0.06	0.09	0.09	0.06	0.10	0.05	0.09	0.03	0.07	0.06	0.04	0.07	0.07	0.02	0.02	0.07	0.04	0.02	0.09	0.09	0.03	0.07	0.06	0.09	0.10	0.11	0.05	0.08
18	0.16	0.11	0.13	0.16	0.21	0.14	0.05	0.07	0.07	0.08	0.10	0.11	0.17	0.08	0.07	0.07	0.06	0.10	0.29	0.06	0.08	0.07	0.03	0.05	0.04	0.06	0.07	0.13	0.05	0.07	0.09		0.10
19	0.09	0.13	0.07	0.06	0.14	0.09	0.05	0.05	0.09	0.10	0.04	0.07	0.02	0.10	0.07	0.05	0.09	0.07	0.11	0.05	0.04	0.13	0.05	0.06	0.03	0.16	0.05	0.08	0.12	0.02	0.09	0.13	0.08
20	0.12	0.07	0.12	0.19	0.09	0.08	0.11	0.03	0.11	0.05	0.12	0.12	0.06	0.08	0.02	0.07	0.06	0.12	0.06	0.05	0.04	0.04	0.06	0.10	0.46	0.13	0.07	0.09	0.02	0.03	0.07		0.09
21	0.12	0.07	0.12	0.08	0.26	0.13	0.02	0.03	0.07	0.07	0.10	0.08	0.07	0.07	0.13	0.08	0.10	0.03	0.14	0.02	0.06	0.02	0.12	0.14	0.06	1.50	0.11	0.12	0.10	0.02	0.02	0.02	0.13
22	0.09	0.05	0.02	0.09	0.13	0.06	0.09	0.18	0.14	0.03	0.01	0.07	0.08	0.07	0.13	0.01	0.04	0.06	0.03	0.11	0.11	0.13	0.16	0.10	0.04	0.02	0.17	0.06	0.03	0.06	0.02		0.08
23	0.12	0.01	0.15	0.14	0.13	0.06	0.09	0.11	0.10	0.01	0.04	0.11	0.05	0.02	0.03	0.04	0.12	0.02	0.10	0.05	0.09	0.05	0.05	0.14	0.07	0.21	0.44	0.10	0.11	0.09	0.12	0.07	0.10

Figure G.5: *Displacements*

Test: C1-15-50-2-0.25-0.03-16 (I601624)

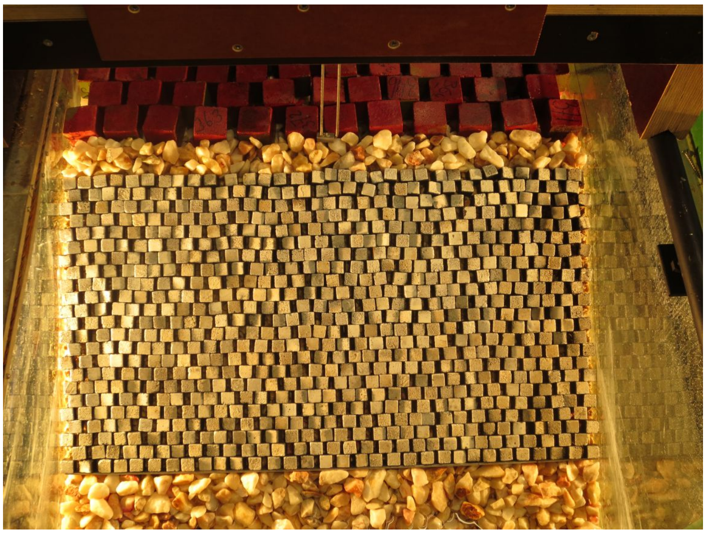

Figure G.6: *Photo before the test*

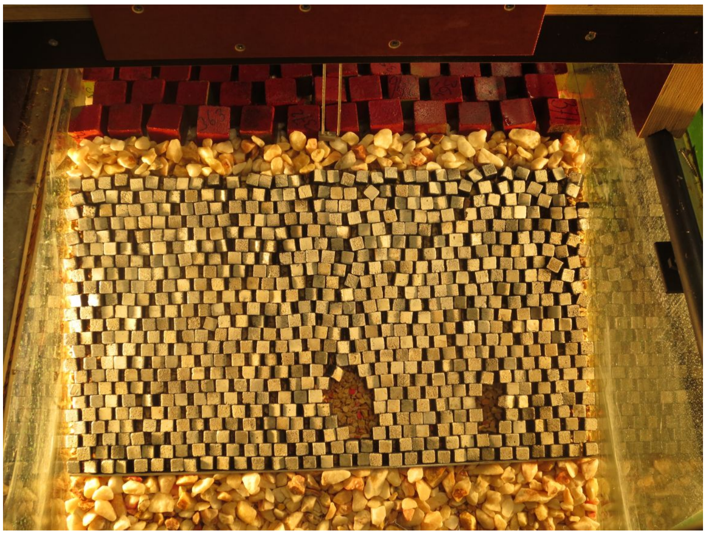

Figure G.7: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.35	0.10	0.11	0.31	0.14	0.18	0.08	0.14	0.10	0.23	0.11	0.37	0.28	0.05	0.47	0.44	0.08	0.37	0.24	0.39	0.40	0.37	0.20	0.45	0.45	0.14	0.52	0.50	0.20	0.21	0.31	0.49	0.27
2	0.55	0.38	0.16	0.22	0.18	0.22	0.16	0.06	0.13	0.27	0.22	0.17	0.12	0.08	0.21	0.22	0.11	0.36	0.52	0.16	0.10	0.05	0.18	0.16	0.28	0.07	0.09	0.19	0.51	0.17	0.43		0.22
3	0.37	0.09	0.23	0.06	0.10	0.17	0.25	0.12	0.03	0.37	0.15	0.16	0.21	0.16	0.19	0.06	0.08	0.15	0.16	0.22	0.21	0.29	0.05	0.36	0.27	0.24	0.42	0.25	0.18	0.37	0.27	0.86	0.22
4	0.26	0.04	0.42	0.14	0.10	0.10	0.16	0.12	0.14	0.23	0.13	0.09	0.17	0.19	0.26	0.25	0.22	0.20	0.11	0.15	0.11	0.25	0.19	0.16	0.04	0.16	0.15	0.22	0.16	0.19	0.27		0.17
5	0.12	0.15	0.14	0.21	0.33	0.14	0.11	0.06	0.01	0.11	0.37	0.42	0.08	0.33	0.11	0.39	0.10	0.36	0.05	0.27	0.10	0.09	0.25	0.06	0.17	0.16	0.21	0.23	0.13	0.22	0.18	0.08	0.18
6	0.18	0.05	0.47	0.29	0.34	0.22	0.06	0.15	0.20	0.42	0.06	0.26	0.27	0.24	0.10	0.28	0.37	0.39	0.16	0.11	0.41	0.12	0.04	0.14	0.40	0.13	0.20	0.18	0.16	0.17	0.35		0.22
7	0.30	0.14	0.15	0.33	0.28	0.20	0.13	0.46	0.30	0.24	0.09	0.47	0.33	0.15	0.15	0.09	0.24	0.20	0.10	0.13	0.09	0.08	0.13	0.13	0.19	0.06	0.24	0.25	0.13	0.14	0.19	0.19	0.20
8	0.24	0.18	0.39	0.28	0.20	0.18	0.13	0.07	0.28	0.27	0.24	0.17	0.12	0.17	0.07	0.27	0.05	0.07	0.04	0.05	0.04	0.05	0.02	0.18	0.15	0.17	0.09	0.13	0.13	0.45	0.12		0.16
9	0.26	0.30	0.05	0.15	0.24	0.21	0.15	0.23	0.06	0.23	0.33	0.18	0.08	0.24	0.33	0.05	0.14	0.22	0.14	0.20	0.08	0.15	0.02	0.19	0.10	0.08	0.11	0.08	0.10	0.12	0.29	0.13	0.16
10	0.35	0.36	0.14	0.26	0.30	0.28	0.17	0.06	0.03	0.17	0.15	0.13	0.14	0.29	0.29	0.10	0.17	0.18	0.05	0.09	0.11	0.11	0.10	0.14	0.14	0.35	0.18	0.15	0.18	0.18	0.13		0.18
11	0.32	0.10	0.20	0.26	0.32	0.20	0.23	0.11	0.09	0.08	0.20	0.10	0.02	0.22	0.12	0.07	0.15	0.13	0.20	0.12	0.10	0.14	0.10	0.22	0.09	0.13	0.08	0.23	0.10	0.19	0.22	0.41	0.16
12	0.27	0.16	0.15	0.29	0.30	0.28	0.21	0.15	0.14	0.18	0.06	0.13	0.19	0.15	0.19	0.14	0.22	0.19	0.23	0.05	0.08	0.04	0.06	0.20	0.07	0.11	0.17	0.10	0.13	0.14	0.09		0.16
13	0.27	0.16	0.22	0.26	0.27	0.20	0.23	0.13	0.11	0.06	0.14	0.13	0.11	0.11	0.18	0.21	0.10	0.24	0.07	0.10	0.12	0.05	0.11	0.25	0.16	0.03	0.22	0.16	0.17	0.12	0.22	0.17	0.16
14	0.34	0.30	0.30	0.33	0.22	0.23	0.17	0.10	0.14	0.19	0.07	0.16	0.06	0.11	0.06	0.07	0.15	0.27	0.07	0.14	0.19	0.25	0.06	0.08	0.05	0.10	0.21	0.20	0.13	0.14	0.25		0.16
15	0.27	0.06	0.32	0.20	0.21	0.10	0.14	0.17	0.12	0.15	0.04	0.18	0.19	0.09	0.10	0.28	0.24	0.27	0.22	0.14	0.10	0.12	0.06	0.17	0.10	0.03	0.13	0.07	0.11	0.15	0.15	0.08	0.15
16	0.25	0.21	0.37	0.32	0.40	0.19	0.13	0.06	0.17	0.17	0.05	0.06	0.13	0.23	0.17	0.83	1.50	0.19	0.06	0.05	0.22	0.14	0.24	0.12	0.12	0.20	0.07	0.10	0.09	0.13	0.15		0.23
17	0.37	0.40	0.28	0.37	0.27	0.21	0.20	0.09	0.16	0.22	0.12	0.22	0.12	0.18	0.14	0.09	1.50	1.50	0.22	0.14	0.20	0.14	0.02	0.12	0.28	0.29	0.08	0.11	0.12	0.17	0.12	0.11	0.27
18	0.34	0.25	0.16	0.40	0.25	0.10	0.06	0.14	0.14	0.13	0.15	0.12	0.12	0.31	0.29	1.50	1.50	1.50	0.04	0.04	0.06	0.08	0.05	0.07	0.09	1.50	0.15	0.10	0.06	0.19	0.15		0.32
19	0.22	0.32	0.31	0.20	0.29	0.22	0.17	0.15	0.16	0.10	0.21	0.18	0.23	0.21	0.27	0.31	1.50	1.50	0.17	0.04	0.12	0.09	0.07	0.15	0.12	1.50	0.61	0.35	0.12	0.08	0.16	0.13	0.32
20	0.31	0.30	0.31	0.29	0.18	0.13	0.18	0.22	0.12	0.21	0.19	0.10	0.17	0.24	0.12	0.20	1.50	1.50	0.02	0.03	0.09	0.05	0.01	0.04	0.29	1.50	0.07	0.12	0.14	0.10	0.14		0.29
21	0.19	0.28	0.21	0.29	0.27	0.20	0.22	0.15	0.15	0.15	0.16	0.08	0.23	0.28	0.31	0.15	0.13	1.50	0.23	0.06	0.14	0.17	0.03	0.10	0.06	1.50	0.20	0.04	0.16	0.16	0.10	0.18	0.25
22	0.31	0.18	0.27	0.22	0.22	0.28	0.06	0.27	0.19	0.15	0.23	0.28	0.13	0.18	0.18	0.04	0.08	0.17	0.10	0.13	0.01	0.07	0.12	0.19	0.06	0.12	0.07	0.06	0.15	0.11	0.12		0.15
23	0.15	0.17	0.33	0.51	0.17	0.32	0.11	0.26	0.28	0.19	0.15	0.13	0.17	0.21	0.24	0.23	0.06	0.10	0.15	0.14	0.06	0.05	0.22	0.08	0.12	0.15	0.00	0.02	0.11	0.17	0.13	0.12	0.17

Figure G.8: *Displacements*

G.4 Configuration 2

Test: C2-10-50-2-0.25-0.03-10 (I651016)

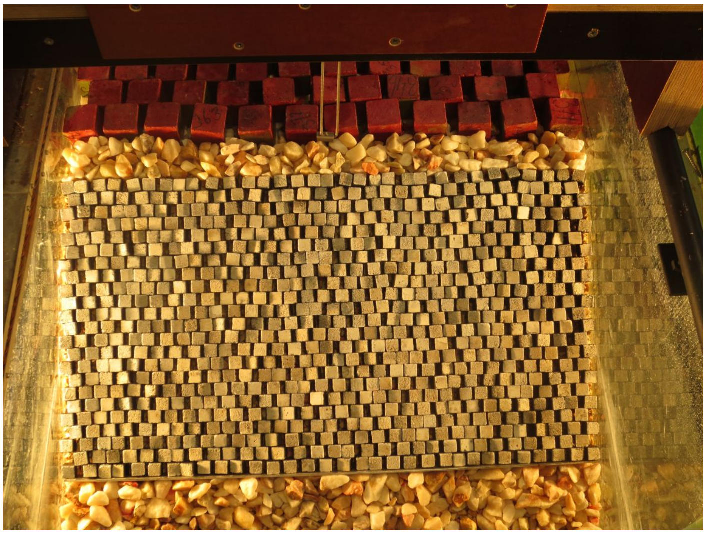

Figure G.9: Photo before the test

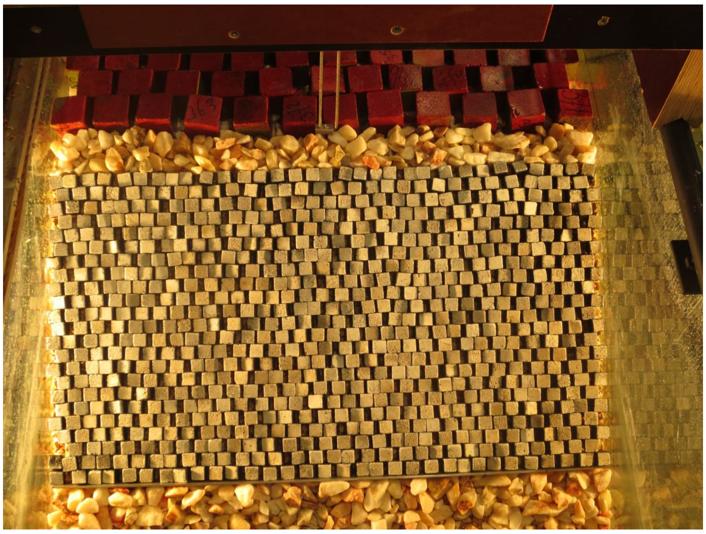

Figure G.10: Photo after the test

Test: C2-10-50-2-0.25-0.03-12 (I651218)

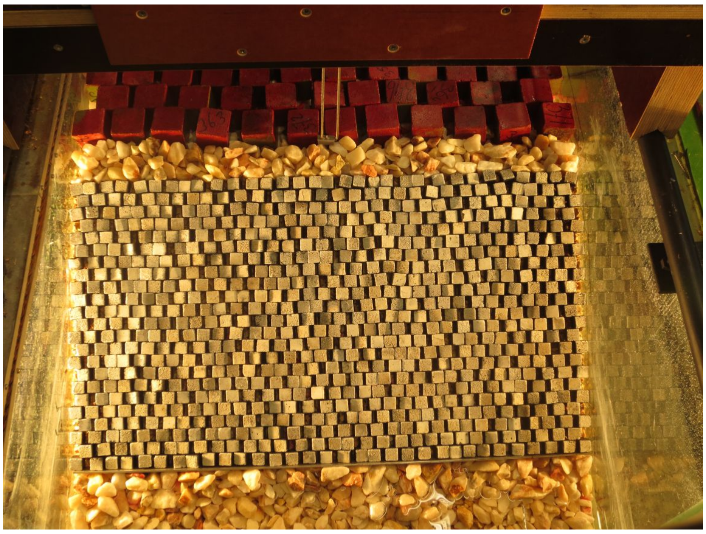

Figure G.11: *Photo before the test*

Figure G.12: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.11	0.06	0.13	0.07	0.07	0.08	0.06	0.03	0.08	0.03	0.11	0.03	0.02	0.07	0.10	0.04	0.05	0.02	0.07	0.05	0.10	0.04	0.05	0.10	0.09	0.03	0.04	0.01	0.10	0.07	0.06	0.07	0.06
2	0.06	0.09	0.04	0.03	0.07	0.04	0.04	0.05	0.14	0.10	0.03	0.10	0.10	0.07	0.05	0.01	0.01	0.04	0.10	0.06	0.09	0.09	0.03	0.06	0.02	0.12	0.05	0.15	0.07	0.07	0.14		0.07
3	0.12	0.13	0.06	0.04	0.02	0.06	0.14	0.12	0.06	0.05	0.11	0.08	0.11	0.08	0.06	0.11	0.07	0.03	0.02	0.04	0.01	0.06	0.13	0.08	0.04	0.09	0.21	0.03	0.06	0.02	0.04	0.04	0.07
4	0.03	0.05	0.07	0.05	0.07	0.03	0.03	0.05	0.03	0.05	0.27	0.09	0.11	0.20	0.06	0.06	0.02	0.05	0.04	0.02	0.01	0.04	0.03	0.05	0.02	0.10	0.17	0.17	0.02	0.08	0.13		0.07
5	0.07	0.05	0.06	0.03	0.04	0.07	0.07	0.04	0.00	0.09	0.05	0.01	0.07	0.05	0.10	0.13	0.01	0.03	0.04	0.05	0.06	0.07	0.03	0.10	0.09	0.10	0.22	0.07	0.10	0.02	0.06	0.11	0.06
6	0.11	0.02	0.03	0.08	0.03	0.05	0.02	0.05	0.05	0.04	0.02	0.10	0.05	0.04	0.13	0.06	0.01	0.07	0.03	0.04	0.10	0.03	0.12	0.09	0.11	0.15	0.06	0.04	0.11	0.12	0.04		0.06
7	0.09	0.11	0.06	0.05	0.01	0.07	0.11	0.07	0.07	0.06	0.09	0.05	0.10	0.10	0.06	0.05	0.09	0.02	0.03	0.03	0.04	0.01	0.04	0.03	0.05	0.13	0.14	0.09	0.10	0.02	0.09	0.06	0.07
8	0.06	0.04	0.09	0.04	0.05	0.09	0.05	0.04	0.07	0.03	0.05	0.04	0.06	0.06	0.08	0.05	0.03	0.03	0.03	0.05	0.04	0.01	0.03	0.05	0.05	0.15	0.07	0.09	0.09	0.06	0.06		0.06
9	0.08	0.04	0.04	0.06	0.05	0.02	0.10	0.01	0.09	0.02	0.10	0.03	0.02	0.11	0.05	0.04	0.05	0.06	0.02	0.02	0.08	0.06	0.05	0.10	0.09	0.03	0.12	0.06	0.11	0.01	0.04	0.07	0.06
10	0.01	0.11	0.09	0.05	0.01	0.09	0.05	0.01	0.04	0.07	0.09	0.04	0.13	0.08	0.01	0.03	0.03	0.06	0.02	0.11	0.07	0.03	0.06	0.05	0.03	0.15	0.09	0.07	0.06	0.03	0.05		0.06
11	0.01	0.07	0.02	0.02	0.07	0.03	0.07	0.05	0.14	0.02	0.05	0.08	0.05	0.12	0.07	0.02	0.03	0.06	0.08	0.07	0.04	0.12	0.06	0.07	0.01	0.02	0.06	0.02	0.04	0.05	0.04	0.11	0.05
12	0.07	0.03	0.03	0.05	0.04	0.06	0.03	0.07	0.03	0.10	0.04	0.04	0.22	0.05	0.02	0.08	0.07	0.04	0.06	0.05	0.05	0.16	0.06	0.02	0.08	0.06	0.06	0.05	0.04	0.04	0.05		0.06
13	0.13	0.09	0.01	0.06	0.09	0.06	0.06	0.04	0.07	0.12	0.06	0.02	0.03	0.11	0.32	0.01	0.07	0.03	0.01	0.03	0.06	0.07	0.08	0.12	0.05	0.07	0.05	0.08	0.04	0.05	0.07	0.07	0.07
14	0.04	0.08	0.02	0.04	0.07	0.06	0.01	0.09	0.04	0.03	0.04	0.10	0.04	0.03	0.04	0.06	0.09	0.07	0.08	0.05	0.04	0.01	0.05	0.05	0.08	0.08	0.09	0.09	0.09	0.03	0.04		0.06
15	0.03	0.03	0.02	0.04	0.03	0.06	0.04	0.06	0.03	0.05	0.07	0.08	0.07	0.04	0.06	0.02	0.03	0.06	0.07	0.05	0.09	0.08	0.06	0.06	0.09	0.03	0.06	0.04	0.02	0.05	0.03	0.08	0.05
16	0.06	0.05	0.06	0.03	0.03	0.06	0.02	0.06	0.06	0.08	0.06	0.04	0.08	0.10	0.02	0.04	0.02	0.08	0.13	0.05	0.06	0.08	0.07	0.07	0.04	0.09	0.06	0.05	0.08	0.03	0.04		0.06
17	0.12	0.05	0.02	0.02	0.06	0.02	0.04	0.15	0.08	0.12	0.08	0.04	0.13	0.06	0.11	0.07	0.10	0.01	0.02	0.03	0.07	0.01	0.13	0.04	0.06	0.08	0.10	0.12	0.07	0.05	0.06	0.03	0.07
18	0.10	0.02	0.02	0.02	0.06	0.03	0.04	0.04	0.04	0.05	0.05	0.02	0.07	0.04	0.06	0.08	0.02	0.06	0.07	0.13	0.11	0.05	0.07	0.10	0.08	0.03	0.05	0.05	0.06	0.03	0.09		0.06
19	0.09	0.06	0.08	0.06	0.08	0.07	0.04	0.12	0.05	0.09	0.10	0.02	0.07	0.02	0.03	0.08	0.06	0.05	0.07	0.04	0.09	0.09	0.03	0.07	0.01	0.04	0.11	0.10	0.10	0.09	0.05	0.10	0.07
20	0.11	0.13	0.09	0.10	0.06	0.07	0.03	0.09	0.07	0.03	0.03	0.10	0.04	0.07	0.01	0.15	0.05	0.08	0.04	0.09	0.10	0.09	0.07	0.11	0.07	0.13	0.06	0.06	0.10	0.01	0.10		0.08
21	0.02	0.05	0.08	0.03	0.03	0.07	0.03	0.04	0.01	0.01	0.02	0.06	0.04	0.05	0.03	0.04	0.05	0.15	0.04	0.03	0.02	0.03	0.07	0.02	0.04	0.03	0.05	0.02	0.11	0.01	0.03	0.07	0.04
22	0.07	0.04	0.10	0.08	0.07	0.06	0.02	0.07	0.08	0.06	0.06	0.05	0.06	0.10	0.08	0.04	0.04	0.08	0.03	0.03	0.05	0.07	0.11	0.02	0.05	0.10	0.04	0.10	0.06	0.04	0.04		0.06
23	0.13	0.08	0.04	0.02	0.09	0.02	0.05	0.10	0.04	0.04	0.05	0.08	0.04	0.05	0.06	0.03	0.06	0.05	0.07	0.07	0.03	0.05	0.06	0.06	0.11	0.04	0.01	0.04	0.03	0.05	0.02	0.01	0.05

Figure G.13: *Displacements*

Test: C2-10-50-2-0.25-0.03-14 (I651421)

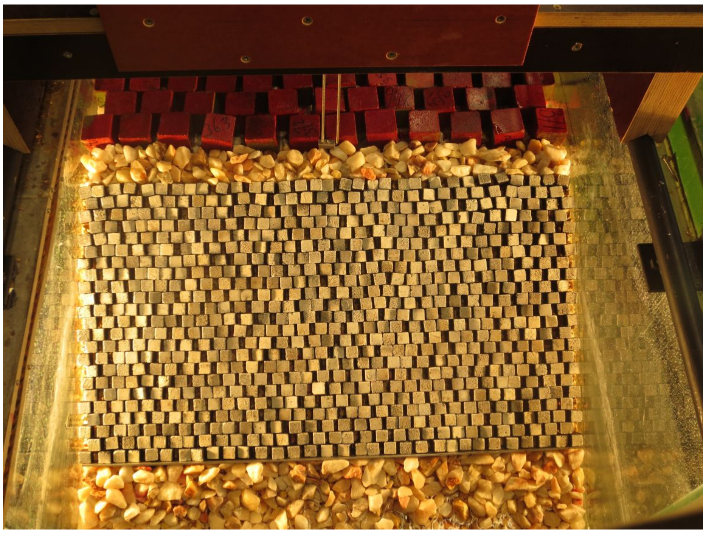

Figure G.14: *Photo before the test*

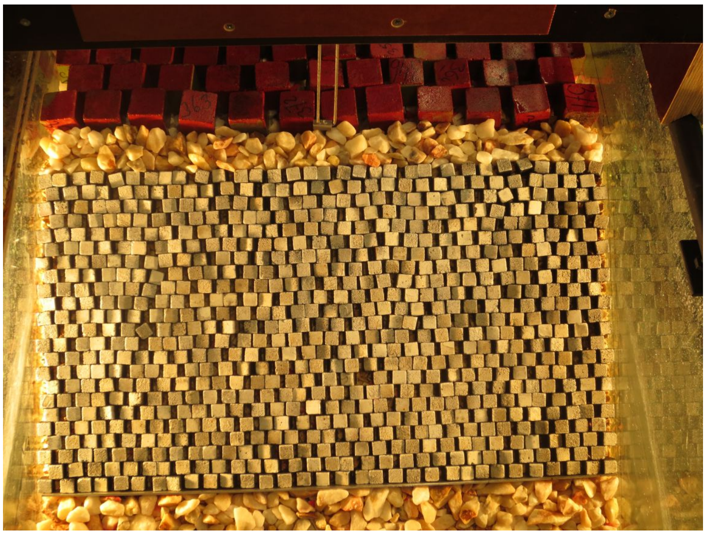

Figure G.15: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.17	0.06	0.09	0.05	0.28	0.04	0.07	0.07	0.07	0.10	0.12	0.20	0.08	0.16	0.07	0.05	0.12	0.13	0.09	0.02	0.09	0.07	0.03	0.07	0.05	0.07	0.06	0.09	0.13	0.03	0.10	0.04	0.09
2	0.10	0.06	0.10	0.09	0.04	0.05	0.03	0.06	0.00	0.06	0.06	0.06	0.05	0.10	0.15	0.08	0.07	0.10	0.01	0.03	0.06	0.03	0.09	0.05	0.04	0.06	0.22	0.04	0.07	0.06	0.10		0.07
3	0.12	0.05	0.05	0.06	0.04	0.11	0.06	0.07	0.08	0.09	0.03	0.13	0.06	0.10	0.16	0.10	0.10	0.05	0.04	0.04	0.07	0.05	0.05	0.02	0.04	0.03	0.26	0.09	0.09	0.13	0.06	0.02	0.08
4	0.02	0.08	0.05	0.10	0.13	0.06	0.05	0.04	0.15	0.04	0.06	0.06	0.06	0.19	0.06	0.03	0.09	0.06	0.08	0.05	0.03	0.04	0.03	0.11	0.09	0.18	0.07	0.02	0.02	0.03	0.10		0.07
5	0.09	0.03	0.08	0.01	0.04	0.15	0.08	0.10	0.06	0.11	0.05	0.02	0.01	0.11	0.23	0.02	0.02	0.02	0.07	0.09	0.00	0.02	0.07	0.11	0.01	0.07	0.01	0.08	0.01	0.06	0.05	0.15	0.06
6	0.03	0.08	0.03	0.15	0.09	0.08	0.08	0.03	0.19	0.06	0.09	0.01	0.11	0.10	0.03	0.06	0.16	0.05	0.01	0.02	0.07	0.05	0.07	0.08	0.10	0.07	0.14	0.04	0.09	0.06	0.04		0.07
7	0.15	0.04	0.03	0.05	0.04	0.03	0.26	0.16	0.13	0.08	0.10	0.18	0.08	0.04	0.05	0.05	0.12	0.02	0.08	0.03	0.04	0.06	0.07	0.07	0.05	0.02	0.16	0.05	0.04	0.05	0.08	0.03	0.08
8	0.05	0.04	0.06	0.05	0.03	0.15	0.35	0.09	0.08	0.05	0.06	0.07	0.14	0.03	0.03	0.08	0.07	0.03	0.03	0.02	0.02	0.06	0.03	0.04	0.05	0.04	0.01	0.02	0.06	0.11	0.03		0.06
9	0.09	0.02	0.12	0.07	0.03	0.05	0.18	0.12	0.11	0.04	0.03	0.07	0.06	0.02	0.03	0.02	0.05	0.05	0.07	0.02	0.01	0.08	0.06	0.03	0.06	0.09	0.07	0.06	0.05	0.04	0.03	0.06	0.06
10	0.02	0.07	0.11	0.08	0.01	0.10	0.15	0.15	0.03	0.10	0.07	0.06	0.13	0.08	0.08	0.06	0.08	0.07	0.08	0.16	0.07	0.09	0.05	0.08	0.04	0.02	0.01	0.06	0.11	0.02	0.18		0.08
11	0.12	0.07	0.07	0.02	0.08	0.03	0.25	0.03	0.22	0.15	0.04	0.04	0.12	0.01	0.03	0.05	0.07	0.02	0.04	0.04	0.08	0.12	0.02	0.04	0.04	0.08	0.03	0.07	0.07	0.09	0.01	0.04	0.07
12	0.13	0.08	0.11	0.04	0.03	0.44	0.08	0.13	0.04	0.06	0.10	0.07	0.07	0.05	0.08	0.11	0.06	0.12	0.09	0.11	0.14	0.04	0.09	0.08	0.07	0.08	0.01	0.09	0.08	0.03	0.05		0.09
13	0.07	0.01	0.12	0.07	0.03	0.15	0.30	0.01	0.08	0.03	0.15	0.05	0.02	0.02	0.04	0.02	0.06	0.17	0.01	0.07	0.12	0.03	0.02	0.08	0.05	0.05	0.02	0.09	0.01	0.03	0.07	0.04	0.07
14	0.04	0.03	0.08	0.05	0.08	0.07	0.12	0.03	0.05	0.13	0.07	0.09	0.04	0.02	0.03	0.03	0.07	0.06	0.05	0.05	0.01	0.08	0.02	0.08	0.04	0.07	0.01	0.05	0.08	0.10	0.02		0.06
15	0.05	0.05	0.09	0.08	0.06	0.04	0.02	0.03	0.06	0.15	0.04	0.04	0.04	0.04	0.01	0.07	0.04	0.07	0.04	0.07	0.09	0.03	0.11	0.05	0.03	0.07	0.01	0.04	0.02	0.07	0.04	0.05	0.05
16	0.02	0.09	0.11	0.06	0.09	0.04	0.06	0.05	0.05	0.02	0.08	0.03	0.09	0.03	0.10	0.07	0.06	1.50	0.08	0.09	0.01	0.04	0.02	0.10	0.03	0.02	0.06	0.04	0.01	0.03	0.03		0.10
17	0.05	0.09	0.07	0.05	0.13	0.04	0.02	0.08	0.02	0.05	0.09	0.07	0.03	0.01	0.01	0.09	0.08	0.03	0.08	0.04	0.08	0.06	0.03	0.05	0.11	0.05	0.02	0.04	0.08	0.02	0.03	0.04	0.05
18	0.13	0.06	0.04	0.01	0.08	0.05	0.10	0.06	0.05	0.05	0.04	0.02	0.15	0.02	0.03	0.09	0.12	0.07	0.10	0.08	0.02	0.04	0.04	0.03	0.11	0.07	0.01	0.06	0.02	0.06	0.04		0.06
19	0.04	0.06	0.06	0.07	0.12	0.06	0.04	0.01	0.12	0.05	0.02	0.07	0.07	0.05	0.05	0.02	0.05	0.11	0.07	0.04	0.04	0.01	0.08	0.02	0.04	0.09	0.06	0.20	0.06	0.03	0.05	0.08	0.06
20	0.06	0.04	0.03	0.07	0.06	0.06	0.09	0.04	0.01	0.06	0.01	0.03	0.07	0.06	0.06	0.02	0.05	0.05	0.03	0.09	0.06	0.06	0.05	0.07	0.05	0.04	0.03	0.09	0.02	0.04	0.08		0.05
21	0.05	0.14	0.08	0.04	0.02	0.03	0.09	0.07	0.05	0.06	0.04	0.13	0.10	0.02	0.05	0.11	0.05	0.04	0.07	0.06	0.07	0.06	0.03	0.06	0.05	0.04	0.13	0.07	0.02	0.03	0.04	0.03	0.06
22	0.11	0.07	0.08	0.02	0.05	0.04	0.06	0.08	0.03	0.06	0.07	0.03	0.12	0.07	0.06	0.07	0.09	0.07	0.06	0.05	0.10	0.07	0.05	0.03	0.01	0.05	0.11	0.07	0.10	0.03	0.06		0.06
23	0.04	0.02	0.02	0.09	0.04	0.08	0.13	0.02	0.02	0.04	0.02	0.14	0.08	0.05	0.07	0.06	0.02	0.06	0.14	0.04	0.05	0.09	0.06	0.09	0.06	0.06	0.10	0.08	0.09	0.01	0.12	0.03	0.06

Figure G.16: *Displacements*

Test: C2-10-50-2-0.25-0.03-16 (I651623)

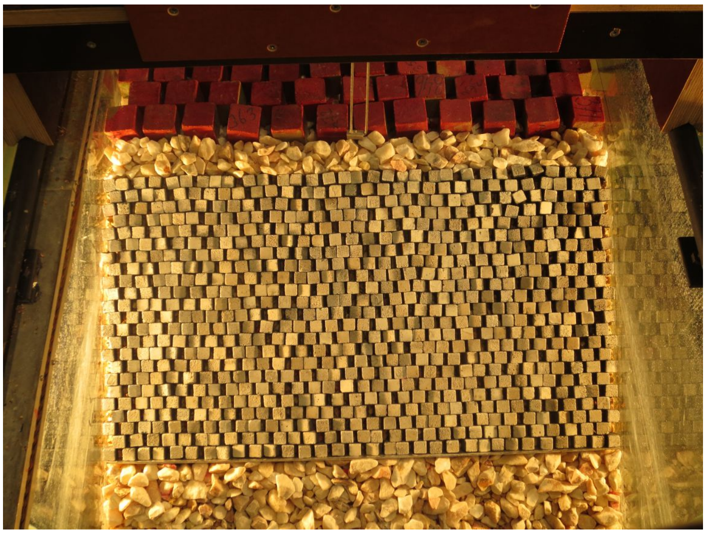

Figure G.17: *Photo before the test*

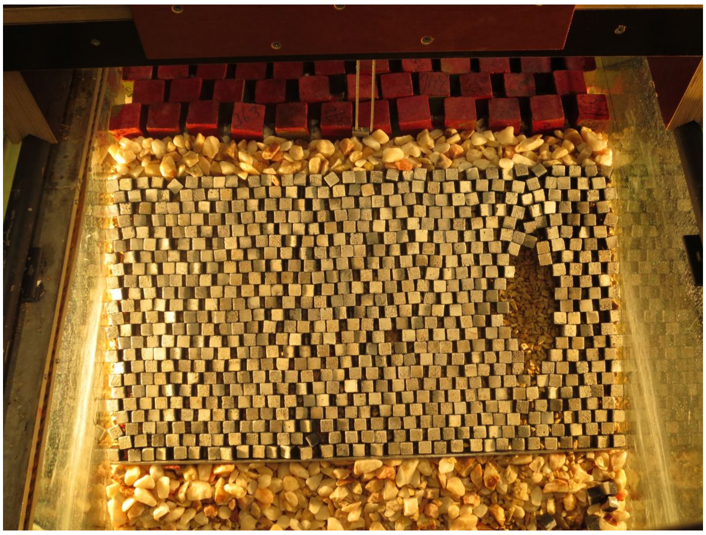

Figure G.18: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.17	0.09	0.18	0.13	0.76	0.27	0.17	0.17	0.05	0.14	0.18	0.17	0.13	0.18	0.48	0.13	0.05	0.18	0.15	0.13	0.28	0.09	0.15	0.08	0.14	0.23	0.07	0.36	0.22	0.08	0.17	0.17	0.19
2	0.09	0.17	0.02	0.02	0.15	0.21	0.11	0.27	0.12	0.26	0.12	0.07	0.09	0.10	0.16	0.03	0.46	0.07	0.07	0.07	0.06	0.09	0.02	0.14	0.12	0.31	0.17	0.02	0.08	0.05	0.02		0.12
3	0.08	0.21	0.14	0.05	0.21	0.06	0.23	0.11	0.11	0.10	0.06	0.09	0.18	0.06	0.15	0.03	0.07	0.07	0.09	0.03	0.07	0.06	0.15	0.04	0.10	0.12	0.44	0.24	0.07	0.08	0.11	0.13	0.12
4	0.02	0.05	0.07	0.16	0.22	0.16	0.15	0.10	0.06	0.06	0.06	0.08	0.03	0.06	0.03	0.07	0.09	0.03	0.11	0.03	0.07	0.11	0.09	0.14	0.04	0.23	0.20	0.16	0.10	0.10	0.05		0.09
5	0.10	0.18	0.05	0.11	0.16	0.13	0.15	0.08	0.06	0.06	0.02	0.08	0.10	0.20	0.03	0.03	0.07	0.07	0.09	0.03	0.07	0.03	0.04	0.07	0.08	0.22	0.69	0.17	0.04	0.11	0.08	0.17	0.11
6	0.05	0.02	0.02	0.05	0.11	0.17	0.11	0.06	0.06	0.07	0.06	0.14	0.06	0.07	0.11	0.10	0.12	0.07	0.13	0.11	0.11	0.03	0.17	0.11	0.02	0.28	0.61	0.02	0.12	0.04	0.09		0.11
7	0.10	0.18	0.11	0.15	0.06	0.23	0.06	0.15	0.06	0.08	0.07	0.10	0.23	0.03	0.16	0.16	0.07	0.11	0.06	0.02	0.06	0.10	0.03	0.10	0.04	0.56	1.50	0.22	0.13	0.13	0.05	0.07	0.16
8	0.14	0.10	0.11	0.22	0.07	0.15	0.07	0.13	0.02	0.08	0.10	0.02	0.07	0.12	0.16	0.07	0.03	0.11	0.06	0.09	0.10	0.09	0.16	0.16	0.05	1.50	1.50	0.40	0.13	0.05	0.05		0.20
9	0.06	0.02	0.05	0.05	0.13	0.11	0.14	0.06	0.10	0.11	0.11	0.15	0.09	0.02	0.03	0.06	0.09	0.03	0.04	0.09	0.02	0.06	0.13	0.03	0.04	0.34	1.50	1.50	0.08	0.05	0.12	0.06	0.17
10	0.07	0.05	0.14	0.10	0.14	0.04	0.14	0.08	0.09	0.06	0.03	0.02	0.11	0.02	0.07	0.03	0.07	0.13	0.07	0.03	0.09	0.11	0.08	0.10	0.08	1.50	1.50	1.50	0.02	0.12	0.11		0.22
11	0.14	0.09	0.15	0.11	0.07	0.11	0.09	0.14	0.12	0.03	0.15	0.10	0.11	0.03	0.06	0.04	0.03	0.07	0.07	0.04	0.07	0.16	0.04	0.03	0.04	1.50	1.50	1.50	0.10	0.08	0.07	0.08	0.22
12	0.27	0.09	0.11	0.05	0.05	0.09	0.41	0.08	0.08	0.11	0.07	0.06	0.06	0.10	0.15	0.07	0.11	0.12	0.12	0.16	0.19	0.24	0.06	0.08	0.08	1.50	1.50	1.50	0.17	0.05	0.07		0.25
13	0.29	0.05	0.09	0.10	0.07	0.09	0.13	0.13	0.05	0.06	0.14	0.10	0.08	0.10	0.33	0.07	0.02	0.07	0.11	0.10	0.09	0.12	0.06	0.07	0.12	1.50	1.50	1.50	0.04	0.05	0.05	0.11	0.23
14	0.29	0.09	0.05	0.05	0.07	0.10	0.10	0.01	0.07	0.06	0.11	0.09	0.11	0.07	0.06	0.15	0.02	1.50	0.19	0.16	0.09	0.02	0.06	0.03	0.09	1.50	1.50	1.50	0.21	0.01	0.13		0.27
15	0.09	0.13	0.06	0.09	0.07	0.07	0.14	0.03	0.07	0.02	0.06	0.06	0.10	0.04	0.04	0.06	0.02	0.04	0.07	0.11	0.06	0.07	0.04	0.03	0.06	0.08	1.50	1.50	0.13	0.03	0.05	0.07	0.16
16	0.04	0.20	0.16	0.04	0.04	0.06	0.03	0.15	0.20	0.07	0.07	0.11	0.11	0.08	0.18	0.13	0.05	0.05	0.13	0.04	0.11	0.04	0.11	0.06	0.06	0.20	1.50	0.02	0.24	0.12	0.22		0.15
17	0.13	0.12	0.08	0.15	0.06	0.03	0.10	0.01	0.14	0.12	0.04	0.11	0.27	0.03	0.07	0.03	0.03	0.03	0.09	0.04	0.07	0.13	0.12	0.16	0.12	0.24	1.50	0.16	0.08	0.32	0.14	0.18	0.15
18	0.08	0.13	0.11	0.16	0.12	0.12	0.13	0.13	0.04	0.02	0.11	0.10	0.06	0.03	0.04	0.12	0.03	0.02	0.07	0.11	0.12	0.02	0.07	0.09	0.11	0.08	0.27	0.20	0.10	0.12	0.13		0.10
19	0.16	0.08	0.08	0.12	0.08	0.08	0.04	0.15	0.07	0.08	0.07	0.16	0.07	0.04	0.05	0.08	0.12	0.03	0.08	0.03	0.10	0.06	0.06	0.12	0.03	0.24	0.13	0.45	0.12	0.16	0.13	0.10	0.11
20	0.14	0.12	0.11	0.08	0.04	0.12	0.04	0.07	0.12	0.07	0.18	0.01	0.12	0.08	0.05	0.05	0.09	0.03	0.05	0.03	0.15	0.07	0.13	0.07	0.27	0.21	0.20	0.03	0.08	0.08	0.14		0.10
21	0.59	0.15	0.04	0.06	0.22	0.08	0.07	0.07	0.12	0.21	0.14	0.20	0.25	0.12	0.03	0.05	0.06	0.12	0.05	0.07	0.06	0.07	0.04	0.10	0.11	0.14	0.15	0.04	0.12	0.13	0.17	0.10	0.12
22	0.06	0.04	0.04	0.14	0.12	0.17	0.15	0.06	0.14	0.11	0.10	0.18	1.50	0.05	0.04	0.12	0.04	0.08	0.06	0.05	0.08	0.12	0.10	0.04	0.02	0.08	0.06	0.08	0.11	0.05	0.06		0.11
23	0.08	0.24	0.15	0.16	0.16	0.14	0.12	0.16	0.10	0.10	0.25	0.52	0.31	0.14	0.04	0.13	0.06	0.07	0.06	0.09	0.17	0.08	0.02	0.15	0.05	0.15	0.08	0.06	0.05	0.08	0.17	0.15	0.13

Figure G.19: *Displacements*

G.5 Configuration 3

Test: C3-5-50-2-0.25-0.03-8 (I700814)

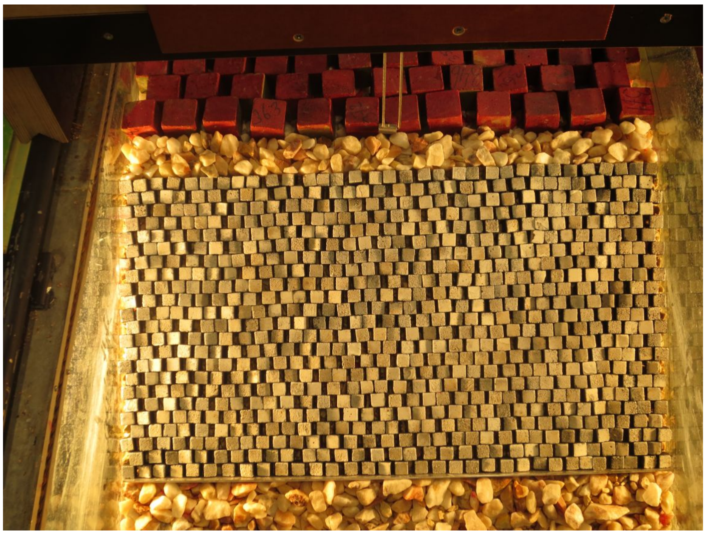

Figure G.20: *Photo before the test*

Figure G.21: *Photo after the test*

Test: C3-5-50-2-0.25-0.03-10 (I701016)

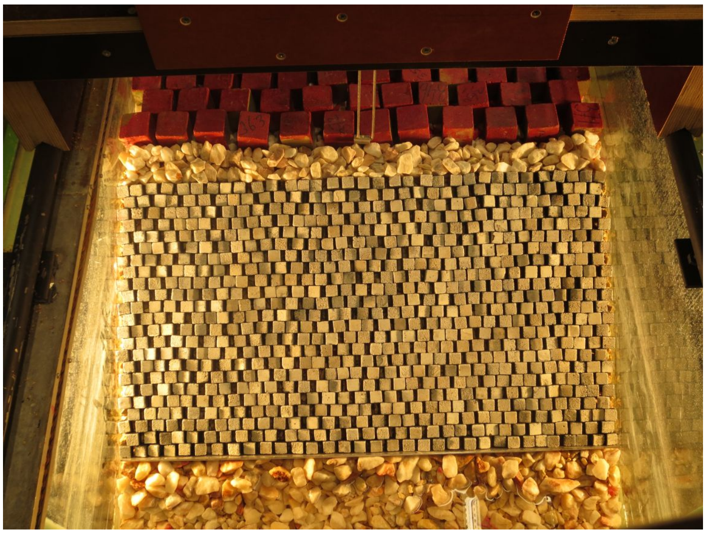

Figure G.22: *Photo before the test*

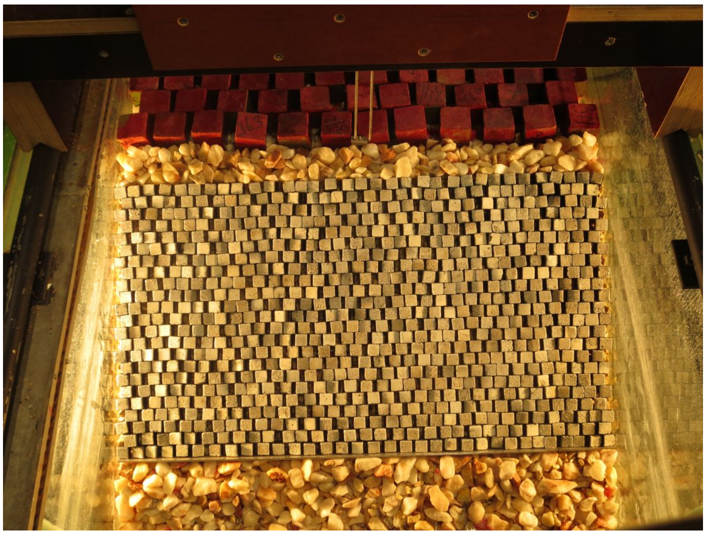

Figure G.23: *Photo after the test*

Test: C3-5-50-2-0.25-0.03-12 (I701218)

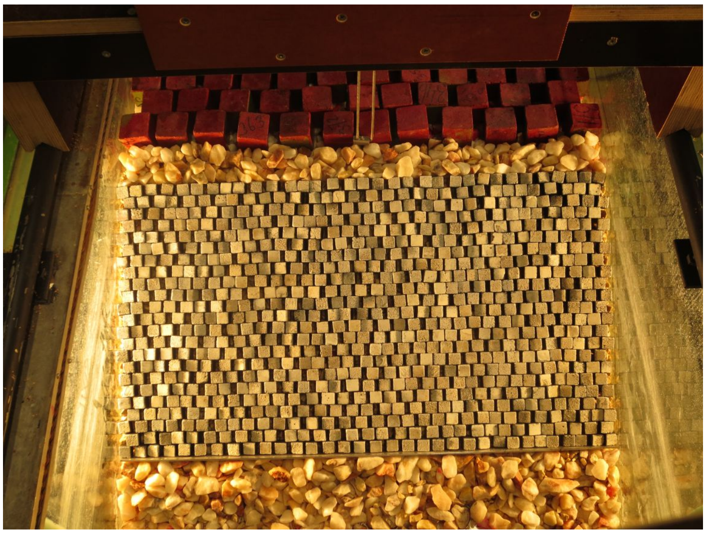

Figure G.24: *Photo before the test*

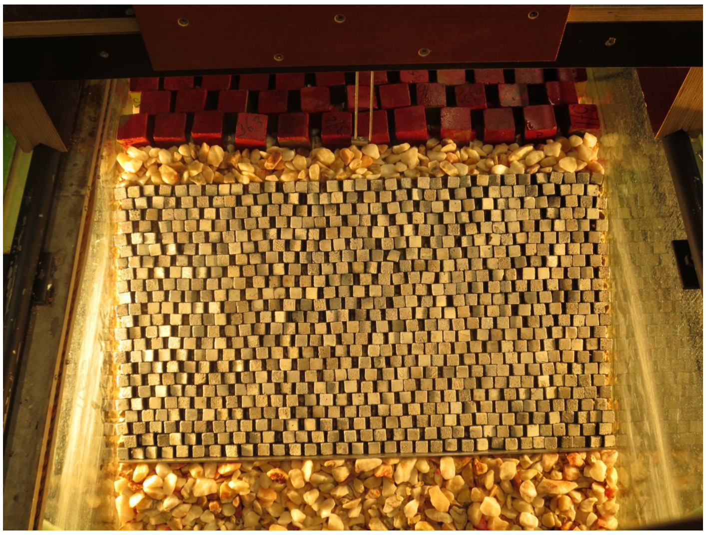

Figure G.25: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.05	0.09	0.09	0.09	0.14	0.18	0.18	0.15	0.18	0.18	0.09	0.14	0.17	0.16	0.20	0.24	0.22	0.22	0.19	0.20	0.14	0.09	0.14	0.17	0.18	0.02	0.22	0.10	0.15	0.24	0.19	0.22	0.16
2	0.10	0.09	0.18	0.14	0.10	0.13	0.20	0.15	0.14	0.05	0.15	0.06	0.14	0.16	0.05	0.14	0.10	0.13	0.20	0.14	0.14	0.20	0.21	0.14	0.14	0.14	0.14	0.09	0.12	0.09	0.09		0.13
3	0.14	0.04	0.16	0.06	0.03	0.09	0.13	0.11	0.09	0.13	0.13	0.09	0.12	0.05	0.13	0.12	0.18	0.13	0.14	0.05	0.14	0.09	0.14	0.09	0.09	0.11	0.19	0.19	0.18	0.20	0.18	0.05	0.12
4	0.10	0.06	0.28	0.16	0.16	0.14	0.11	0.09	0.09	0.17	0.11	0.05	0.05	0.09	0.04	0.09	0.26	0.16	0.09	0.09	0.14	0.10	0.14	0.22	0.09	0.11	0.18	0.15	0.19	0.06	0.15		0.13
5	0.17	0.09	0.10	0.04	0.15	0.13	0.14	0.09	0.12	0.09	0.11	0.17	0.09	0.19	0.10	0.08	0.14	0.18	0.14	0.16	0.10	0.14	0.22	0.11	0.11	0.17	0.09	0.13	0.09	0.13	0.09	0.14	0.12
6	0.09	0.12	0.16	0.13	0.13	0.09	0.13	0.17	0.11	0.09	0.11	0.09	0.19	0.15	0.09	0.15	0.15	0.09	0.14	0.10	0.11	0.16	0.14	0.04	0.20	0.14	0.23	0.08	0.09	0.12	0.08		0.12
7	0.23	0.10	0.09	0.01	0.08	0.14	0.07	0.10	0.10	0.12	0.11	0.14	0.22	0.21	0.05	0.12	0.13	0.13	0.24	0.12	0.16	0.15	0.04	0.11	0.14	0.08	0.12	0.08	0.13	0.09	0.11	0.06	0.12
8	0.09	0.11	0.08	0.13	0.12	0.08	0.16	0.18	0.12	0.13	0.04	0.17	0.21	0.21	0.13	0.19	0.12	0.18	0.08	0.09	0.13	0.08	0.08	0.08	0.12	0.14	0.11	0.09	0.06	0.12	0.15		0.12
9	0.12	0.11	0.04	0.06	0.03	0.08	0.12	0.07	0.08	0.08	0.12	0.07	0.05	0.09	0.04	0.11	0.13	0.15	0.11	0.05	0.06	0.18	0.11	0.07	0.08	0.10	0.23	0.12	0.18	0.11	0.11	0.09	0.10
10	0.15	0.09	0.09	0.09	0.03	0.07	0.10	0.16	0.08	0.16	0.02	0.08	0.11	0.13	0.06	0.09	0.03	0.22	0.13	0.15	0.15	0.08	0.08	0.11	0.04	0.16	0.10	0.12	0.08	0.08	0.17		0.10
11	0.11	0.08	0.09	0.07	0.11	0.09	0.13	0.12	0.07	0.17	0.08	0.08	0.09	0.07	0.12	0.03	0.05	0.09	0.08	0.07	0.07	0.06	0.12	0.08	0.07	0.10	0.17	0.10	0.03	0.16	0.12	0.12	0.09
12	0.22	0.14	0.12	0.08	0.11	0.07	0.13	0.11	0.10	0.09	0.12	0.11	0.12	0.07	0.03	0.12	0.16	0.07	0.09	0.11	0.08	0.16	0.13	0.16	0.03	0.38	0.21	0.14	0.17	0.05	0.14		0.12
13	0.16	0.08	0.12	0.10	0.07	0.07	0.11	0.09	0.09	0.03	0.04	0.10	0.07	0.11	0.11	0.17	0.08	0.11	0.11	0.15	0.12	0.03	0.09	0.07	0.09	0.17	0.12	0.10	0.14	0.10	0.08	0.14	0.10
14	0.06	0.16	0.05	0.07	0.06	0.06	0.07	0.11	0.11	0.12	0.09	0.04	0.13	0.02	0.09	0.05	0.07	0.08	0.11	0.12	0.09	0.03	0.03	0.09	0.13	0.11	0.07	0.10	0.12	0.12	0.14		0.09
15	0.06	0.02	0.11	0.07	0.08	0.10	0.06	0.11	0.12	0.11	0.11	0.11	0.12	0.06	0.07	0.11	0.14	0.06	0.18	0.11	0.21	0.11	0.11	0.11	0.07	0.11	0.13	0.12	0.11	0.13	0.04	0.17	0.11
16	0.07	0.04	0.16	0.07	0.06	0.13	0.06	0.09	0.06	0.06	0.06	0.10	0.13	0.08	0.10	0.09	0.17	0.14	0.17	0.11	0.12	0.15	0.13	0.11	0.11	0.11	0.10	0.13	0.11	0.10	0.07		0.10
17	0.10	0.02	0.11	0.19	0.15	0.08	0.02	0.04	0.09	0.11	0.16	0.03	0.06	0.10	0.04	0.13	0.15	0.10	0.08	0.12	0.15	0.15	0.09	0.12	0.15	0.09	0.07	0.15	0.07	0.13	0.11	0.07	0.10
18	0.13	0.10	0.06	0.07	0.09	0.12	0.06	0.10	0.06	0.06	0.06	0.08	0.05	0.07	0.07	0.07	0.09	0.02	0.10	0.06	0.06	0.06	0.10	0.07	0.09	0.12	0.06	0.12	0.07	0.10	0.08		0.08
19	0.14	0.16	0.10	0.10	0.12	0.10	0.14	0.01	0.06	0.01	0.10	0.10	0.05	0.05	0.05	0.10	0.11	0.14	0.09	0.11	0.11	0.15	0.12	0.16	0.11	0.07	0.14	0.05	0.14	0.14	0.14	0.10	0.10
20	0.12	0.06	0.10	0.16	0.13	0.01	0.07	0.09	0.15	0.14	0.14	0.05	0.05	0.08	0.09	0.09	0.02	0.05	0.10	0.14	0.09	0.09	0.06	0.09	0.09	0.14	0.10	0.09	0.05	0.09	0.05		0.09
21	0.10	0.09	0.12	0.19	0.15	0.09	0.06	0.08	0.01	0.17	0.15	0.14	0.09	0.15	0.09	0.18	0.14	0.11	0.17	0.09	0.09	0.11	0.05	0.11	0.06	0.05	0.10	0.09	0.09	0.16	0.13	0.05	0.11
22	0.06	0.12	0.18	0.09	0.05	0.06	0.06	0.05	0.03	0.13	0.14	0.11	0.11	0.05	0.09	0.11	0.11	0.11	0.18	0.09	0.05	0.05	0.06	0.05	0.09	0.05	0.05	0.10	0.09	0.06	0.04		0.09
23	0.00	0.04	0.14	0.10	0.04	0.10	0.15	0.07	0.13	0.19	0.09	0.09	0.11	0.08	0.13	0.15	0.11	0.09	0.14	0.05	0.18	0.01	0.09	0.22	0.13	0.09	0.14	0.10	0.10	0.14	0.18	0.22	0.11

Figure G.26: *Displacements*

Test: C3-5-50-2-0.25-0.03-14 (I701420)

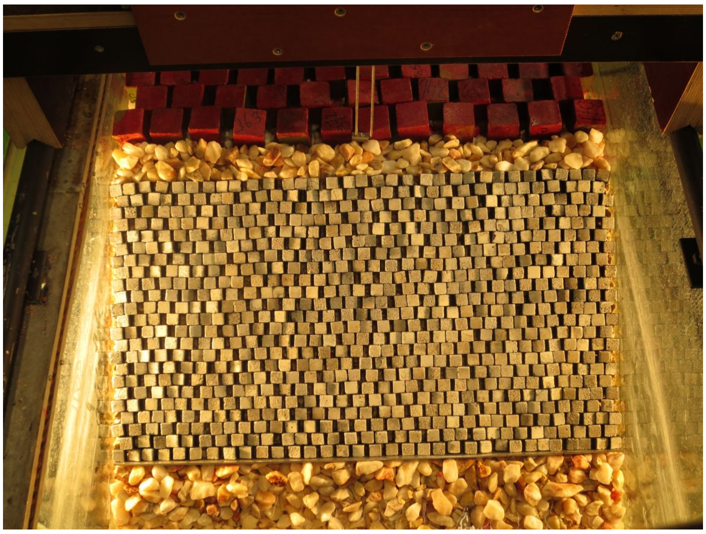

Figure G.27: Photo before the test

Figure G.28: Photo after the test

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.10	0.16	0.19	0.15	0.09	0.13	0.10	0.04	0.13	0.09	0.04	0.03	0.11	0.06	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.19	0.11	0.12	0.07	0.03	0.03	0.02	0.17	0.07	0.19	0.45
2	0.04	0.02	0.04	0.03	0.05	0.09	0.06	0.10	0.01	0.07	0.06	0.04	0.08	0.16	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.14	0.06	0.06	0.10	0.03	0.07	0.07	0.05	0.05		0.43
3	0.07	0.08	0.07	0.06	0.09	0.09	0.16	0.10	0.07	0.05	0.01	0.02	0.03	0.07	0.15	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.06	0.01	0.12	0.08	0.06	0.04	0.09	0.13	0.09	0.02	0.39
4	0.04	0.17	0.34	0.20	0.14	0.07	0.11	0.05	0.03	0.09	0.17	0.06	0.08	0.03	0.06	1.50	1.50	1.50	1.50	1.50	1.50	0.16	0.07	0.03	0.05	0.07	0.10	0.08	0.09	0.03	0.11		0.37
5	0.10	0.05	0.08	0.04	0.05	0.05	0.12	0.10	0.08	0.08	0.13	0.06	0.05	0.04	0.11	1.50	1.50	1.50	1.50	1.50	1.50	0.06	0.11	0.15	0.06	0.10	0.10	0.05	0.07	0.06	0.11	0.04	0.34
6	0.07	0.02	0.15	0.03	0.08	0.05	0.04	0.03	0.04	0.09	0.08	0.02	0.12	0.04	0.09	1.50	1.50	1.50	1.50	1.50	0.07	0.08	0.71	0.02	0.06	0.05	0.05	0.05	0.02	0.10	0.06		0.31
7	0.06	0.18	0.07	0.10	0.07	0.06	0.08	0.04	0.06	0.04	0.11	0.08	0.10	0.17	0.13	1.50	1.50	1.50	1.50	1.50	0.24	0.10	0.15	0.07	0.02	0.06	0.07	0.18	0.09	0.06	0.03	0.11	0.31
8	0.08	0.09	0.17	0.13	0.02	0.06	0.10	0.11	0.10	0.05	0.09	0.05	0.13	0.09	0.09	0.84	1.50	1.50	1.50	0.09	0.18	0.11	0.14	0.09	0.10	0.09	0.22	0.09	0.13	0.12	0.13		0.26
9	0.04	0.09	0.05	0.14	0.13	0.09	0.15	0.08	0.12	0.12	0.14	0.10	0.14	0.11	0.09	0.11	0.23	1.50	1.50	1.50	0.16	0.18	0.03	0.05	0.14	0.16	0.23	0.04	0.09	0.07	0.17	0.06	0.24
10	0.15	0.08	0.13	0.16	0.08	0.11	0.07	0.14	0.12	0.05	0.10	0.04	0.06	0.19	0.14	0.13	1.50	1.50	1.50	0.25	0.18	0.11	0.13	0.10	0.11	0.10	0.05	0.17	0.17	0.12	0.13		0.25
11	0.05	0.10	0.07	0.14	0.13	0.02	0.03	0.05	0.09	0.07	0.06	0.08	0.12	0.07	0.05	0.15	0.28	1.50	1.50	1.50	0.04	0.10	0.14	0.09	0.11	0.08	0.10	0.12	0.13	0.08	0.08	0.10	0.23
12	0.09	0.12	0.05	0.02	0.17	0.07	0.14	0.14	0.03	0.09	0.09	0.05	0.08	0.12	0.15	0.10	0.12	1.50	0.09	0.16	0.18	0.16	0.10	0.18	0.20	0.09	0.19	0.09	0.03	0.06	0.03		0.15
13	0.06	0.07	0.20	0.17	0.08	0.13	0.12	0.13	0.15	0.13	0.10	0.12	0.26	0.11	0.05	0.19	0.25	0.27	0.08	0.10	0.20	0.10	0.14	0.12	0.11	0.10	0.10	0.11	0.16	0.09	0.13	0.17	0.14
14	0.12	0.03	0.06	0.03	0.08	0.12	0.13	0.06	0.03	0.04	0.08	0.34	0.16	0.13	0.15	0.17	0.10	0.12	0.09	0.15	0.13	0.15	0.12	0.13	0.16	0.15	0.16	0.17	0.11	0.08	0.10		0.12
15	0.17	0.11	0.03	0.18	0.01	0.10	0.08	0.03	0.08	0.09	0.08	0.08	0.22	0.21	0.14	0.10	0.14	0.11	0.01	0.07	0.12	0.10	0.02	0.19	0.11	0.06	0.10	0.19	0.06	0.20	0.09	0.23	0.11
16	0.12	0.11	0.09	0.07	0.05	0.06	0.08	0.08	0.09	0.14	0.05	0.09	0.07	0.09	0.10	0.04	0.02	0.04	0.05	0.09	0.09	0.14	0.17	0.23	0.12	0.07	0.03	0.19	0.11	0.12	0.14		0.09
17	0.06	0.10	0.10	0.11	0.09	0.19	0.18	0.05	0.07	0.08	0.07	0.02	0.20	0.09	0.10	0.04	0.14	0.04	0.11	0.09	0.08	0.10	0.14	0.09	0.13	0.11	0.15	0.25	0.03	0.07	0.10	0.08	0.10
18	0.16	0.14	0.12	0.08	0.13	0.17	0.17	0.06	0.09	0.07	0.12	0.13	0.24	0.13	0.11	0.13	0.07	0.10	0.06	0.11	0.05	0.07	0.11	0.15	0.04	0.06	0.08	0.02	0.09	0.12	0.15		0.11
19	0.09	0.08	0.06	0.05	0.09	0.14	0.14	0.04	0.17	0.06	0.08	0.16	0.04	0.04	0.08	0.16	0.09	0.16	0.12	0.06	0.12	0.07	0.09	0.05	0.07	0.13	0.12	0.06	0.11	0.12	0.05	0.04	0.09
20	0.11	0.04	0.08	0.11	0.14	0.06	0.12	0.11	0.08	0.08	0.13	0.05	0.09	0.17	0.13	0.20	0.19	0.08	0.12	0.02	0.09	0.13	0.14	0.06	0.13	0.22	0.03	0.13	0.15	0.12	0.19		0.11
21	0.18	0.14	0.16	0.12	0.14	0.00	0.11	0.09	0.12	0.14	0.09	0.10	0.12	0.26	0.15	0.05	0.05	0.20	0.12	0.12	0.07	0.18	0.06	0.09	0.05	0.04	0.04	0.07	0.11	0.16	0.02	0.12	0.11
22	0.13	0.07	0.04	0.08	0.10	0.13	0.08	0.21	0.10	0.11	0.17	0.15	0.20	0.15	0.13	0.09	0.13	0.06	0.07	0.10	0.13	0.04	0.01	0.13	0.07	0.01	0.08	0.10	0.13	0.06	0.02		0.10
23	0.20	0.06	0.16	0.11	0.08	0.04	0.06	0.07	0.13	0.18	0.16	0.11	0.22	0.26	0.15	0.12	0.08	0.10	0.13	0.06	0.04	0.08	0.03	0.02	0.04	0.28	0.02	0.09	0.11	0.09	0.02	0.02	0.10

Figure G.29: Displacements

G.6 Configuration 4

Test: C4-10-50-2-0.25-0.04-10 (I651013)

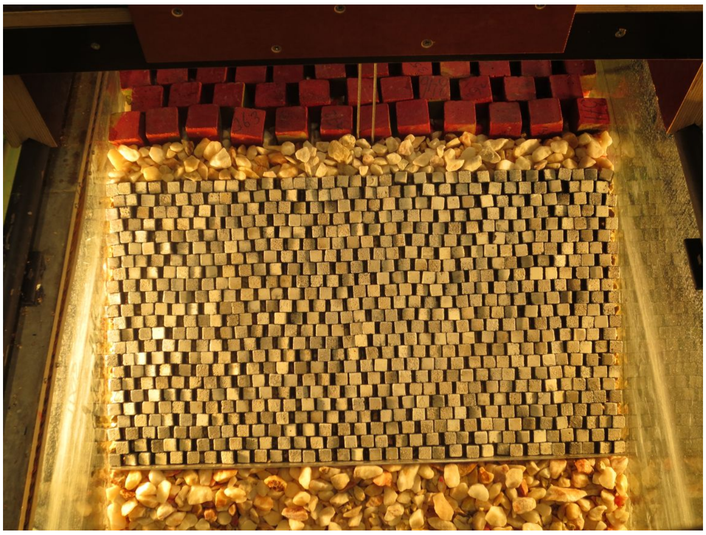

Figure G.30: *Photo before the test*

Test: C4-10-50-2-0.25-0.04-12 (I651215)

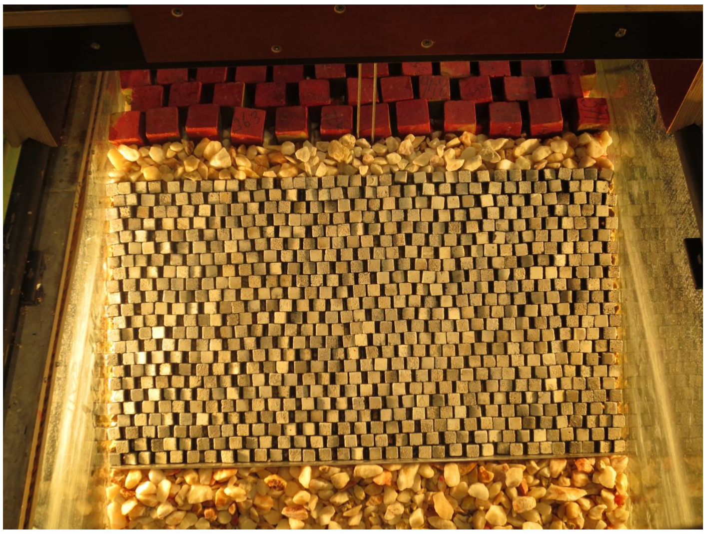

Figure G.31: *Photo before the test*

Figure G.32: *Photo after the test*

Test: C4-10-50-2-0.25-0.04-14 (I651417)

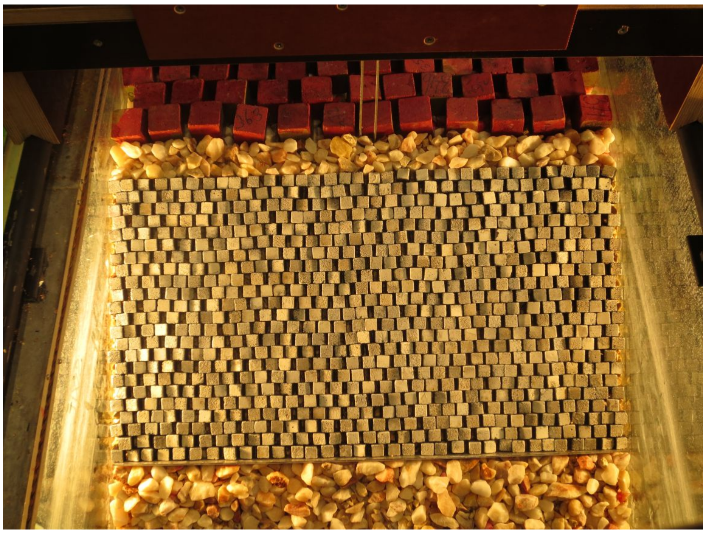

Figure G.33: *Photo before the test*

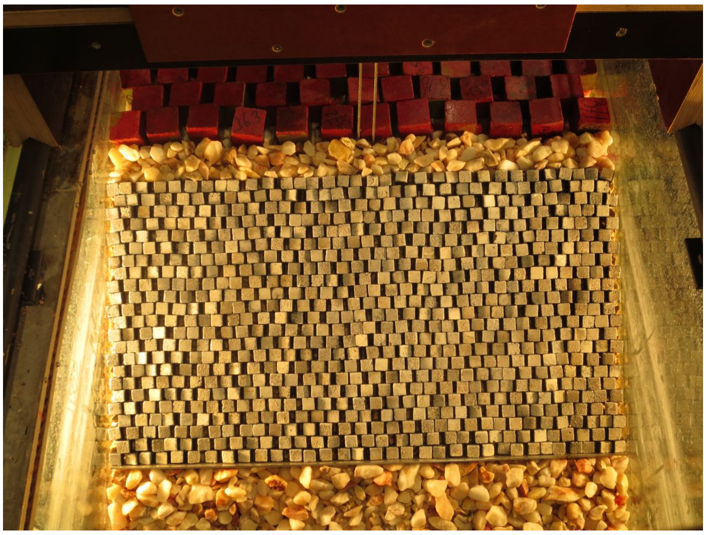

Figure G.34: *Photo after the test*

Test: C4-10-50-2-0.25-0.04-16 (I651618)

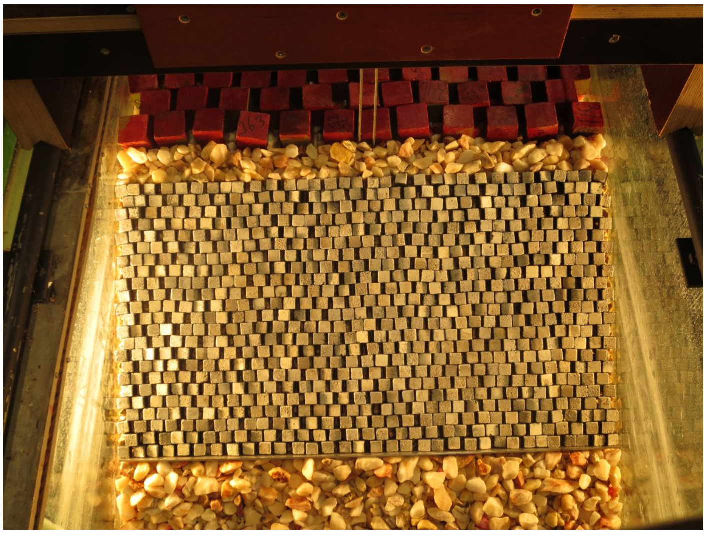

Figure G.35: *Photo before the test*

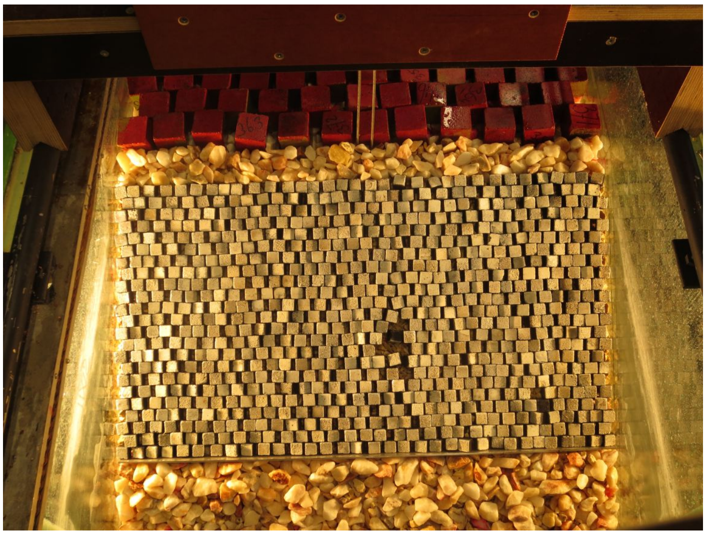

Figure G.36: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.12	0.15	0.14	0.02	0.08	0.11	0.15	0.05	0.06	0.08	0.14	0.07	0.09	0.13	0.05	0.07	0.10	0.02	0.12	0.12	0.06	0.23	0.07	0.08	0.05	0.04	0.13	0.07	0.07	0.11	0.14	0.05	0.09
2	0.12	0.01	0.10	0.02	0.02	0.07	0.01	0.18	0.06	0.11	0.08	0.08	0.08	0.05	0.05	0.04	0.03	0.10	0.05	0.04	0.06	0.14	0.06	0.10	0.08	0.13	0.14	0.09	0.02	0.14	0.07		0.07
3	0.05	0.04	0.11	0.07	0.09	0.16	0.11	0.02	0.04	0.13	0.04	0.08	0.02	0.07	0.12	0.11	0.09	0.02	0.03	0.02	0.05	0.05	0.15	0.04	0.12	0.17	0.11	0.14	0.13	0.16	0.14	0.08	0.09
4	0.02	0.02	0.16	0.13	0.03	0.08	0.12	0.14	0.14	0.03	0.07	0.07	0.09	0.02	0.12	0.09	0.13	0.29	0.22	0.05	0.14	0.10	0.03	0.13	0.14	0.13	0.09	0.02	0.13	0.07	0.07		0.10
5	0.23	0.06	0.06	0.06	0.08	0.05	0.04	0.05	0.11	0.03	0.03	0.12	0.12	0.06	0.15	0.14	0.04	0.11	0.27	0.03	0.05	0.11	0.09	0.03	0.17	0.04	0.06	0.10	0.09	0.09	0.09	0.04	0.09
6	0.05	0.11	0.11	0.04	0.20	0.03	0.07	0.18	0.08	0.04	0.11	0.08	0.15	0.06	0.14	0.02	0.10	0.03	0.05	0.09	0.11	0.15	0.09	0.04	0.13	0.09	0.10	0.18	0.08	0.24	0.10		0.10
7	0.09	0.07	0.05	0.06	0.15	0.03	0.08	0.14	0.05	0.05	0.02	0.05	0.12	0.07	0.14	0.07	0.11	0.10	0.12	0.05	0.09	0.17	0.12	0.03	0.03	0.01	0.07	0.05	0.11	0.14	0.05	0.17	0.08
8	0.16	0.09	0.07	0.12	0.07	0.09	0.04	0.04	0.11	0.11	0.03	0.04	0.10	0.10	0.07	0.08	0.09	0.05	0.06	0.14	0.09	0.07	0.06	0.03	0.10	0.12	0.13	0.05	0.05	0.05	0.08		0.08
9	0.07	0.08	0.10	0.11	0.11	0.07	0.07	0.04	0.02	0.08	0.02	0.11	0.07	0.07	0.12	0.06	0.02	0.04	0.13	0.07	0.07	0.09	0.06	0.04	0.02	0.17	0.08	0.02	0.03	0.03	0.07	0.07	0.07
10	0.05	0.12	0.03	0.03	0.03	0.03	0.04	0.06	0.05	0.04	0.03	0.07	0.09	0.03	0.06	0.11	0.11	0.08	0.07	0.11	0.07	0.03	0.08	0.09	0.05	0.04	0.11	0.11	0.03	0.07	0.08		0.06
11	0.04	0.03	0.10	0.02	0.11	0.08	0.08	0.05	0.05	0.13	0.12	0.10	0.10	0.08	0.12	0.15	0.05	0.14	0.31	0.15	0.11	0.17	0.07	0.07	0.05	0.14	0.09	0.04	0.03	0.04	0.16	0.05	0.09
12	0.05	0.06	0.08	0.08	0.08	0.10	0.11	0.06	0.01	0.12	0.10	0.11	0.07	0.06	0.01	0.09	0.12	0.39	0.16	0.07	0.04	0.03	0.03	0.03	0.09	0.12	0.10	0.03	0.06	0.02	0.12		0.08
13	0.14	0.06	0.05	0.05	0.08	0.09	0.13	0.15	0.09	0.05	0.09	0.10	0.10	0.07	0.05	0.08	0.06	0.11	1.50	0.11	0.12	0.08	0.14	0.14	0.13	0.10	0.08	0.15	0.07	0.10	0.12	0.14	0.14
14	0.13	0.14	0.04	0.06	0.05	0.05	0.12	0.09	0.13	0.09	0.05	0.05	0.11	0.09	0.14	0.13	0.13	1.50	0.15	0.09	0.04	0.07	0.09	0.06	0.05	0.07	0.25	0.10	0.08	0.07	0.21		0.14
15	0.28	0.09	0.09	0.03	0.08	0.05	0.09	0.06	0.06	0.14	0.11	0.11	0.17	0.11	0.10	0.15	0.31	1.50	1.50	0.20	0.08	0.09	0.13	0.13	0.06	0.13	0.14	0.11	0.11	0.11	0.13	0.09	0.21
16	0.10	0.09	0.10	0.14	0.05	0.10	0.04	0.05	0.06	0.06	0.02	0.06	0.12	0.14	0.05	0.06	0.23	0.21	0.35	0.20	0.14	0.09	0.35	0.10	0.05	0.01	0.11	0.02	0.02	0.10	0.10		0.11
17	0.14	0.07	0.10	0.07	0.02	0.04	0.10	0.05	0.01	0.06	0.09	0.04	0.06	0.11	0.05	0.07	0.10	0.28	1.50	0.11	0.09	0.06	0.07	0.10	0.05	0.07	0.13	0.10	0.02	0.11	0.01	0.17	0.13
18	0.05	0.06	0.02	0.11	0.07	0.04	0.17	0.13	0.07	0.11	0.08	0.31	0.07	0.07	0.10	0.02	0.14	0.18	0.18	0.15	0.16	0.07	0.10	0.10	0.10	0.06	0.14	0.06	0.08	0.06	0.06		0.10
19	0.17	0.11	0.02	0.06	0.20	0.17	0.04	0.10	0.02	0.11	0.14	0.11	0.07	0.03	0.02	0.02	0.02	0.11	0.28	0.03	0.07	0.08	0.04	0.09	0.05	0.10	0.17	1.50	0.03	0.09	0.08	0.11	0.13
20	0.05	0.04	0.16	0.03	0.16	0.10	0.12	0.09	0.05	0.07	0.03	0.07	0.07	0.03	0.04	0.02	0.14	0.11	0.15	0.17	0.12	0.03	0.10	0.08	0.11	0.10	0.03	0.94	0.07	0.13	0.05		0.11
21	0.17	0.06	0.03	0.07	0.02	0.03	0.10	0.07	0.05	0.05	0.04	0.08	0.20	0.07	0.05	0.07	0.12	0.32	0.13	0.21	0.17	0.08	0.12	0.11	0.08	0.10	0.08	0.33	0.07	0.09	0.04	0.08	0.10
22	0.06	0.06	0.13	0.02	0.10	0.06	0.08	0.09	0.10	0.10	0.19	0.06	0.07	0.08	0.11	0.01	0.08	0.08	0.17	0.15	0.06	0.16	0.14	0.05	0.11	0.02	0.07	0.04	0.16	0.03	0.11		0.09
23	0.00	0.06	0.06	0.06	0.02	0.04	0.12	0.05	0.04	0.01	0.07	0.07	0.08	0.09	0.09	0.14	0.09	0.09	0.05	0.16	0.08	0.19	0.35	0.08	0.13	0.05	0.08	0.02	0.11	0.07	0.08	0.17	0.09

Figure G.37: *Displacements*

G.7 Configuration 5

Test: C5-10-50-2-0.25-0.02-10 (I651022)

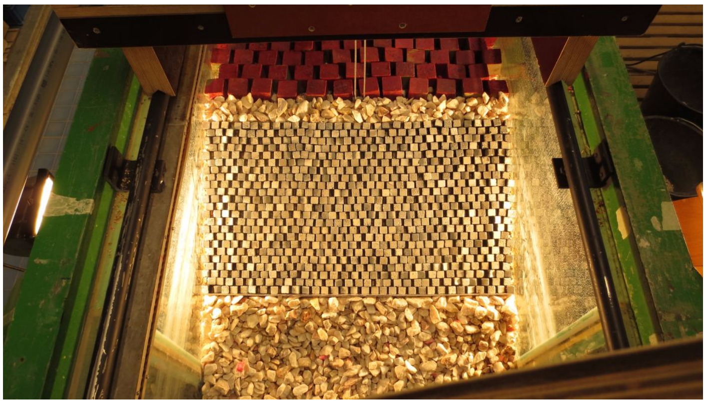

Figure G.38: *Photo before the test*

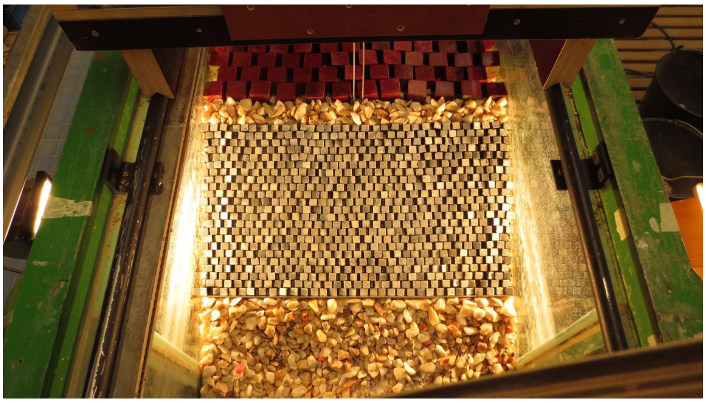

Figure G.39: *Photo after the test*

Test: C5-10-50-2-0.25-0.02-12 (I651225)

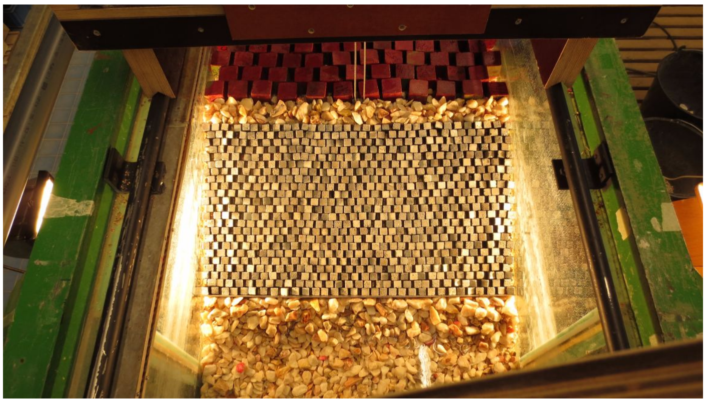

Figure G.40: *Photo before the test*

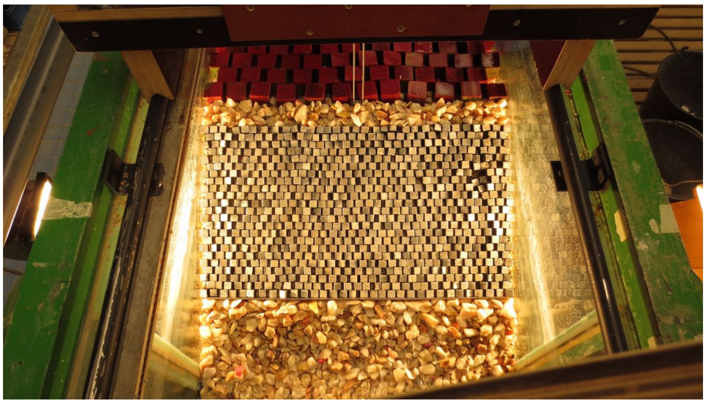

Figure G.41: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.06	0.06	0.11	0.15	0.06	0.11	0.10	0.10	0.10	0.20	0.09	0.15	0.09	0.04	0.04	0.04	0.20	0.04	0.08	0.05	0.38	0.15	0.25	0.17	0.15	0.17	0.18	0.11	0.18	0.15	0.15	0.25	0.13
2	0.11	0.07	0.03	0.06	0.06	0.07	0.10	0.03	0.05	0.32	0.13	0.08	0.09	0.09	0.09	0.04	0.12	0.04	0.08	0.09	0.04	0.03	0.10	0.05	0.16	0.16	0.15	0.12	0.26	0.10	0.20		0.10
3	0.25	0.08	0.08	0.10	0.08	0.05	0.18	0.05	0.14	0.03	0.10	0.16	0.09	0.04	0.04	0.04	0.09	0.09	0.04	0.09	0.11	0.08	0.15	0.09	0.11	0.15	0.03	0.15	0.14	0.25	0.27	0.25	0.11
4	0.18	0.14	0.08	0.06	0.07	0.05	0.07	0.05	0.05	0.03	0.05	0.08	0.09	0.09	0.04	0.09	0.09	0.09	0.04	0.15	0.05	0.08	0.08	0.14	0.11	0.08	0.15	0.15	0.15	0.14	0.25		0.10
5	0.15	0.14	0.18	0.10	0.17	0.03	0.14	0.03	0.03	0.03	0.10	0.13	0.05	0.04	0.08	0.04	0.09	0.04	0.04	0.09	0.05	0.03	0.08	0.11	0.09	0.13	0.09	0.08	0.27	0.29	0.15	0.03	0.10
6	0.10	0.06	0.06	0.06	0.06	0.05	0.07	0.05	0.05	0.10	0.10	0.03	0.04	0.04	0.04	0.09	0.09	0.04	0.09	0.04	0.04	0.03	0.10	0.03	0.03	0.08	0.03	0.25	0.19	0.25	0.14		0.08
7	0.06	0.11	0.11	0.08	0.16	0.09	0.07	0.05	0.03	0.09	0.10	0.04	0.14	0.09	0.05	0.09	0.09	0.04	0.09	0.04	0.04	0.04	0.04	0.14	0.10	0.03	0.14	0.17	1.50	0.22	0.13	0.15	0.14
8	0.07	0.08	0.19	0.18	0.11	0.06	0.09	0.10	0.05	0.06	0.07	0.16	0.08	0.10	0.08	0.11	0.03	0.06	0.08	0.10	0.12	0.12	0.18	0.08	0.17	0.13	0.05	0.72	1.50	0.27	0.23		0.17
9	0.12	0.05	0.08	0.11	0.11	0.11	0.06	0.11	0.07	0.08	0.05	0.01	0.05	0.01	0.11	0.14	0.10	0.06	0.06	0.05	0.17	0.00	0.08	0.18	0.17	0.06	0.13	0.17	0.34	0.25	0.22	0.25	0.11
10	0.11	0.06	0.13	0.06	0.10	0.10	0.02	0.10	0.12	0.08	0.08	0.11	0.01	0.07	0.11	0.06	0.10	0.09	0.15	0.10	0.12	0.18	0.06	0.13	0.27	0.22	0.17	0.28	0.45	0.19	0.20		0.13
11	0.13	0.11	0.06	0.04	0.12	0.07	0.15	0.15	0.07	0.06	0.05	0.13	0.06	0.09	0.06	0.19	0.08	0.09	0.15	0.05	0.06	0.18	0.13	0.07	0.13	0.10	0.20	0.27	0.17	0.20	0.20	0.32	0.12
12	0.13	0.06	0.02	0.12	0.10	0.03	0.07	0.12	0.12	0.05	0.11	0.12	0.09	0.13	0.14	0.14	0.12	0.15	0.10	0.17	0.05	0.11	0.13	0.14	0.20	0.15	0.18	0.25	0.15	0.35	0.20		0.13
13	0.13	0.16	0.09	0.12	0.11	0.21	0.07	0.10	0.08	0.13	0.09	0.13	0.14	0.12	0.14	0.03	0.15	0.16	0.11	0.22	0.13	0.13	0.06	0.14	0.14	0.22	0.23	0.27	0.23	0.35	0.32	0.24	0.16
14	0.14	0.09	0.10	0.07	0.15	0.08	0.08	0.15	0.10	0.02	0.04	0.09	0.10	0.02	0.04	0.14	0.11	0.12	0.07	0.11	0.07	0.09	0.02	0.07	0.13	0.11	0.16	0.16	0.18	0.32	0.21		0.11
15	0.14	0.14	0.13	0.08	0.19	0.11	0.04	0.15	0.14	0.09	0.13	0.09	0.17	0.02	0.08	0.15	0.14	0.03	0.08	0.11	0.05	0.17	0.19	0.15	0.13	0.19	0.19	0.15	0.19	0.32	0.25	0.27	0.14
16	0.28	0.05	0.09	0.08	0.12	0.11	0.12	0.03	0.02	0.06	0.15	0.08	0.10	0.03	0.11	0.31	0.15	0.05	0.14	0.09	0.11	0.14	0.07	0.15	0.23	0.11	0.14	0.17	0.14	0.25	0.09		0.12
17	0.19	0.23	0.10	0.05	0.04	0.09	0.09	0.20	0.08	0.07	0.22	0.07	0.11	0.19	0.09	0.12	0.04	0.05	0.05	0.05	0.14	0.10	0.07	0.15	0.03	0.09	0.04	0.09	0.20	0.29	0.29	0.22	0.12
18	0.14	0.11	0.10	0.04	0.09	0.04	0.16	0.13	0.06	0.11	0.12	0.07	0.09	0.04	0.12	0.04	0.15	0.15	0.13	0.10	0.11	0.12	0.18	0.11	0.14	0.20	0.21	0.22	0.13	0.20	0.22		0.12
19	0.11	0.04	0.09	0.12	0.16	0.05	0.04	0.10	0.09	0.11	0.11	0.11	0.07	0.09	0.09	0.09	0.05	0.10	0.10	0.11	0.19	0.14	0.12	0.16	0.19	0.12	0.17	0.27	0.04	0.15	0.23	0.26	0.12
20	0.10	0.06	0.04	0.10	0.05	0.15	0.10	0.17	0.14	0.16	0.07	0.24	0.10	0.16	0.09	0.15	0.10	0.13	0.06	0.14	0.16	0.11	0.11	0.16	0.29	0.17	0.17	0.17	0.29	0.23	0.19		0.14
21	0.16	0.15	0.16	0.11	0.10	0.10	0.13	0.15	0.06	0.16	0.04	0.12	0.12	0.16	0.13	0.10	0.10	0.15	0.06	0.11	0.04	0.10	0.12	0.13	0.02	0.24	0.18	0.21	0.18	0.22	0.24	0.27	0.14
22	0.12	0.15	0.17	0.13	0.22	0.16	0.11	0.17	0.11	0.12	0.07	0.10	0.16	0.17	0.17	0.14	0.11	0.19	0.10	0.11	0.18	0.13	0.12	0.13	0.19	0.17	0.33	0.18	0.16	0.29	0.23		0.16
23	0.12	0.05	0.04	0.13	0.13	0.11	0.22	0.14	0.12	0.12	0.12	0.12	0.16	0.09	0.19	0.10	0.06	0.09	0.10	0.11	0.07	0.11	0.01	0.16	0.17	0.09	0.11	0.19	0.21	0.19	0.15	0.17	0.12

7	0.06	0.11	0.11	0.08	0.16	0.09	0.07	0.05	0.03	0.09	0.10	0.04	0.14	0.09	0.05	0.09	0.09	0.04	0.09	0.04	0.04	0.04	0.04	0.14	0.10	0.03	0.14	0.17	1.50	0.22	0.13	0.15	0.14
7	0.04	0.10	0.08	0.06	0.08	0.03	0.05	0.05	0.02	0.11	0.07	0.07	0.08	0.08	0.11	0.09	0.09	0.05	0.05	0.11	0.14	0.11	0.12	0.13	0.13	0.14	0.17	0.16	1.50	0.22	0.19	0.31	0.15

Figure G.42: *Displacements*

Test: C5-10-50-2-0.25-0.02-14 (I651429)

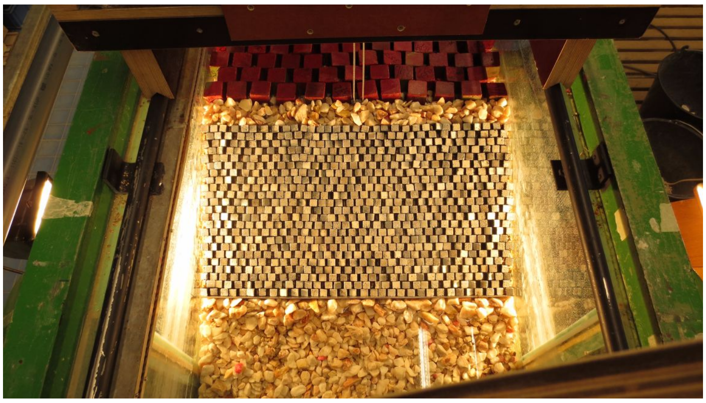

Figure G.43: *Photo before the test*

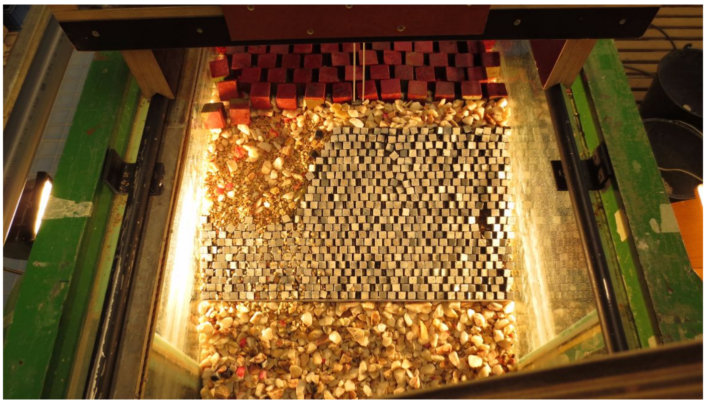

Figure G.44: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.25	0.25	0.10	0.34	0.17	0.16	0.35	0.04	0.45	0.38	0.30	0.13	0.16	0.19	0.29	0.26	0.46	0.25	0.80
2	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.17	0.16	0.26	0.28	0.11	0.19	0.19	0.09	0.19	0.06	0.31	0.23	0.06	0.04	0.17	0.16	0.14	0.25		0.73
3	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.33	0.21	0.24	0.24	0.19	0.21	0.33	0.08	0.22	0.10	0.16	0.05	0.08	0.09	0.17	0.08	0.21	0.20	0.08	0.71
4	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.21	0.33	0.24	0.32	0.24	0.23	0.11	0.81	0.08	0.11	0.18	0.21	0.04	0.14	0.04	0.16	0.39	0.14	0.29		0.72
5	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.40	0.21	0.19	0.12	0.28	0.19	0.15	0.18	0.09	0.29	0.16	0.10	0.19	0.20	0.20	0.16	0.04	0.18	0.18	0.11	0.68
6	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.67	0.32	0.18	0.27	0.28	0.31	0.15	0.27	0.16	0.07	0.04	0.13	0.16	0.15	0.21	0.05	0.04	0.06	0.40	0.11		0.66
7	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.54	0.33	0.18	0.36	0.33	0.20	0.18	0.25	0.02	0.33	0.19	0.28	0.11	0.12	0.08	0.07	0.10	0.13	0.28	0.04	0.27	0.65
8	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.20	0.17	0.25	0.31	0.12	0.23	0.19	0.14	0.20	0.27	0.01	0.27	0.02	0.22	0.09	0.10	0.26	0.20	0.10	0.23		0.65
9	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.23	0.31	0.23	0.19	0.18	0.30	0.22	0.27	0.14	0.17	0.06	0.06	0.09	0.19	0.13	0.10	0.14	0.14	0.01	0.12	0.15	0.62
10	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.11	0.08	0.12	0.06	0.17	0.19	0.33	0.25	0.21	0.12	0.00	0.25	0.09	0.11	0.06	0.43	0.54	0.19	0.17	0.18	0.23		0.61
11	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.17	0.12	0.29	0.29	0.30	0.18	0.21	0.11	0.17	0.11	0.34	0.12	0.16	0.06	0.15	0.31	0.10	0.02	0.19	0.01	0.28	0.23	0.59
12	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.22	0.16	0.31	0.27	0.30	0.33	0.23	0.30	0.24	0.19	0.17	0.12	0.15	0.05	0.07	0.02	0.09	0.12	0.19	1.50	0.18	0.13		0.61
13	0.30	1.50	1.50	1.50	0.22	1.50	1.50	1.50	0.05	0.27	0.04	0.12	0.10	0.11	0.35	0.20	0.17	0.19	0.20	0.18	0.15	0.04	0.28	0.06	0.11	0.09	0.03	0.08	1.50	0.19	0.20	0.23	0.45
14	0.33	1.50	0.40	0.09	0.20	1.50	0.07	0.16	0.31	0.17	0.06	0.26	0.30	0.16	0.17	0.25	0.14	0.13	0.12	0.04	0.19	0.19	0.11	0.04	0.12	0.03	0.20	0.15	1.50	0.14	0.13		0.30
15	0.24	0.50	0.16	0.15	0.04	0.10	0.26	0.32	0.08	0.14	0.26	0.24	0.34	0.23	0.30	0.28	0.20	0.09	0.20	0.11	0.10	0.02	0.02	0.09	0.08	0.04	0.19	0.08	0.31	0.24	0.19	0.19	0.18
16	0.44	0.03	0.16	0.13	0.17	0.28	0.15	0.29	0.20	0.47	0.11	0.26	0.13	0.10	0.44	0.20	0.30	0.10	0.03	0.15	0.14	0.33	0.09	0.03	0.05	0.21	0.21	0.03	0.08	0.13	0.18		0.18
17	0.40	0.33	0.03	0.09	0.09	0.09	0.24	0.29	0.21	0.15	0.18	0.06	0.11	0.22	0.17	0.24	0.16	0.11	0.11	0.22	0.12	0.06	0.10	0.13	0.05	0.16	0.16	0.16	0.13	0.08	0.25	0.10	0.16
18	0.23	0.06	0.21	0.20	0.03	0.14	0.19	0.25	0.15	0.34	0.26	0.13	0.21	0.24	0.26	0.26	0.27	0.14	0.09	0.24	0.14	0.06	0.03	0.05	0.04	0.09	0.14	0.24	0.09	0.15	0.30		0.17
19	0.24	0.05	0.23	0.32	0.22	0.16	0.19	0.55	0.13	0.25	0.21	0.20	0.19	0.28	0.22	0.27	0.23	0.15	0.18	0.14	0.14	0.13	0.05	0.10	0.07	0.08	0.12	0.08	0.09	0.15	0.16	0.16	0.18
20	0.17	0.27	0.51	0.21	0.08	0.08	0.19	0.20	0.14	0.22	0.09	0.06	0.24	0.27	0.24	0.21	0.26	0.13	0.14	0.19	0.14	0.18	0.16	0.13	0.26	0.31	0.11	0.22	0.10	0.32	0.29		0.20
21	0.23	0.12	0.33	0.20	0.20	0.16	0.26	0.40	0.17	0.36	0.09	0.01	0.14	0.18	0.21	0.26	0.10	0.24	0.25	0.14	0.09	0.09	0.14	0.05	0.15	0.08	0.09	0.08	0.19	0.04	0.11	0.33	0.17
22	0.28	0.33	0.21	0.14	0.15	0.12	0.37	0.17	0.21	0.33	0.23	0.25	0.08	0.18	0.35	0.11	0.20	0.10	0.16	0.19	0.23	0.16	0.16	0.06	0.09	0.03	0.08	0.19	0.20	0.20	0.42		0.19
23	0.12	0.33	0.07	0.07	0.09	0.28	0.14	0.52	0.23	0.13	0.28	0.13	0.26	0.20	0.19	0.31	0.14	0.10	0.14	0.09	0.17	0.05	0.22	0.15	0.21	0.03	0.14	0.06	0.04	0.27	0.16	0.05	0.17

Figure G.45: *Displacements*

G.8 Configuration 6

Test: C6-10-30-2-0.25-0.03-10 (I651016)

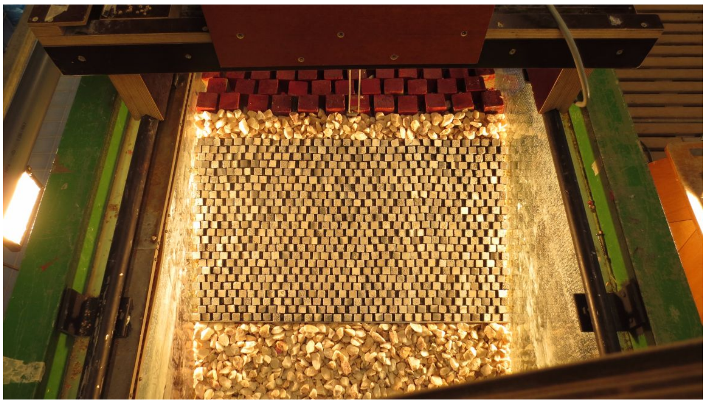

Figure G.46: *Photo before the test*

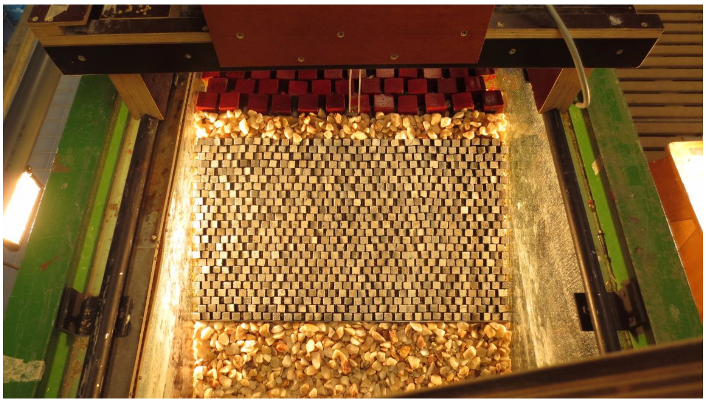

Figure G.47: *Photo after the test*

Test: C6-10-30-2-0.25-0.03-12 (I651218)

Figure G.48: *Photo before the test*

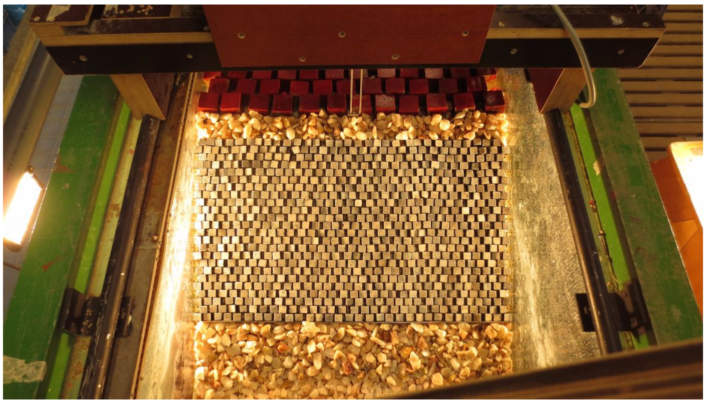

Figure G.49: *Photo after the test*

Test: C6-10-30-2-0.25-0.03-14 (I651421)

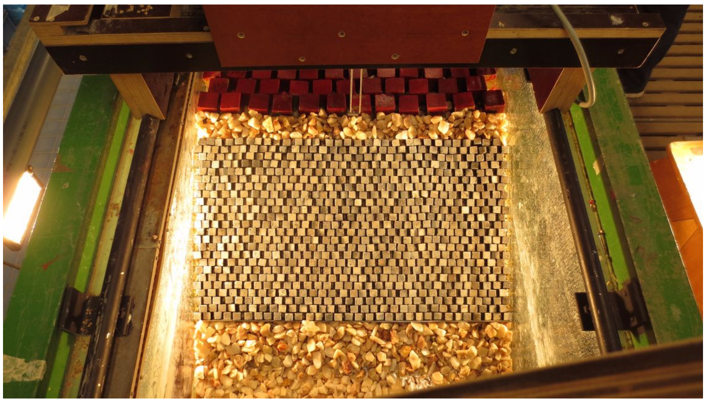

Figure G.50: *Photo before the test*

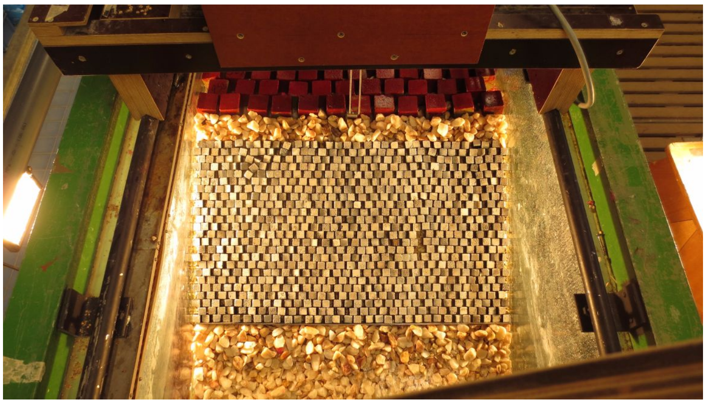

Figure G.51: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.18	0.26	0.11	0.10	0.06	0.17	0.25	0.22	0.10	0.48	0.48	0.04	0.28	0.21	0.16	0.24	0.12	0.16	0.12	0.13	0.11	0.05	0.14	0.05	0.10	0.07	0.02	0.10	0.10	0.09	0.08		0.15
2	0.14	0.12	0.16	0.16	0.16	0.54	0.29	0.11	0.14	0.20	0.26	0.22	0.14	0.09	0.09	0.14	0.12	0.09	0.16	0.08	0.09	0.11	0.20	0.20	0.07	0.03	0.10	0.07	0.12	0.19	0.10	0.10	0.15
3	0.03	0.18	0.16	0.10	0.20	0.18	0.58	0.28	0.09	0.09	0.28	0.20	0.11	0.08	0.16	0.04	0.04	0.08	0.23	0.12	0.12	0.08	0.18	0.20	0.10	0.05	0.10	0.10	0.08	0.06	0.13		0.14
4	0.20	0.06	0.06	0.10	0.20	0.29	0.96	0.25	0.20	0.25	0.15	0.14	0.16	0.04	0.20	0.14	0.14	0.21	0.12	0.08	0.09	0.08	0.08	0.03	0.07	0.11	0.03	0.09	0.07	0.06	0.10	0.06	0.15
5	0.11	0.03	0.11	0.13	0.03	0.68	0.32	0.20	0.18	0.05	0.10	0.04	0.04	0.09	0.04	0.14	0.09	0.11	0.16	0.03	0.14	0.08	0.08	0.11	0.03	0.10	0.10	0.05	0.14	0.03	0.10		0.12
6	0.15	0.03	0.23	0.06	0.05	0.03	0.24	0.09	0.17	0.08	0.14	0.09	0.09	0.04	0.04	0.11	0.08	0.04	0.04	0.08	0.09	0.18	0.10	0.03	0.10	0.03	0.07	0.11	0.05	0.10	0.03	0.14	0.09
7	0.02	0.10	0.06	0.08	0.03	0.10	0.14	0.12	0.12	0.12	0.16	0.27	0.09	0.03	0.08	0.09	0.08	0.03	0.14	0.04	0.16	0.04	0.05	0.05	0.09	0.03	0.06	0.08	0.16	0.02	0.03		0.09
8	0.19	0.17	0.16	0.21	0.09	0.02	0.13	0.12	0.21	0.09	0.08	0.09	0.08	0.08	0.08	0.03	0.09	0.08	0.15	0.08	0.10	0.08	0.12	0.10	0.12	0.05	0.08	0.10	0.09	0.14	0.11	0.11	0.11
9	0.02	0.18	0.02	0.03	0.13	0.07	0.14	0.12	0.10	0.10	0.08	0.12	0.05	0.11	0.14	0.11	0.09	0.08	0.03	0.03	0.04	0.11	0.04	0.05	0.15	0.15	0.07	0.07	0.11	0.11	0.14		0.09
10	0.06	0.10	0.06	0.06	0.09	0.13	0.16	0.17	0.07	0.08	0.08	0.04	0.09	0.05	0.13	0.13	0.23	0.20	0.13	0.23	0.20	0.15	0.04	0.15	0.09	0.06	0.06	0.07	0.06	0.04	0.02	0.07	0.10
11	0.14	0.11	0.06	0.07	0.02	0.12	0.04	0.10	0.02	0.13	0.08	0.20	0.03	0.08	0.08	0.13	0.19	0.15	0.04	0.08	0.09	0.12	0.13	0.07	0.14	0.13	0.07	0.10	0.09	0.07	0.04		0.09
12	0.07	0.06	0.05	0.21	0.11	0.11	0.07	0.08	0.08	0.13	0.04	0.13	0.14	0.04	0.08	0.13	0.05	0.03	0.08	0.10	0.28	0.08	0.13	0.07	0.07	0.13	0.10	0.05	0.09	0.04	0.06	0.12	0.09
13	0.09	0.06	0.22	0.02	0.08	0.10	0.11	0.07	0.07	0.07	0.15	0.10	0.05	0.08	0.10	0.08	0.03	0.08	0.14	0.36	0.02	0.08	1.50	0.02	0.10	0.12	0.04	0.07	0.09	0.15	0.06		0.14
14	0.11	0.05	0.05	0.15	0.08	0.05	0.00	0.05	0.11	0.08	0.05	0.11	0.08	0.11	0.40	0.05	0.11	0.05	0.05	0.05	0.77	0.05	0.16	0.08	0.00	0.05	0.11	0.16	0.12	0.16	0.12	0.20	0.12
15	0.04	0.05	0.07	0.05	0.12	0.16	0.02	0.15	0.06	0.18	0.04	0.16	0.08	0.09	0.11	0.11	0.13	0.05	0.10	0.04	0.15	0.25	1.50	0.07	0.13	0.09	0.08	0.08	0.01	0.11	0.11		0.14
16	0.01	0.13	0.13	0.21	0.16	0.21	0.07	0.19	0.04	0.07	0.08	0.15	0.15	0.07	0.11	0.12	0.07	0.15	0.03	0.05	0.25	0.13	0.04	0.08	0.02	0.05	0.07	0.01	0.17	0.11	0.04	0.12	0.10
17	0.04	0.17	0.12	0.05	0.17	0.12	0.13	0.12	0.11	0.13	0.05	0.07	0.07	0.03	0.03	0.03	0.14	0.07	0.07	0.04	0.07	0.09	0.06	0.04	0.08	0.05	0.05	0.07	0.11	0.05	0.06		0.08
18	0.08	0.06	0.08	0.06	0.08	0.06	0.05	0.11	0.07	0.06	0.04	0.11	0.07	0.03	0.11	0.08	0.14	0.09	0.06	0.03	0.02	0.02	0.09	0.15	0.11	0.04	0.08	0.10	0.10	0.09	0.06	0.13	0.08
19	0.05	0.01	0.11	0.05	0.10	0.01	0.04	0.10	0.07	0.06	0.19	0.09	0.14	0.10	0.07	0.07	0.07	0.03	0.05	0.02	0.10	0.02	0.05	0.05	0.06	0.12	0.06	0.08	0.06	0.08	0.06		0.07
20	0.11	0.08	0.05	0.17	0.11	0.01	0.08	0.11	0.16	0.11	0.02	0.14	0.10	0.09	0.10	0.10	0.10	0.25	0.02	0.02	0.14	0.04	0.06	0.06	0.01	0.13	0.05	0.05	0.07	0.08	0.11	0.12	0.09
21	0.13	0.05	0.06	0.05	0.12	0.07	0.13	0.06	0.11	0.07	0.15	0.06	0.11	0.10	0.14	0.07	0.06	0.14	0.14	0.11	0.07	0.07	0.04	0.04	0.11	0.09	0.06	0.06	0.10	0.12	0.12		0.09
22	0.08	0.06	0.06	0.15	0.15	0.17	0.01	0.10	0.07	0.06	0.12	0.12	0.07	0.13	0.06	0.15	0.14	0.20	0.08	0.02	0.14	0.10	0.09	0.09	0.08	0.06	0.16	0.01	0.05	0.18	0.12	0.05	0.10
23	0.07	0.07	0.11	0.06	0.17	0.01	0.23	0.01	0.02	0.04	0.18	0.17	0.03	0.14	0.11	0.03	0.25	0.15	0.08	0.06	0.02	0.15	0.07	0.10	0.13	0.05	0.01	0.13	0.12	0.05	0.05		0.09
24	0.00	0.12	0.08	0.05	0.01	0.10	0.16	0.21	0.12	0.04	0.04	0.11	0.11	0.15	0.06	0.14	0.03	0.17	0.10	0.08	0.09	0.14	0.07	0.01	0.09	0.05	0.13	0.08	0.20	0.06	0.06	0.11	0.09

Figure G.52: *Displacements*

Test: C6-10-30-2-0.25-0.03-16 (I651623)

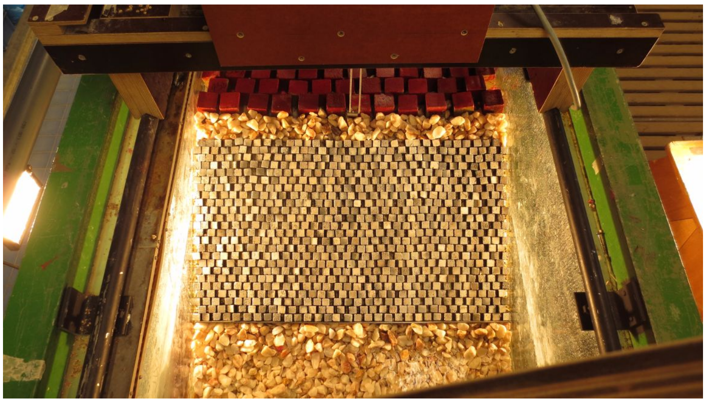

Figure G.53: *Photo before the test*

Figure G.54: *Photo after the test*

G.9 Configuration 7

Test: C7-10-30-2-0.30-0.03-10 (I651016)

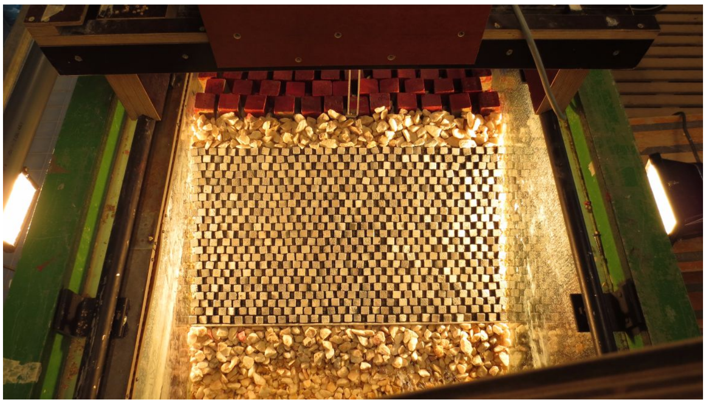

Figure G.55: *Photo before the test*

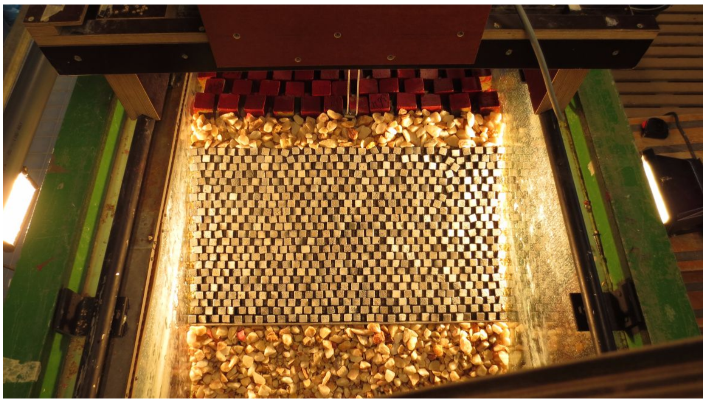

Figure G.56: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Mean
1	0.06	0.03	0.03	0.07	0.06	0.07	0.05	0.26	0.14	0.26	0.05	0.05	0.04	0.09	0.04	0.09	0.09	0.19	0.09	0.08	0.08	0.03	0.08	0.18	0.26	0.03	0.05	0.09	0.03	0.09
2	0.21	0.14	0.11	0.06	0.06	0.16	0.10	0.08	0.13	0.23	0.03	0.08	0.08	0.03	0.11	0.09	0.04	0.04	0.04	0.14	0.09	0.05	0.08	0.71	0.11	0.12	0.10	0.11		0.12
3	0.03	0.06	0.03	0.06	0.07	0.10	0.10	0.05	0.09	0.09	0.15	0.11	0.09	0.12	0.16	0.20	0.11	0.04	0.04	0.03	0.03	0.11	0.03	0.08	0.34	0.03	0.05	0.08	0.17	0.09
4	0.06	0.06	0.08	0.02	0.11	0.10	0.17	0.03	0.10	0.15	0.15	0.05	0.09	0.09	0.04	0.08	0.11	0.08	0.04	0.08	0.08	0.04	0.05	0.10	0.07	0.12	0.06	0.07		0.08
5	0.06	0.06	0.11	0.16	0.08	0.02	0.17	0.12	0.10	0.12	0.12	0.08	0.09	0.08	0.09	0.09	0.08	0.04	0.04	0.12	0.08	0.08	0.03	0.13	0.08	0.10	0.09	0.06	0.08	0.09
6	0.09	0.06	0.14	0.06	0.11	0.05	0.05	0.05	0.09	0.12	0.12	0.12	0.05	0.15	0.11	0.08	0.11	0.08	0.04	0.05	0.05	0.08	0.13	0.13	0.07	0.12	0.03	0.09		0.09
7	0.10	0.02	0.14	0.11	0.02	0.06	0.10	0.10	0.05	0.10	0.08	0.15	0.16	0.05	0.16	0.09	0.16	0.03	0.08	0.08	0.03	0.13	0.07	0.30	0.08	0.07	0.14	0.03	0.10	0.10
8	0.10	0.16	0.06	0.05	0.05	0.06	0.12	0.17	0.17	0.08	0.13	0.04	0.09	0.09	0.13	0.13	0.08	0.20	0.04	0.04	0.13	0.09	0.24	0.02	0.07	0.13	0.02	0.11		0.10
9	0.02	0.04	0.11	0.11	0.06	0.04	0.15	0.06	0.10	0.05	0.07	0.08	0.03	0.08	0.08	0.05	0.03	0.04	0.03	0.04	0.08	0.10	0.13	0.07	0.07	0.07	0.06	0.02	0.15	0.07
10	0.16	0.07	0.04	0.04	0.02	0.05	0.02	0.07	0.07	0.07	0.13	0.03	0.08	0.08	0.11	0.14	0.05	0.14	0.10	0.04	0.15	0.09	0.02	0.04	0.06	0.08	0.06	0.16		0.08
11	0.07	0.11	0.05	0.16	0.16	0.09	0.05	0.08	0.13	0.10	0.10	0.08	0.04	0.03	0.05	0.09	0.03	0.05	0.09	0.03	0.08	0.08	0.04	0.04	0.07	0.02	0.07	0.09	0.05	0.07
12	0.11	0.07	0.22	0.16	0.11	0.05	0.12	0.04	0.02	0.02	0.02	0.10	0.21	0.05	0.05	0.08	0.05	0.05	0.03	0.10	0.04	0.04	0.07	0.12	0.02	0.12	0.04	0.11		0.08
13	0.09	0.04	0.11	0.10	0.14	0.11	0.04	0.02	0.17	0.10	0.09	0.13	0.04	0.10	0.05	0.03	0.09	0.11	0.08	0.09	0.09	0.07	0.04	0.06	0.02	0.11	0.06	0.06	0.07	0.08
14	0.12	0.11	0.01	0.06	0.14	0.08	0.07	0.11	0.07	0.07	0.10	0.06	0.09	0.05	0.09	0.22	0.14	0.09	0.10	0.08	0.16	0.08	0.05	0.02	0.11	0.16	0.10	0.07		0.09
15	0.07	0.11	0.11	0.01	0.06	0.06	0.04	0.15	0.11	0.06	0.15	0.15	0.09	0.02	0.03	0.05	0.05	0.09	0.10	0.08	0.05	0.07	0.13	0.06	0.06	0.10	0.05	0.17	0.01	0.08
16	0.12	0.09	0.11	0.05	0.08	0.11	0.16	0.02	0.08	0.05	0.12	0.02	0.02	0.13	0.05	0.11	0.10	0.03	0.10	0.10	0.09	0.07	0.11	0.16	0.13	0.16	0.01	0.04		0.09
17	0.07	0.07	0.07	0.12	0.05	0.11	0.15	0.05	0.08	0.15	0.02	0.04	0.10	0.11	0.05	0.08	0.09	0.17	0.09	0.17	0.04	0.10	0.10	0.02	0.05	0.10	0.06	0.11	0.12	0.09
18	0.12	0.15	0.16	0.01	0.05	0.01	0.14	0.05	0.07	0.04	0.12	0.04	0.03	0.11	0.05	0.03	0.05	0.09	0.09	0.06	0.02	0.05	0.02	0.02	0.05	0.06	0.10	0.16		0.07
19	0.07	0.01	0.07	0.06	0.01	0.06	0.08	0.11	0.02	0.04	0.09	0.09	0.03	0.05	0.11	0.03	0.11	0.08	0.05	0.09	0.06	0.09	0.04	0.04	0.06	0.10	0.11	0.07	0.10	0.07
20	0.07	0.10	0.05	0.01	0.07	0.07	0.10	0.04	0.04	0.15	0.09	0.05	0.06	0.06	0.03	0.13	0.06	0.06	0.02	0.02	0.15	0.11	0.11	0.06	0.11	0.05	0.05	0.07		0.07
21	0.17	0.08	0.07	0.12	0.07	0.05	0.11	0.11	0.11	0.05	0.15	0.13	0.06	0.10	0.06	0.07	0.06	0.03	0.06	0.11	0.05	0.06	0.06	0.09	0.05	0.05	0.12	0.11	0.15	0.09
22	0.06	0.05	0.05	0.05	0.08	0.05	0.04	0.16	0.07	0.07	0.14	0.03	0.14	0.03	0.06	0.06	0.14	0.11	0.09	0.09	0.04	0.05	0.13	0.04	0.07	0.13	0.07	0.18		0.08
23	0.05	0.08	0.12	0.12	0.07	0.07	0.11	0.01	0.07	0.06	0.04	0.06	0.09	0.06	0.06	0.11	0.08	0.10	0.08	0.09	0.03	0.02	0.09	0.09	0.11	0.01	0.05	0.07	0.07	0.07

Figure G.57: *Displacements*

Test: C7-10-30-2-0.30-0.03-12 (I651218)

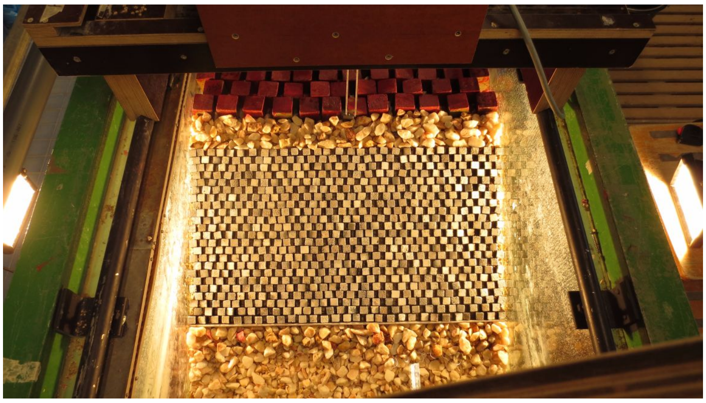

Figure G.58: *Photo before the test*

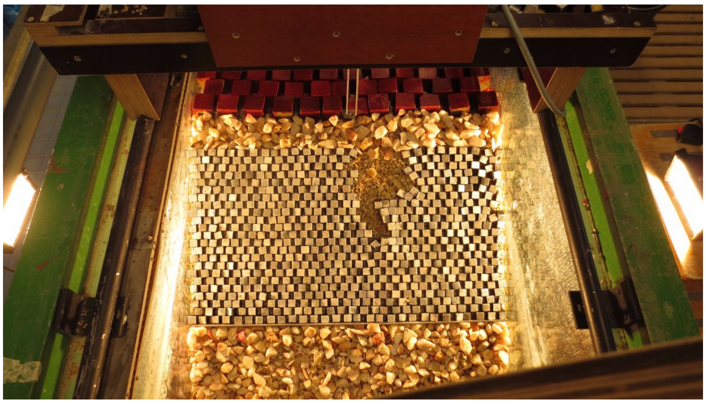

Figure G.59: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Mean
1	0.20	0.06	0.14	0.06	0.03	0.17	0.15	0.15	0.21	0.15	0.04	0.14	0.09	0.12	0.04	0.55	1.50	1.50	1.50	1.50	0.68	0.48	0.10	0.05	0.17	0.20	0.08	0.48	0.44	0.38
2	0.14	0.08	0.03	0.27	0.08	0.11	0.09	0.14	0.18	0.20	0.09	0.16	0.20	0.12	0.16	1.50	1.50	1.50	1.50	1.50	0.42	0.20	0.13	0.10	0.08	0.14	0.43	0.31		0.41
3	0.14	0.14	0.14	0.10	0.03	0.05	0.20	0.14	0.15	0.14	0.14	0.11	0.14	0.04	0.09	1.50	1.50	1.50	1.50	1.50	1.11	0.48	0.15	0.13	0.20	0.15	0.20	0.69	0.41	0.44
4	0.15	0.20	0.19	0.09	0.03	0.15	0.05	0.14	0.09	0.10	0.08	0.16	0.08	0.12	0.28	0.47	1.50	1.50	1.50	1.50	0.87	0.14	0.08	0.14	0.18	0.08	0.22	0.52		0.38
5	0.22	0.08	0.06	0.16	0.20	0.07	0.17	0.10	0.05	0.05	0.16	0.04	0.11	0.14	0.04	0.30	1.50	1.50	1.50	1.50	1.50	0.19	0.03	0.08	0.14	0.06	0.16	0.17	0.49	0.37
6	0.06	0.03	0.22	0.23	0.05	0.10	0.03	0.15	0.10	0.04	0.14	0.08	0.11	0.16	0.19	1.50	1.50	1.50	1.50	1.50	1.01	0.19	0.14	0.14	0.41	0.09	0.10	0.17		0.41
7	0.06	0.14	0.08	0.05	0.14	0.07	0.13	0.09	0.15	0.03	0.16	0.20	0.03	0.14	0.09	0.16	1.50	1.50	1.50	0.93	0.42	0.40	0.13	0.16	0.03	0.14	0.13	0.13	0.30	0.31
8	0.22	0.14	0.07	0.14	0.09	0.10	0.14	0.14	0.08	0.15	0.03	0.08	0.03	0.08	0.14	0.14	1.14	0.79	0.29	0.21	0.08	0.07	0.13	0.02	0.05	0.11	0.07	0.13		0.17
9	0.09	0.09	0.02	0.06	0.08	0.14	0.10	0.10	0.04	0.04	0.04	0.08	0.08	0.04	0.08	0.19	1.50	1.36	0.68	0.18	0.15	0.14	0.14	0.08	0.13	0.08	0.14	0.29	1.22	0.25
10	0.06	0.11	0.20	0.07	0.09	0.06	0.04	0.18	0.08	0.08	0.03	0.08	0.08	0.09	0.08	0.15	1.50	0.49	0.18	0.20	0.24	0.07	0.20	0.09	0.13	0.17	0.13	0.37		0.19
11	0.09	0.13	0.06	0.07	0.02	0.13	0.14	0.19	0.13	0.10	0.08	0.04	0.08	0.08	0.15	0.15	0.16	1.50	0.30	0.15	0.19	0.14	0.24	0.20	0.19	0.24	0.04	0.13	0.07	0.18
12	0.07	0.13	0.12	0.02	0.12	0.10	0.09	0.04	0.07	0.15	0.04	0.15	0.20	0.05	0.15	0.03	0.23	1.50	0.46	0.07	0.07	0.10	0.12	0.13	0.05	0.09	0.13	0.17		0.17
13	0.07	0.02	0.11	0.05	0.16	0.12	0.07	0.14	0.14	0.13	0.10	0.04	0.11	0.08	0.08	0.08	0.36	1.31	0.39	0.22	0.07	0.12	0.10	0.07	0.02	0.07	0.13	0.05	0.04	0.15
14	0.13	0.13	0.06	0.04	0.04	0.04	0.08	0.02	0.12	0.16	0.04	0.08	0.09	0.18	0.03	0.08	0.31	0.15	0.10	0.07	0.08	0.07	0.12	0.14	0.08	0.12	0.05	0.01		0.09
15	0.18	0.12	0.17	0.01	0.06	0.12	0.13	0.07	0.07	0.02	0.04	0.08	0.09	0.07	0.03	0.12	0.11	0.03	0.13	0.15	0.18	0.08	0.08	0.10	0.07	0.06	0.05	0.05	0.12	0.09
16	0.01	0.06	0.07	0.17	0.11	0.08	0.07	0.04	0.13	0.08	0.10	0.05	0.09	0.05	0.03	0.03	0.14	0.07	0.07	0.05	0.07	0.07	0.04	0.06	0.07	0.07	0.01	0.18		0.07
17	0.05	0.06	0.05	0.06	0.09	0.12	0.08	0.07	0.04	0.15	0.07	0.12	0.03	0.08	0.05	0.05	0.05	0.13	0.11	0.13	0.04	0.07	0.10	0.12	0.16	0.12	0.06	0.12	0.07	0.08
18	0.13	0.05	0.01	0.05	0.08	0.13	0.05	0.11	0.07	0.07	0.05	0.09	0.10	0.05	0.14	0.03	0.07	0.11	0.02	0.09	0.16	0.11	0.05	0.05	0.11	0.11	0.01	0.12		0.08
19	0.13	0.07	0.05	0.05	0.05	0.06	0.04	0.07	0.04	0.06	0.04	0.09	0.05	0.05	0.14	0.15	0.07	0.08	0.07	0.04	0.14	0.02	0.11	0.07	0.16	0.05	0.06	0.07	0.07	0.07
20	0.11	0.12	0.06	0.07	0.05	0.04	0.10	0.07	0.05	0.07	0.11	0.06	0.03	0.12	0.07	0.03	0.12	0.15	0.12	0.04	0.07	0.04	0.06	0.12	0.01	0.08	0.12	0.06		0.08
21	0.12	0.28	0.06	0.17	0.12	0.04	0.09	0.01	0.09	0.07	0.07	0.08	0.12	0.08	0.03	0.10	0.10	0.09	0.05	0.07	0.11	0.17	0.10	0.10	0.01	0.08	0.20	0.16	0.12	0.10
22	0.00	0.06	0.16	0.13	0.09	0.07	0.10	0.19	0.13	0.09	0.07	0.03	0.14	0.08	0.10	0.06	0.15	0.09	0.14	0.02	0.09	0.11	0.12	0.10	0.06	0.01	0.06	0.12		0.09
23	0.12	0.06	0.15	0.12	0.07	0.15	0.07	0.11	0.11	0.13	0.11	0.10	0.06	0.06	0.10	0.03	0.14	0.12	0.14	0.11	0.04	0.10	0.21	0.19	0.19	0.05	0.12	0.05	0.06	0.11

Figure G.60: *Displacements*

G.10 Configuration 8

Test: C8-10-15-2-0.25-0.03-10 (I651016)

Figure G.61: *Photo before the test*

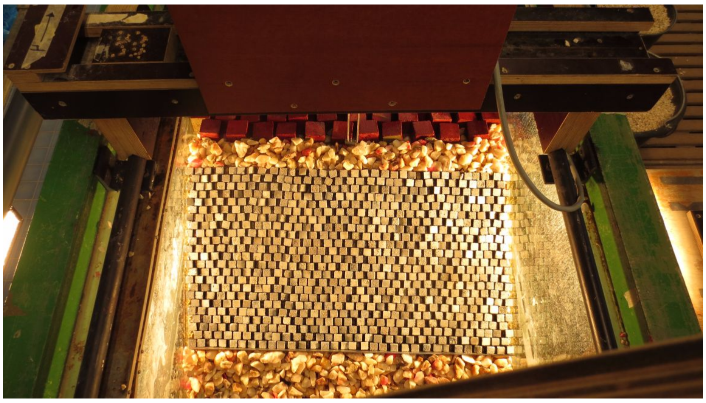

Figure G.62: *Photo after the test*

Test: C8-10-15-2-0.25-0.03-12 (I651218)

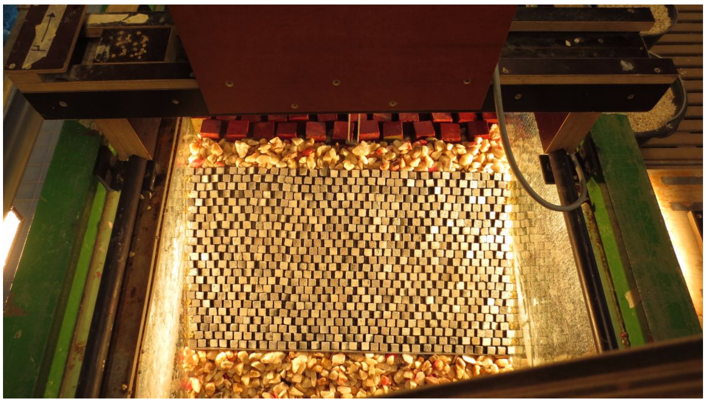

Figure G.63: *Photo before the test*

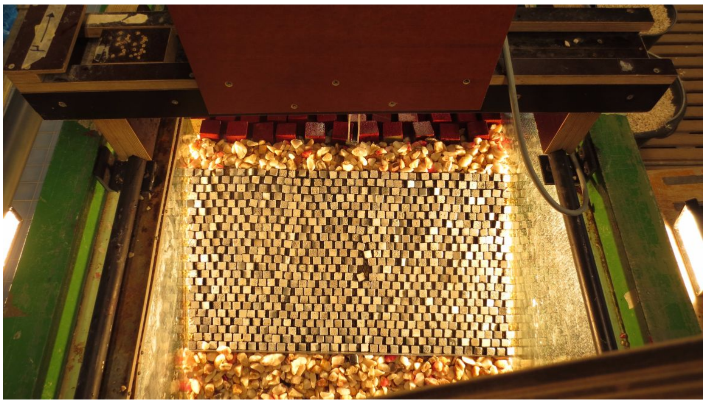

Figure G.64: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.03	0.03	0.06	0.03	0.14	0.07	0.07	0.10	0.10	0.03	0.08	0.08	0.09	0.09	0.04	0.09	0.04	0.04	0.16	0.09	0.04	0.08	0.08	0.14	0.15	0.14	0.03	0.13	0.07	0.05	0.10	0.09	0.08
2	0.03	0.03	0.18	0.06	0.10	0.03	0.10	0.05	0.14	0.03	0.09	0.12	0.08	0.08	0.09	0.04	0.19	0.08	0.04	0.08	0.04	0.16	0.03	0.03	0.15	0.07	0.03	0.12	0.17	0.13	0.03		0.08
3	0.11	0.08	0.11	0.17	0.06	0.13	0.10	0.05	0.14	0.03	0.08	0.07	0.11	0.03	0.09	0.09	0.04	0.14	0.04	0.03	0.14	0.09	0.09	0.09	0.12	0.03	0.10	0.03	0.05	0.08	0.03	0.18	0.09
4	0.11	0.02	0.03	0.07	0.07	0.17	0.03	0.10	0.03	0.08	0.03	0.08	0.08	0.12	0.09	0.13	0.04	0.08	0.08	0.04	0.04	0.09	0.11	0.03	0.09	0.05	0.03	0.10	0.02	0.09	0.10		0.07
5	0.11	0.06	0.06	0.07	0.15	0.05	0.07	0.07	0.14	0.03	0.03	0.04	0.08	0.08	0.08	0.11	0.09	0.09	0.04	0.04	0.04	0.09	0.08	0.08	0.04	0.03	0.08	0.15	0.05	0.09	0.10	0.02	0.07
6	0.16	0.14	0.11	0.06	0.02	0.09	0.05	0.07	0.05	0.15	0.03	0.09	0.09	0.03	0.04	0.04	0.15	0.08	0.03	0.04	0.05	0.10	0.08	0.12	0.13	0.14	0.13	0.07	0.07	0.07	0.09		0.08
7	0.51	0.06	0.06	0.06	0.14	0.03	0.03	0.17	0.10	0.09	0.09	0.20	0.20	0.18	0.09	0.14	0.08	0.18	0.09	0.11	0.09	0.08	0.03	0.08	0.05	0.04	0.07	0.14	0.02	0.07	0.27	0.02	0.11
8	0.22	0.05	0.06	0.13	0.05	0.06	0.07	0.13	0.04	0.08	0.10	0.11	0.09	0.04	0.04	0.08	0.04	0.03	0.09	0.03	0.12	0.09	0.04	0.04	0.09	0.04	0.14	0.12	0.02	0.18	0.16		0.08
9	0.02	0.11	0.12	0.06	0.11	0.06	0.02	0.10	0.10	0.08	0.09	0.08	0.05	0.03	0.08	0.03	0.03	0.20	0.08	0.03	0.04	0.10	0.19	0.13	0.10	0.13	0.08	0.14	0.06	0.08	0.05	0.16	0.09
10	0.10	0.11	0.06	0.11	0.02	0.04	0.02	0.04	0.09	0.04	0.10	0.10	0.09	0.03	0.04	0.09	0.15	0.09	0.03	0.05	0.10	0.04	0.02	0.07	0.12	0.20	0.02	0.08	0.07	0.02	0.05		0.07
11	0.02	0.09	0.12	0.07	0.12	0.05	0.04	0.06	0.10	0.05	0.02	0.08	0.02	0.09	0.03	0.15	0.08	0.10	0.10	0.05	0.09	0.13	0.10	0.04	0.14	0.07	0.23	0.08	0.02	0.02	0.07	0.05	0.08
12	0.04	0.05	0.06	0.06	0.11	0.02	0.12	0.04	0.04	0.10	0.15	0.05	0.05	0.08	0.05	0.09	0.12	0.09	0.07	0.03	0.30	0.05	0.13	0.08	0.07	0.19	0.07	0.08	0.12	0.07	0.16		0.09
13	0.21	0.07	0.08	0.11	0.05	0.04	0.02	0.08	0.04	0.04	0.06	0.09	0.09	0.05	0.15	0.10	0.11	1.50	0.05	0.09	0.05	0.10	0.09	0.08	0.04	0.06	0.07	0.08	0.09	0.05	0.06	0.08	0.12
14	0.06	0.05	0.06	0.12	0.06	0.01	0.08	0.04	0.02	0.08	0.14	0.07	0.09	0.03	0.07	0.03	0.28	0.13	0.07	0.05	0.03	0.07	0.10	0.04	0.16	0.07	0.04	0.08	0.01	0.08	0.06		0.07
15	0.17	0.11	0.05	0.06	0.08	0.10	0.06	0.08	0.06	0.04	0.09	0.07	0.10	0.04	0.14	0.03	0.12	0.10	0.08	0.03	0.12	0.07	0.14	0.07	0.17	0.21	0.18	0.12	0.23	0.06	0.12	0.06	0.10
16	0.11	0.05	0.08	0.04	0.05	0.16	0.01	0.11	0.05	0.13	0.06	0.09	0.10	0.02	0.08	0.07	0.10	0.05	0.07	0.05	0.07	0.03	0.04	0.09	0.02	0.07	0.04	0.12	0.01	0.08	0.08		0.07
17	0.04	0.01	0.01	0.06	0.07	0.01	0.11	0.05	0.08	0.06	0.05	0.09	0.02	0.05	0.03	0.08	0.07	0.07	0.08	0.07	0.06	0.02	0.12	0.02	0.12	0.06	0.12	0.09	0.04	0.09	0.01	0.08	0.06
18	0.01	0.05	0.05	0.06	0.08	0.11	0.17	0.07	0.01	0.08	0.06	0.07	0.06	0.02	0.03	0.10	0.09	0.13	0.03	0.02	0.02	0.07	0.06	0.10	0.11	0.11	0.07	0.09	0.06	0.09	0.08		0.07
19	0.06	0.01	0.01	0.10	0.15	0.06	0.08	0.11	0.05	0.04	0.04	0.06	0.02	0.09	0.03	0.06	0.05	0.03	0.03	0.09	0.02	0.09	0.06	0.14	0.07	0.07	0.07	0.06	0.07	0.07	0.06	0.12	0.07
20	0.12	0.07	0.05	0.05	0.01	0.08	0.04	0.07	0.07	0.02	0.06	0.07	0.06	0.12	0.10	0.08	0.11	0.06	0.11	0.06	0.06	0.10	0.06	0.04	0.04	0.14	0.06	0.04	0.08	0.06	0.06		0.07
21	0.07	0.05	0.05	0.05	0.12	0.07	0.04	0.10	0.07	0.01	0.06	0.02	0.19	0.09	0.06	0.08	0.10	0.06	0.03	0.08	0.11	0.03	0.03	0.04	0.09	0.13	0.07	0.01	0.06	0.12	0.08	0.12	0.07
22	0.05	0.05	0.11	0.05	0.10	0.06	0.06	0.01	0.04	0.11	0.09	0.10	0.09	0.06	0.10	0.06	0.06	0.08	0.10	0.17	0.06	0.06	0.11	0.11	0.12	0.09	0.07	0.11	0.11	0.06	0.12		0.08
23	0.05	0.07	0.10	0.07	0.01	0.16	0.16	0.11	0.01	0.11	0.11	0.06	0.06	0.06	0.06	0.06	0.10	0.11	0.08	0.06	0.08	0.14	0.11	0.16	0.14	0.14	0.06	0.06	0.01	0.08	0.22	0.05	0.09

Figure G.65: *Displacements*

Test: C8-10-15-2-0.25-0.03-14 (I651421)

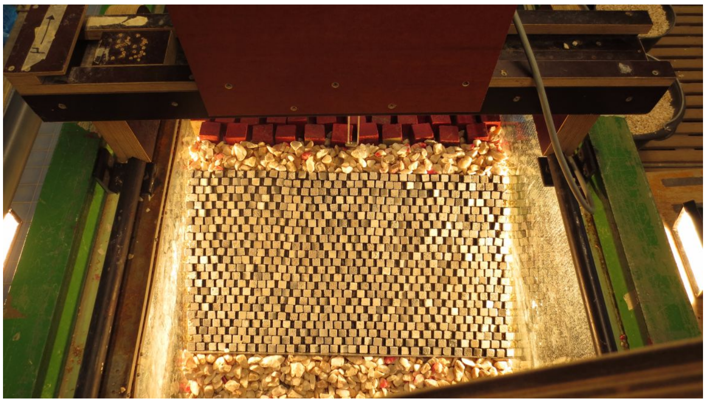

Figure G.66: *Photo before the test*

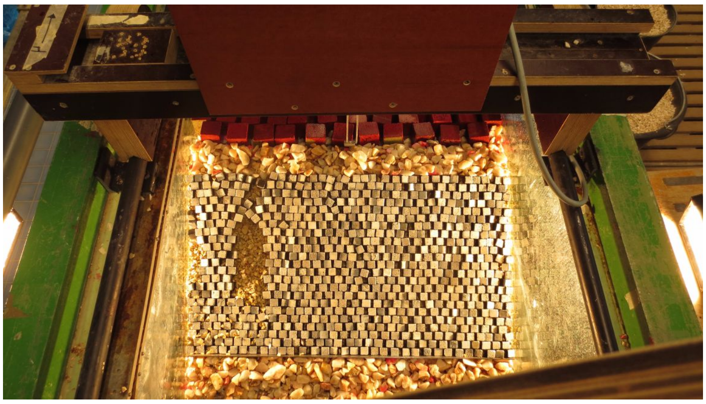

Figure G.67: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.32	0.28	0.10	0.32	0.21	0.19	0.31	1.50	0.25	0.06	0.38	0.11	0.25	0.15	0.10	0.66	0.34	0.19	0.17	0.16	0.34	0.38	0.17	0.20	0.30	0.25	0.18	0.21	0.33	0.25	0.39	0.37	0.29
2	0.25	0.43	0.41	0.09	0.39	0.26	1.50	0.43	0.06	0.11	0.69	0.24	0.25	0.35	0.23	0.30	0.28	0.25	0.08	0.13	0.09	0.47	0.16	0.30	0.22	0.22	0.26	0.23	0.33	0.44	0.16		0.31
3	0.25	0.27	0.17	0.32	0.24	0.16	1.50	0.49	0.22	0.16	0.18	0.22	0.17	0.38	0.19	0.24	0.13	0.19	0.23	0.21	0.32	0.24	0.20	0.25	0.27	0.30	0.27	0.31	0.29	0.32	0.40	0.46	0.30
4	0.51	0.36	0.25	0.30	0.09	0.72	0.47	0.39	0.28	0.11	0.18	0.13	0.09	0.42	0.25	0.25	0.15	0.29	0.15	0.19	0.21	0.24	0.21	0.31	0.30	0.27	0.13	0.27	0.37	0.36	0.26		0.27
5	1.36	0.31	0.26	0.30	0.30	0.37	0.71	0.30	0.22	0.43	0.34	0.21	0.27	0.24	0.27	0.40	0.23	0.18	0.26	0.23	0.30	0.29	0.25	0.31	0.35	0.30	0.23	0.35	0.19	0.41	0.33	0.31	0.34
6	1.43	0.46	0.46	0.20	0.67	1.50	0.75	0.29	0.17	0.32	0.26	0.26	0.20	0.33	0.37	0.32	0.31	0.15	0.15	0.26	0.37	0.25	0.24	0.26	0.31	0.25	0.26	0.21	0.31	0.47	0.29		0.39
7	1.50	0.38	0.33	0.41	0.50	1.50	1.50	0.33	0.29	0.76	0.27	0.18	0.10	0.26	0.27	0.35	0.29	0.23	0.30	0.11	0.28	0.26	0.46	0.22	0.21	0.24	0.23	0.34	0.37	0.32	0.33	0.18	0.42
8	1.50	0.59	0.49	1.38	0.86	1.50	1.50	0.18	0.22	0.32	0.39	0.23	0.25	0.25	0.30	0.24	0.10	0.16	0.26	0.30	0.22	0.48	0.25	0.36	0.32	0.31	0.38	0.36	0.16	0.33	0.39		0.47
9	1.50	0.30	0.57	0.30	0.26	1.50	1.50	1.50	0.17	0.16	0.11	0.15	0.27	0.25	0.29	0.33	0.50	0.44	0.24	0.30	0.30	0.26	0.40	0.31	0.25	0.31	0.21	0.32	0.28	0.38	0.40	0.29	0.45
10	1.50	0.23	0.31	0.25	1.50	1.50	1.50	0.17	0.24	0.21	0.16	0.30	0.21	0.25	0.36	0.24	0.22	0.21	0.24	0.34	0.26	0.37	0.37	0.34	0.26	0.28	0.29	0.27	0.32	0.31	0.49		0.44
11	1.50	1.50	0.23	0.46	0.57	1.50	1.50	1.50	0.33	0.37	0.22	0.26	0.14	0.21	0.36	0.45	0.18	0.37	0.21	0.27	0.19	0.37	0.44	0.16	0.32	0.30	0.23	0.25	0.49	0.24	0.64	0.19	0.50
12	1.50	0.23	0.30	0.53	1.50	1.50	1.50	0.45	0.20	0.16	0.40	0.16	0.26	0.29	0.32	0.34	0.29	0.32	0.24	0.34	0.37	0.30	0.37	0.28	0.29	0.23	0.34	0.32	0.29	0.24	0.30		0.46
13	1.50	0.41	0.28	0.25	0.08	1.50	1.50	1.50	0.28	0.28	0.20	0.37	0.28	0.18	0.27	0.38	0.46	0.40	0.39	0.27	0.23	0.30	0.42	0.37	0.31	0.33	0.33	0.35	0.37	0.31	0.28	0.23	0.46
14	1.50	0.31	0.25	0.24	1.50	1.50	1.50	0.28	0.20	0.20	0.12	0.31	0.26	0.23	0.22	0.25	0.12	0.25	0.32	0.28	0.32	0.34	0.34	0.38	0.29	0.34	0.39	0.36	0.30	0.37	0.62		0.45
15	0.43	0.47	0.21	0.31	0.09	1.50	1.50	1.50	0.32	0.34	0.24	0.22	0.31	0.19	0.27	0.26	0.33	0.36	0.36	0.32	0.25	0.20	0.30	0.27	0.31	0.31	0.29	0.35	0.21	0.35	0.42	0.35	0.41
16	0.26	0.31	0.25	0.25	1.50	1.50	1.50	0.15	0.21	0.25	0.31	0.26	0.27	0.30	0.34	0.31	0.29	0.33	0.40	0.35	0.28	0.46	0.30	0.36	0.23	0.35	0.31	0.26	0.40	0.32	0.23		0.41
17	0.37	0.36	0.26	0.30	0.35	0.15	1.50	1.50	0.33	0.38	0.09	0.32	0.24	0.19	0.34	0.26	0.26	0.25	0.41	0.39	0.33	0.28	0.31	0.38	0.25	0.27	0.34	0.34	0.31	0.38	0.29	0.31	0.38
18	0.43	0.36	0.20	0.26	0.14	0.30	0.14	0.45	0.21	0.30	0.28	0.24	0.31	0.21	0.19	0.30	0.22	0.18	0.25	0.25	0.36	0.39	0.31	0.38	0.38	0.37	0.30	0.30	0.41	0.30	0.40		0.29
19	0.38	0.17	0.42	0.36	0.45	0.25	0.15	0.24	0.33	0.22	0.32	0.24	0.32	0.24	0.33	0.19	0.32	0.30	0.38	0.25	0.36	0.20	0.32	0.40	0.28	0.34	0.16	0.23	0.22	0.25	0.34	0.43	0.29
20	0.27	0.26	0.25	0.30	0.23	0.29	0.20	0.24	0.30	0.25	0.29	0.28	0.36	0.39	0.24	0.44	0.30	0.41	0.23	0.33	0.34	0.36	0.29	0.36	0.38	0.30	0.37	0.39	0.41	0.30	0.27		0.31
21	0.18	0.18	0.52	0.38	0.42	0.35	0.30	0.21	0.22	0.33	0.33	0.29	0.28	0.32	0.25	0.31	0.42	0.31	0.23	0.29	0.33	0.33	0.21	0.28	0.32	0.35	0.27	0.34	0.28	0.28	0.39	0.26	0.31
22	0.11	0.20	0.26	0.25	0.24	0.10	0.41	0.31	0.19	0.42	0.26	0.25	0.22	0.27	0.24	0.38	0.36	0.31	0.26	0.38	0.35	0.40	0.34	0.26	0.35	0.27	0.36	0.31	0.26	0.37	0.35		0.29
23	0.05	0.10	0.42	0.19	0.26	0.31	0.37	0.41	0.15	0.22	0.00	0.40	0.37	0.25	0.15	0.25	0.35	0.29	0.38	0.26	0.38	0.30	0.39	0.46	0.44	0.36	0.39	0.50	0.48	0.27	0.45	0.42	0.31

Figure G.68: *Displacements*

G.11 Configuration 9

Test: C9-10-15-2-0.30-0.03-8 (I650814)

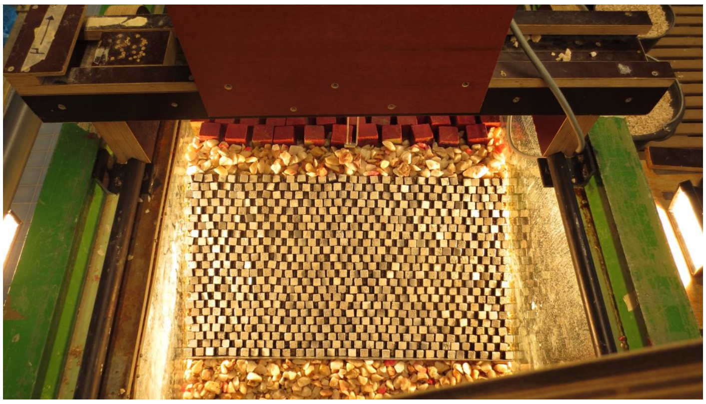

Figure G.69: *Photo before the test*

Figure G.70: *Photo after the test*

Test: C9-10-15-2-0.30-0.03-10 (I651016)

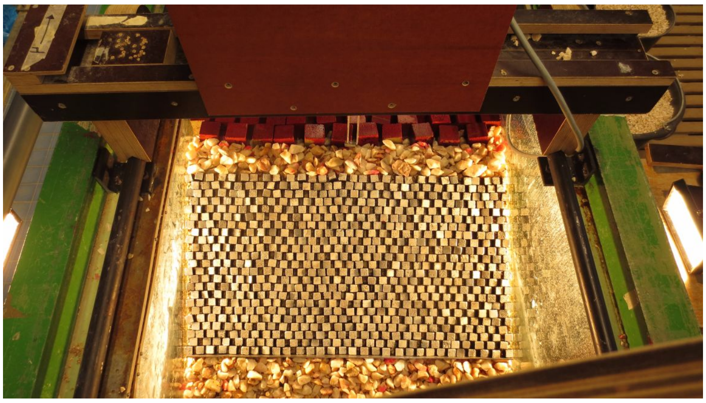

Figure G.71: *Photo before the test*

Figure G.72: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Mean
1	0.11	0.48	0.24	0.17	0.15	0.20	0.12	0.46	0.42	0.15	0.19	0.19	0.15	0.15	0.15	0.11	0.15	0.15	0.28	0.08	0.10	0.14	0.12	0.25	0.23	0.06	0.02	0.02	0.11	0.18
2	0.17	0.05	0.24	0.15	0.15	0.21	0.26	0.78	0.50	0.16	0.16	0.16	0.08	0.08	0.03	0.08	0.15	0.22	0.15	0.15	0.23	0.03	0.07	0.10	0.22	0.11	0.11	0.09		0.17
3	0.18	0.20	0.16	0.15	0.21	0.17	0.17	1.33	0.79	0.16	0.14	0.14	0.16	0.11	0.13	0.18	0.15	0.13	0.29	0.22	0.12	0.10	0.17	0.22	0.07	0.17	0.13	0.11	0.11	0.22
4	0.16	0.22	0.16	0.22	0.17	0.22	0.21	1.15	0.69	0.16	0.19	0.16	0.14	0.15	0.23	0.11	0.15	0.13	0.15	0.19	0.07	0.17	0.17	0.08	0.06	0.16	0.18	0.16		0.21
5	0.13	0.29	0.27	0.21	0.15	0.22	0.09	0.12	0.74	0.34	0.19	0.09	0.16	0.16	0.13	0.15	0.13	0.13	0.15	0.07	0.03	0.14	0.10	0.17	0.13	0.18	0.11	0.13	0.11	0.17
6	0.16	0.26	0.09	0.26	0.07	0.27	0.17	0.30	0.87	0.12	0.12	0.14	0.14	0.14	0.04	0.13	0.20	0.20	0.24	0.15	0.19	0.05	0.10	0.10	0.21	0.11	0.11	0.13		0.18
7	0.25	0.16	0.18	0.13	0.09	0.07	0.17	0.19	0.78	1.44	0.12	0.12	0.19	0.19	0.13	0.19	0.20	0.18	0.13	0.08	0.22	0.07	0.19	0.14	0.33	0.11	0.22	0.14	0.11	0.22
8	0.27	0.13	0.16	0.17	0.44	0.22	0.09	0.26	1.50	0.14	0.16	0.09	0.09	0.13	0.16	0.08	0.08	0.13	0.13	0.18	0.11	0.14	0.07	0.12	0.18	0.23	0.22	0.06		0.21
9	0.30	0.18	0.11	0.17	0.17	0.10	0.25	0.17	0.81	0.27	0.09	0.09	0.12	0.14	0.09	0.16	0.09	0.23	0.18	0.23	0.12	0.18	0.19	0.07	0.09	0.10	0.18	0.11	0.18	0.18
10	0.16	0.11	0.18	0.25	0.24	0.15	0.42	0.52	0.11	0.16	0.14	0.19	0.14	0.12	0.19	0.19	0.08	0.08	0.20	0.19	0.23	0.10	0.07	0.15	0.10	0.22	0.11	0.14		0.18
11	0.13	0.16	0.25	0.21	0.13	0.20	0.20	0.09	0.47	0.17	0.24	0.16	0.24	0.16	0.20	0.12	0.18	0.18	0.11	0.11	0.17	0.07	0.07	0.11	0.11	0.11	0.18	0.04	0.11	0.16
12	0.28	0.14	0.18	0.21	0.22	0.22	0.17	0.53	0.21	0.14	0.16	0.24	0.03	0.19	0.16	0.23	0.13	0.15	0.15	0.15	0.12	0.12	0.11	0.14	0.15	0.14	0.28	0.04		0.18
13	0.11	0.18	0.16	0.10	0.26	0.17	0.10	0.25	0.19	0.15	0.13	0.14	0.16	0.12	0.16	0.09	0.12	0.13	0.08	0.07	0.13	0.12	0.15	0.17	0.07	0.14	0.11	0.09	0.14	0.14
14	0.23	0.21	0.21	0.22	0.15	0.34	0.22	0.20	0.05	0.15	0.19	0.09	0.24	0.14	0.24	0.12	0.24	0.16	0.20	0.07	0.11	0.12	0.07	0.11	0.11	0.19	0.11	0.07		0.16
15	0.18	0.16	0.16	0.16	0.26	0.21	0.13	0.17	0.17	0.19	0.15	0.13	0.09	0.09	0.08	0.16	0.13	0.13	0.20	0.13	0.23	0.11	0.15	0.15	0.12	0.12	0.17	0.12	0.05	0.15
16	0.16	0.16	0.21	0.16	0.22	0.18	0.09	0.22	0.17	0.20	0.14	0.35	0.14	0.19	0.19	0.08	0.16	0.18	0.20	0.08	0.07	0.15	0.15	0.11	0.12	0.14	0.16	0.05		0.16
17	0.01	0.11	0.16	0.21	0.18	0.11	0.15	0.13	0.14	0.21	0.10	0.24	0.09	0.26	0.18	0.16	0.16	0.13	0.19	0.18	0.13	0.16	0.12	0.22	0.11	0.19	0.19	0.11	0.16	0.16
18	0.27	0.14	0.11	0.21	0.15	0.21	0.10	0.13	0.17	0.15	0.09	0.19	0.13	0.14	0.14	0.19	0.13	0.16	0.19	0.18	0.17	0.12	0.17	0.11	0.07	0.12	0.23	0.01		0.15
19	0.21	0.23	0.18	0.29	0.21	0.14	0.20	0.20	0.15	0.16	0.25	0.20	0.13	0.09	0.13	0.14	0.16	0.20	0.13	0.12	0.08	0.05	0.13	0.12	0.24	0.11	0.22	0.05	0.11	0.16
20	0.19	0.14	0.18	0.18	0.14	0.16	0.14	0.25	0.20	0.20	0.20	0.17	0.19	0.09	0.19	0.14	0.24	0.16	0.13	0.25	0.17	0.13	0.20	0.08	0.12	0.12	0.15	0.12		0.16
21	0.07	0.21	0.21	0.14	0.21	0.21	0.15	0.20	0.14	0.27	0.20	0.10	0.14	0.14	0.14	0.16	0.14	0.14	0.10	0.09	0.08	0.08	0.06	0.17	0.17	0.12	0.16	0.15	0.15	0.15
22	0.22	0.21	0.22	0.18	0.26	0.18	0.26	0.15	0.10	0.15	0.21	0.17	0.14	0.06	0.13	0.09	0.13	0.13	0.09	0.13	0.17	0.18	0.13	0.08	0.12	0.08	0.12	0.10		0.14
23	0.12	0.23	0.21	0.26	0.22	0.25	0.15	0.11	0.20	0.22	0.22	0.25	0.22	0.17	0.21	0.17	0.20	0.13	0.24	0.20	0.20	0.20	0.12	0.08	0.06	0.15	0.19	0.12	0.10	0.18

Figure G.73: *Displacements*

Test: C9-10-15-2-0.30-0.03-12 (I651218)

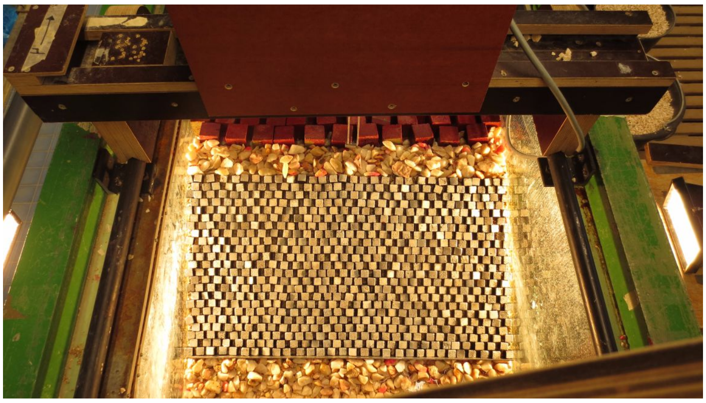

Figure G.74: *Photo before the test*

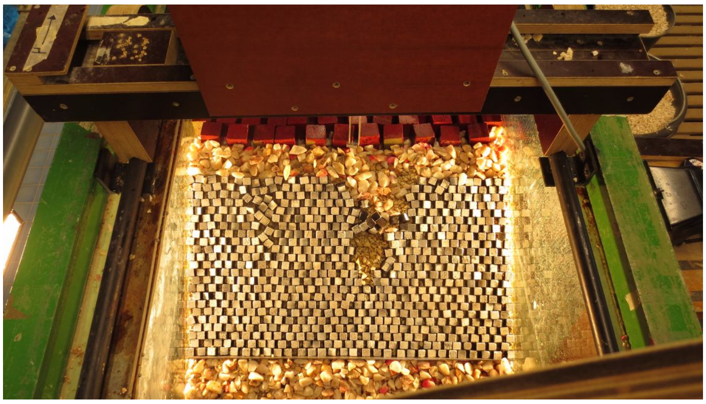

Figure G.75: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Mean
1	0.29	0.31	0.27	0.23	0.52	0.55	0.88	0.38	0.29	0.25	0.47	0.18	0.23	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.24	0.26	0.55	0.15	0.20	0.18	0.22	0.23	0.64
2	0.20	0.22	0.28	0.22	0.57	0.90	0.66	0.40	0.14	0.13	0.16	0.18	0.18	0.73	1.50	1.50	1.50	1.50	1.50	1.50	0.17	0.23	0.30	0.28	0.19	0.13	0.17	0.11		0.54
3	0.27	0.27	0.22	0.11	0.07	0.84	0.92	0.64	0.27	0.17	0.23	0.20	0.20	0.24	0.39	1.50	1.50	1.50	1.50	1.50	0.37	0.14	0.23	0.20	0.23	0.08	0.17	0.12	0.22	0.48
4	0.19	0.15	0.21	0.11	0.16	1.28	1.12	0.82	0.13	0.23	0.17	0.16	0.11	0.21	0.29	0.38	1.50	1.50	1.50	1.50	0.13	0.06	0.11	0.20	0.16	0.27	0.22	0.21		0.46
5	0.19	0.07	0.14	0.22	0.14	0.16	1.07	0.43	0.28	0.22	0.17	0.11	0.11	0.19	0.11	0.27	1.50	1.50	1.50	1.50	0.13	0.18	0.11	0.22	0.16	0.12	0.10	0.17	0.08	0.38
6	0.23	0.11	0.17	0.18	0.11	0.35	0.67	0.24	0.13	0.11	0.17	0.08	0.21	0.23	0.11	1.50	1.50	1.50	0.22	0.36	0.28	0.22	0.17	0.11	0.08	0.05	0.15	0.12		0.33
7	0.10	0.21	0.22	0.14	0.17	0.16	0.10	0.72	0.16	0.17	0.12	0.18	0.12	0.16	0.10	0.86	0.64	1.50	1.50	1.50	0.24	0.17	0.26	0.11	0.15	0.16	0.18	0.10	0.11	0.35
8	0.11	0.15	0.06	0.05	0.13	0.05	0.77	0.42	0.27	0.16	0.12	0.08	0.22	0.11	0.19	1.50	1.50	1.03	0.42	0.17	0.15	0.32	0.13	0.20	0.05	0.04	0.11	0.07		0.30
9	0.10	0.25	0.11	0.10	0.15	0.15	0.20	0.95	0.27	0.19	0.12	0.15	0.11	0.04	0.20	1.50	1.50	1.50	0.86	0.32	0.24	0.15	0.15	0.05	0.04	0.08	0.07	0.16	0.14	0.33
10	0.25	0.27	0.13	0.15	0.17	0.24	0.28	0.16	0.16	0.19	0.09	0.11	0.15	0.11	0.16	1.50	1.50	0.95	0.65	0.17	0.10	0.09	0.15	0.19	0.15	0.15	0.14	0.14		0.30
11	0.18	0.14	0.17	0.06	0.13	0.24	0.20	0.19	0.23	0.11	0.11	0.09	0.09	0.10	0.20	1.50	1.50	1.50	0.61	0.17	0.16	0.23	0.09	0.21	0.19	0.14	0.14	0.15	0.14	0.30
12	0.10	0.10	0.13	0.13	0.20	0.26	0.14	0.23	0.08	0.13	0.14	0.15	0.10	0.10	0.14	1.50	1.50	0.77	0.14	0.09	0.14	0.21	0.11	0.03	0.09	0.15	0.10	0.15		0.25
13	0.18	0.21	0.10	0.10	0.12	0.16	0.14	0.16	0.14	0.22	0.03	0.09	0.10	0.14	0.15	0.14	1.50	0.22	0.33	0.19	0.12	0.19	0.12	0.08	0.08	0.05	0.08	0.08	0.14	0.18
14	0.17	0.13	0.17	0.12	0.09	0.08	0.04	0.15	0.08	0.03	0.14	0.14	0.11	0.08	0.08	0.10	0.59	0.19	0.14	0.04	0.11	0.11	0.08	0.15	0.13	0.14	0.03	0.06		0.12
15	0.11	0.11	0.09	0.10	0.09	0.08	0.16	0.08	0.15	0.08	0.15	0.08	0.17	0.13	0.17	0.13	0.05	0.05	0.08	0.08	0.08	0.04	0.08	0.09	0.14	0.09	0.09	0.13	0.08	0.10
16	0.11	0.10	0.12	0.12	0.09	0.04	0.08	0.15	0.13	0.14	0.13	0.19	0.16	0.13	0.11	0.14	0.28	0.12	0.12	0.08	0.15	0.08	0.13	0.04	0.07	0.09	0.07	0.13		0.12
17	0.06	0.13	0.05	0.05	0.09	0.14	0.13	0.20	0.08	0.14	0.14	0.07	0.11	0.13	0.13	0.05	0.12	0.08	0.13	0.11	0.14	0.13	0.08	0.04	0.04	0.07	0.17	0.13	0.14	0.11
18	0.07	0.05	0.08	0.12	0.08	0.08	0.05	0.10	0.07	0.02	0.17	0.09	0.14	0.09	0.09	0.14	0.13	0.08	0.08	0.13	0.03	0.08	0.12	0.13	0.10	0.09	0.02	0.07		0.09
19	0.31	0.12	0.05	0.15	0.12	0.15	0.19	0.12	0.18	0.14	0.13	0.07	0.02	0.09	0.11	0.08	0.12	0.19	0.10	0.07	0.07	0.03	0.07	0.07	0.12	0.12	0.08	0.17	0.07	0.11
20	0.20	0.11	0.21	0.15	0.15	0.07	0.15	0.05	0.10	0.07	0.08	0.12	0.09	0.08	0.08	0.17	0.11	0.08	0.15	0.07	0.10	0.14	0.02	0.12	0.02	0.13	0.10	0.13		0.11
21	0.21	0.10	0.08	0.07	0.04	0.11	0.15	0.15	0.13	0.09	0.07	0.12	0.09	0.11	0.13	0.06	0.08	0.06	0.07	0.11	0.10	0.12	0.17	0.06	0.07	0.06	0.06	0.06	0.13	0.10
22	0.12	0.12	0.15	0.11	0.18	0.10	0.06	0.03	0.17	0.13	0.11	0.13	0.08	0.06	0.11	0.11	0.18	0.09	0.07	0.10	0.11	0.21	0.07	0.09	0.01	0.01	0.06	0.06		0.10
23	0.17	0.10	0.11	0.07	0.12	0.09	0.14	0.11	0.13	0.13	0.07	0.13	0.06	0.00	0.05	0.06	0.15	0.18	0.07	0.10	0.10	0.06	0.06	0.09	0.07	0.12	0.06	0.06	0.08	0.09

Figure G.76: *Displacements*

G.12 Configuration 10

Test: C10-10-15-1.5-0.25-0.03-10 (I651016)

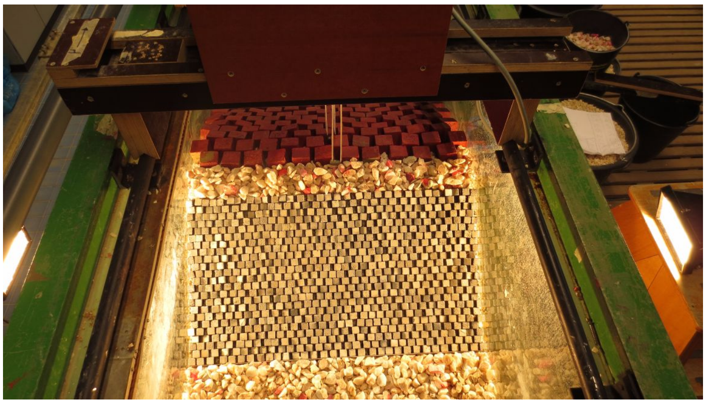

Figure G.77: *Photo before the test*

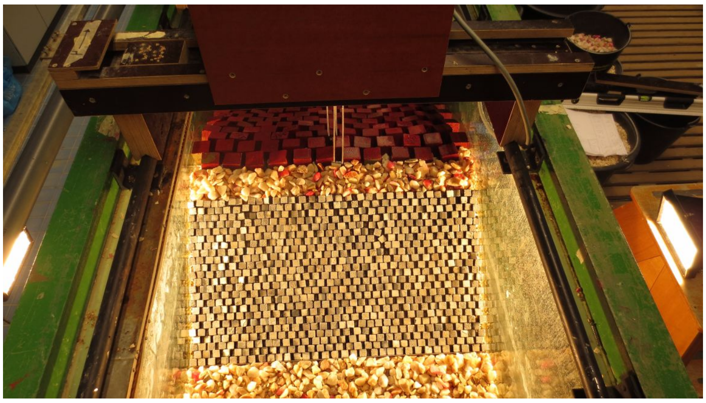

Figure G.78: *Photo after the test*

Test: C10-10-15-1.5-0.25-0.03-12 (I651218)

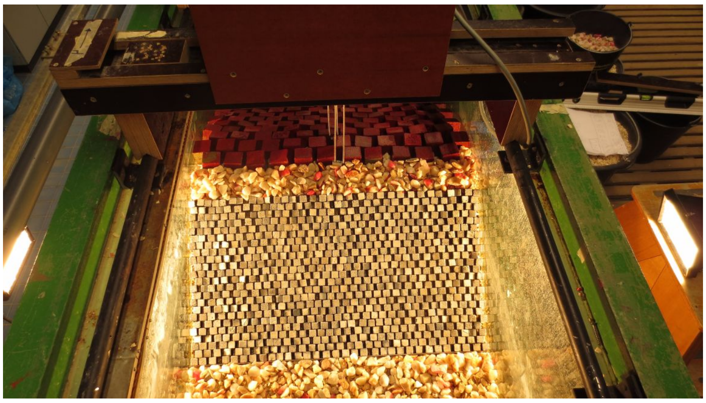

Figure G.79: *Photo before the test*

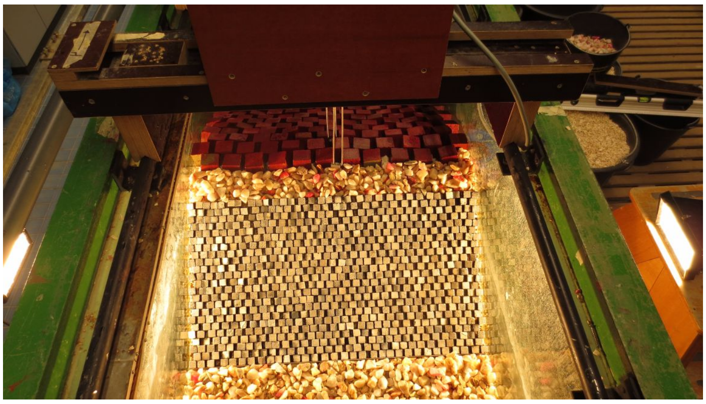

Figure G.80: *Photo after the test*

Test: C10-10-15-1.5-0.25-0.03-14 (I651421)

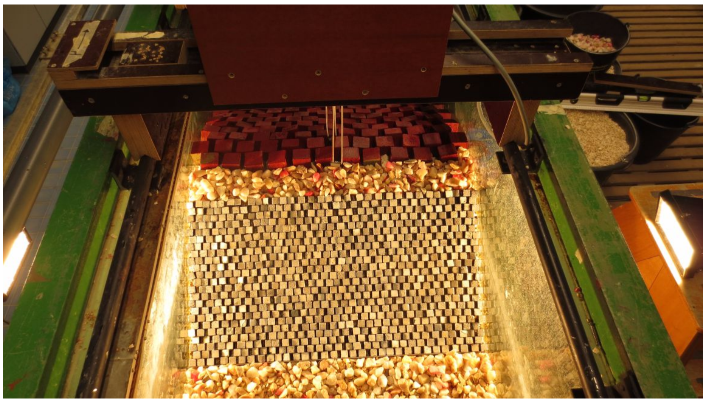

Figure G.81: *Photo before the test*

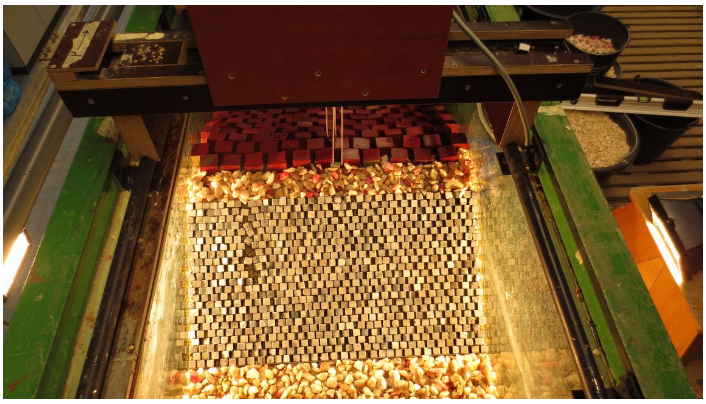

Figure G.82: *Photo after the test*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Mean
1	0.13	0.08	0.01	0.07	0.09	0.09	0.07	0.19	0.10	0.11	0.15	0.15	0.07	0.12	0.12	0.12	0.08	0.01	0.06	0.08	0.01	0.13	0.13	0.20	0.15	0.08	0.07	0.21	0.12	0.10	0.10	0.12	0.10
2	0.12	0.13	0.17	0.07	0.05	0.16	0.20	0.04	0.03	0.24	0.07	0.11	0.07	0.12	0.05	0.16	0.08	0.13	0.06	0.05	0.06	0.13	0.14	0.08	0.15	0.20	0.06	0.16	0.15	0.17	0.07		0.11
3	0.06	0.06	0.08	0.06	0.01	0.07	0.02	0.04	0.03	0.03	0.03	0.06	0.02	0.04	0.12	0.08	0.06	0.06	0.06	0.13	0.07	0.13	0.14	0.08	0.10	0.08	0.06	0.21	0.07	0.07	0.10	0.22	0.08
4	0.06	0.08	0.21	0.01	0.09	0.12	0.65	0.16	0.15	0.09	0.03	0.07	0.17	0.16	0.20	0.07	0.01	0.06	0.09	0.12	0.07	0.07	0.15	0.08	0.03	0.14	0.21	0.07	0.16	0.10	0.23		0.13
5	0.09	0.01	0.06	0.09	0.07	0.07	0.16	0.47	0.06	0.06	0.11	0.02	0.06	0.04	0.10	0.01	0.06	0.13	0.13	0.05	0.27	0.13	0.09	0.20	0.14	0.21	0.19	0.15	0.04	0.22	0.07	0.17	0.12
6	0.09	0.13	0.05	0.05	0.05	0.08	0.49	0.08	0.10	0.03	0.18	0.11	0.02	0.19	0.05	0.05	0.07	0.12	0.01	0.06	0.13	0.07	0.13	0.20	0.14	0.16	0.15	0.15	0.10	0.06	0.10		0.11
7	0.12	0.07	0.05	0.01	0.07	0.02	0.10	0.32	0.05	0.09	0.03	0.04	0.12	0.05	0.08	0.08	0.11	0.01	0.06	0.01	0.35	0.07	0.07	0.09	0.10	0.15	0.15	0.16	0.16	0.17	0.17	0.17	0.10
8	0.07	0.02	0.07	0.10	0.09	0.05	1.50	0.14	0.11	0.10	0.03	0.10	0.10	0.05	0.07	0.05	0.11	0.12	0.06	0.01	0.05	0.09	0.09	0.20	0.08	0.10	0.16	0.15	0.22	0.16	0.17		0.14
9	0.06	0.07	0.07	0.07	0.21	0.11	0.34	0.28	0.03	0.10	0.12	0.08	0.04	0.06	0.11	0.09	0.05	0.09	0.07	0.02	0.07	0.07	0.08	0.08	0.11	0.09	0.16	0.10	0.06	0.16	0.06	0.11	0.10
10	0.14	0.04	0.08	0.09	0.02	0.22	1.50	0.25	0.09	0.10	0.10	0.10	0.13	0.02	0.09	0.11	0.06	0.06	0.12	0.12	0.15	0.10	0.20	0.09	0.16	0.11	0.15	0.10	0.12	0.14	0.11		0.16
11	0.11	0.08	0.06	0.08	0.10	0.09	0.10	1.50	0.09	0.04	0.03	0.10	0.09	0.06	0.05	0.09	0.12	0.02	0.02	0.07	0.08	0.13	0.08	0.11	0.21	0.15	0.05	0.17	0.10	0.11	0.02	0.13	0.13
12	0.12	0.12	0.07	0.08	0.03	0.05	0.21	0.09	0.04	0.09	0.05	0.11	0.10	0.04	0.11	0.04	0.18	0.07	0.07	0.07	0.13	0.04	0.14	0.20	0.14	0.09	0.09	0.05	0.10	0.10	0.22		0.10
13	0.10	0.07	0.09	0.06	0.03	0.10	0.21	0.10	0.09	0.04	0.10	0.03	0.05	0.10	0.11	0.11	0.10	0.08	0.15	0.07	0.03	0.11	0.08	0.14	0.12	0.04	0.04	0.10	0.16	0.05	0.11	0.11	0.09
14	0.07	0.16	0.07	0.06	0.08	0.04	0.04	0.04	0.09	0.09	0.04	0.09	0.10	0.11	0.06	0.11	0.06	0.03	0.12	0.15	0.07	0.03	0.08	0.14	0.14	0.12	0.15	0.09	0.18	0.05	0.17		0.09
15	0.02	0.07	0.06	0.03	0.12	0.10	0.10	0.04	0.09	0.05	0.04	0.05	0.09	0.03	0.03	0.09	0.11	0.07	0.06	0.21	0.07	0.11	0.03	0.08	0.17	0.22	0.13	0.17	0.18	0.05	0.16	0.22	0.10
16	0.09	0.04	0.05	0.08	0.08	0.05	0.04	0.12	0.05	0.10	0.03	0.10	0.09	0.11	0.11	0.11	0.03	0.10	0.03	0.13	0.08	0.09	0.03	0.09	0.17	0.15	0.21	0.33	0.10	0.18	0.10		0.10
17	0.06	0.12	0.07	0.04	0.04	0.08	0.04	0.13	0.05	0.10	0.05	0.10	0.06	0.05	0.11	0.02	0.12	0.06	0.13	0.07	0.12	0.19	0.21	0.09	0.09	0.20	0.10	0.15	0.16	0.22	0.11	0.06	0.10
18	0.15	0.08	0.08	0.10	0.08	0.16	0.10	0.09	0.10	0.13	0.10	0.16	0.11	0.05	0.06	0.12	0.12	0.07	0.07	0.04	0.19	0.14	0.20	0.09	0.10	0.10	0.05	0.05	0.14	0.06	0.11		0.10
19	0.10	0.10	0.15	0.07	0.10	0.13	0.17	0.03	0.11	0.05	0.10	0.06	0.02	0.05	0.05	0.04	0.12	0.12	0.04	0.07	0.13	0.04	0.02	0.05	0.20	0.03	0.05	0.05	0.14	0.05	0.17	0.05	0.08
20	0.11	0.11	0.05	0.05	0.02	0.02	0.06	0.11	0.15	0.11	0.19	0.11	0.05	0.11	0.11	0.18	0.12	0.06	0.04	0.13	0.07	0.05	0.22	0.09	0.14	0.15	0.05	0.22	0.10	0.11	0.05		0.10
21	0.06	0.13	0.07	0.05	0.04	0.02	0.09	0.14	0.07	0.09	0.11	0.02	0.07	0.11	0.11	0.01	0.07	0.07	0.01	0.12	0.13	0.17	0.13	0.05	0.08	0.11	0.06	0.10	0.11	0.10	0.17	0.12	0.09
22	0.08	0.14	0.01	0.07	0.05	0.06	0.06	0.10	0.15	0.06	0.12	0.10	0.17	0.20	0.12	0.16	0.06	0.05	0.08	0.05	0.05	0.09	0.09	0.05	0.20	0.06	0.09	0.06	0.16	0.07	0.12		0.09
23	0.08	0.13	0.11	0.09	0.06	0.17	0.04	0.12	0.12	0.03	0.12	0.16	0.11	0.07	0.11	0.08	0.11	0.13	0.13	0.05	0.10	0.14	0.08	0.14	0.14	0.18	0.18	0.11	0.10	0.12	0.18	0.17	0.11

Figure G.83: *Displacements*

G.13 Configuration 11

Test: C11-10-15-1.5-0.30-0.03-8 (I650814)

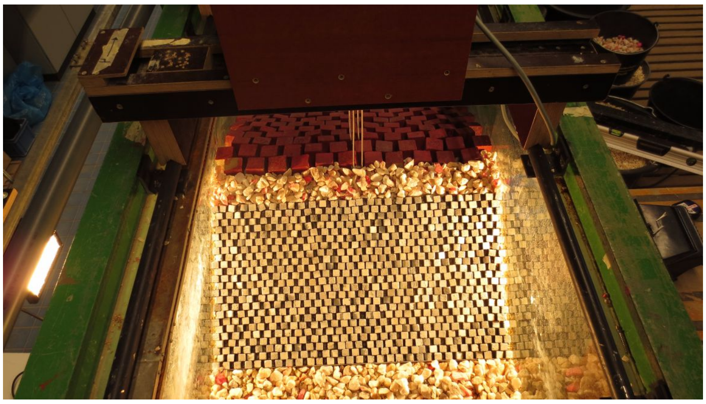

Figure G.84: *Photo before the test*

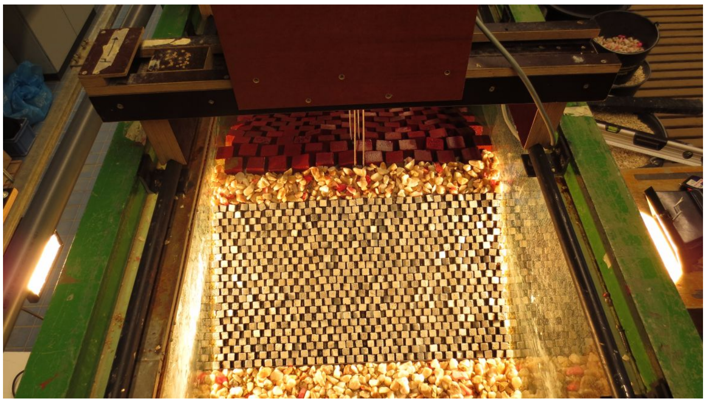

Figure G.85: *Photo after the test*

Test: C11-10-15-1.5-0.30-0.03-10 (I651016)

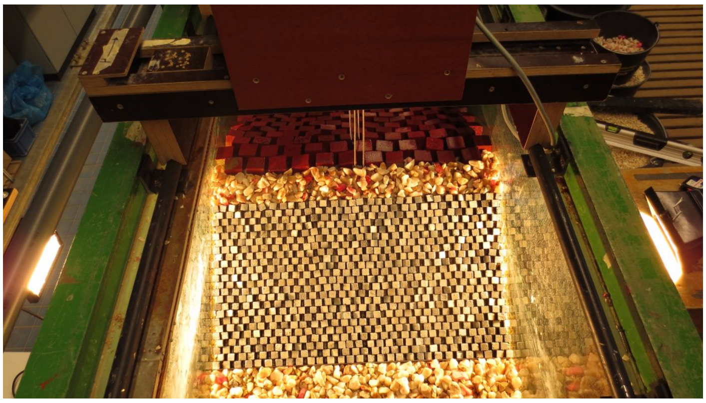

Figure G.86: *Photo before the test*

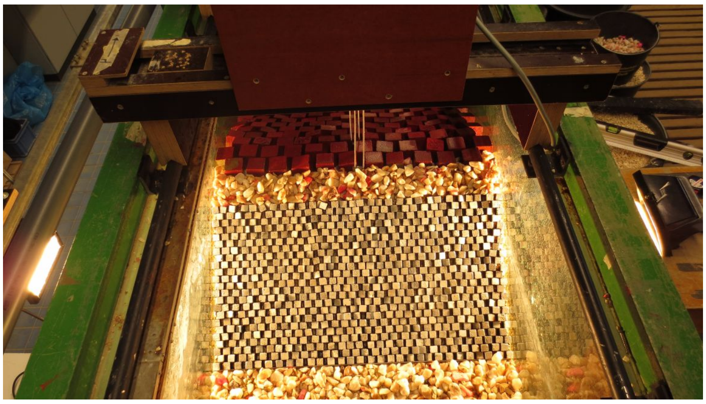

Figure G.87: *Photo after the test*

Test: C11-10-15-1.5-0.30-0.03-12 (I651218)

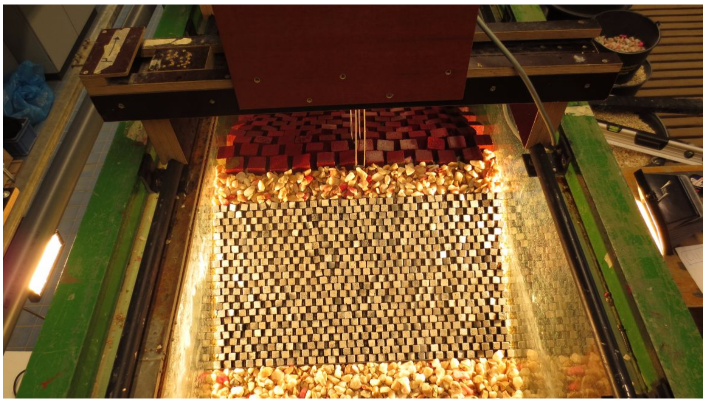

Figure G.88: *Photo before the test*

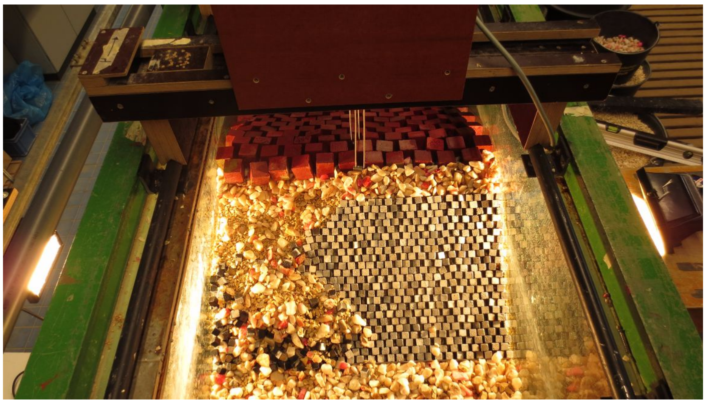

Figure G.89: *Photo after the test*

H | Overtopping front velocity

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The overtopping front velocity is measured by two wave gauges on the crest of the breakwater (see figure H.1). The output of the wave gauges is a data set containing the voltage of both gauges for every hundreds of a second. The resulting overtopping velocity is determined by a routine written in Python (see next pages). The following list summarizes the processing steps within this routine.

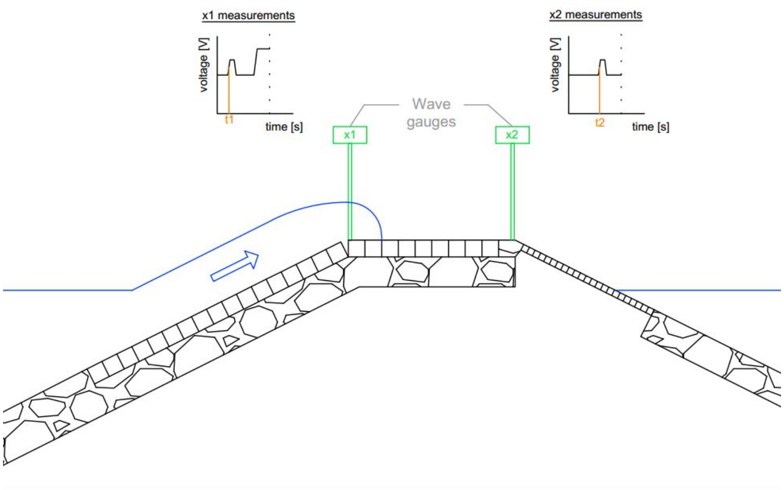

Figure H.1: *Sketch of overtopping front velocity measurements*

- First, the data set of a single test is imported. The first three columns are used, namely time, voltage of wave gauge x1 and voltage of wave gauge x2.
- Subsequently, the voltage data of both wave gauges are adjusted. Values above the threshold are replaced by a 1 and below the threshold by a 0.
- Measuring errors within the obtained list of zeros and ones are removed by using a minimal wave length and minimal wave pause length. The values for both parameters are determined iterative and are calibrated on the number of overtopping waves. The observed number of overtopping waves should be the same as the calculated one.
- The start of a wave can be identified by finding the first 1 value in a row of ones. This processing step is performed for both wave gauges and results in two lists of starting times of the waves.

- The start of the overtopping waves at the second wave gauge (t2) is correlated to the start of the wave at the first wave gauge (t1). Since not all waves arrive at the second wave gauge, a minimal time between the two wave signals is applied. The distance between the wave gauges (dist_x1x2) is divided by the time difference between the wave passing wave gauge x1 and wave gauge x2 (t2-t1), resulting in the overtopping front velocity of all individual overtopping waves.

- The number of waves, the maximum and the mean overtopping front velocity are obtained from the list of velocities.

- This same procedure is carried out for all the other tests and all necessary output parameters are saved in csv-files.

- The highest two percent overtopping front velocity is determined with a second routine (see next pages). The non-overtopping waves are added to the list of overtopping velocities as zero values. This list is sorted and the highest 2 percent velocities are removed. The highest remaining value is the $u_{2\%}$ value.

```python
import numpy as np
import pandas as pd
from math import ceil
import re


configurations = [
    {
        'id': '1',
        'disabled': True,
        'dist_x1x2': 0.485,
        'tests': [
            {'name': 'I601219'},
            {'name': 'I601421'},
            {'name': 'I601624'},
        ]
    },
    {
        'id': '2',
        'disabled': True,
        'dist_x1x2': 0.485,
        'tests': [
            {'name': 'I651016'},
            {'name': 'I651218'},
            {'name': 'I651421'},
            {'name': 'I651623'},
        ]
    },
    {
        'id': '3',
        'disabled': True,
        'dist_x1x2': 0.485,
        'tests': [
            {'name': 'I700814'},
            {'name': 'I701016'},
            {'name': 'I701218'},
            {'name': 'I701420'},
        ]
    },
    {
        'id': '4',
        'disabled': True,
        'dist_x1x2': 0.485,
        'threshold': 0,
        'min_wave_length':5,
        'min_pause_length':50,
        'tests': [
            {'name': 'I651013'},
            {'name': 'I651215'},
            {'name': 'I651417'},
            {'name': 'I651618'},
        ]
    },
    {
        'id': '5',
        'disabled': True,
        'dist_x1x2': 0.471,
        'threshold': 0.75,
```

```
        'min_wave_length':50,
        'min_pause_length':50,
        'tests': [
            {'name': 'I651022'},
            {'name': 'I651225'},
            {'name': 'I651429'},
        ]
    },
    {
        'id': '6',
        'disabled': True,
        'dist_x1x2': 0.283,
        'threshold': 0,
        'min_wave_length':1,
        'min_pause_length':50,
        'tests': [
            {'name': 'I651016'},
            {'name': 'I651218'},
            {'name': 'I651421'},
            {'name': 'I651623'},
        ]
    },
    {
        'id': '7',
        'disabled': True,
        'dist_x1x2': 0.285,
        'threshold': 0.75,
        'min_wave_length': 1,
        'min_pause_length': 50,
        'tests': [
            {'name': 'I651016_new'},
            {'name': 'I651218'},
        ]
    },
    {
        'id': '8',
        'disabled': True,
        'dist_x1x2': 0.134,
        'threshold': 0,
        'min_wave_length': 1,
        'min_pause_length': 50,
        'tests': [
            {'name': 'I651016'},
            {'name': 'I651218'},
            {'name': 'I651421'},
        ]
    },
    {
        'id': '9',
        'disabled': False,
        'dist_x1x2': 0.134,
        'threshold': 0.75,
        'min_wave_length': 10,
        'min_pause_length': 50,
        'tests': [
            {'name': 'I650814'},
            {'name': 'I651016'},
            {'name': 'I651218'},
```

```
        ]
    },
    {
        'id': '10',
        'disabled': False,
        'dist_x1x2': 0.134,
        'threshold': 0,
        'min_wave_length': 1,
        'min_pause_length': 50,
        'tests': [
            {'name': 'I651016'},
            {'name': 'I651218'},
            {'name': 'I651421'},
        ]
    },
    {
        'id': '11',
        'disabled': False,
        'dist_x1x2': 0.134,
        'threshold': 0.75,
        'min_wave_length': 1,
        'min_pause_length': 50,
        'tests': [
            {'name': 'I650814'},
            {'name': 'I651016'},
            {'name': 'I651218'},
        ]
    },]


N_ow_all=[]
u_max_all=[]
u_m_all=[]


for configuration in configurations:
    if configuration['disabled']:
        print "CONFIGURATION %s is disabled, skipping" % configuration['id']
        continue

    print "CONFIGURATION %s" % configuration['id']

    for test in configuration['tests']:
        print "TEST %s" % test['name']

        # set vars
        dist_x1x2 = configuration['dist_x1x2']
        name = test['name']
        threshold = configuration.get('threshold', 0.25)
        # amount of subsequent ones:
        min_wave_length = configuration.get('min_wave_length', 10)
        # amount of subsequent zeros:
        min_pause_length = configuration.get('min_pause_length', 50)
        max_wave_speed = configuration.get('max_wave_speed', 2.5)


        #for thres in np.arange(1,4,0.25):
        df = pd.read_csv("""C:\Users\Lisette\Google Drive\Mijn studie\Master
```

```python
df.columns = ['time', 'x2', 'x1', 'G1', 'G2', 'G3', 'G4']
del df['G1'], df['G2'], df['G3'], df['G4']

# Calculate mean before changing values into 0 & 1
mean_x1= df['x1'].mean()
mean_x2 =df['x2'].mean()

thres_x1 = mean_x1+abs(threshold * mean_x1)
thres_x2 = mean_x2+abs(threshold * mean_x2)

if thres_x1<0:
    df['x1'][df['x1'] >= (thres_x1)] = 1
    df['x2'][df['x2'] >= (thres_x2)] = 1

    df['x1'][df['x1'] < (thres_x1)] = 0
    df['x2'][df['x2'] < (thres_x2)] = 0
else:
    df['x1'][df['x1'] < (thres_x1)] = 0
    df['x2'][df['x2'] < (thres_x2)] = 0

    df['x1'][df['x1'] >= (thres_x1)] = 1
    df['x2'][df['x2'] >= (thres_x2)] = 1

x1_wave_string = ''
x2_wave_string = ''

for row in df.iterrows():
    x1_wave_string += str(int(row[1]['x1']))
    x2_wave_string += str(int(row[1]['x2']))

p = re.compile(r"((0{%i,%i})(1{%i,%i}))"
% (min_pause_length, len(x1_wave_string), min_wave_length,
len(x1_wave_string)))

gauges = ['x1', 'x2']
x1_waves = []
x2_waves = []
for gauge in gauges:
    wave_string = x1_wave_string if gauge == 'x1' else x2_wave_strir

    for m in p.finditer(wave_string):
        start = m.start()
        start_wave = m.group().find('1')
        position = start + start_wave

        if gauge == 'x1':
            x1_waves.append(position)
        else:
            x2_waves.append(position)

velocities = []
x1_waves = sorted(x1_waves, reverse=True)
x2_waves = sorted(x2_waves)

for t2 in x2_waves:
    for t1 in x1_waves:
        min_time = dist_x1x2 / max_wave_speed
```

```
                if (t1+min_time*100) < t2:
                    velocities.append(dist_x1x2/(t2-t1)*100)
                    break

        N_ow=len(velocities)
        u_max=np.max(velocities)
        u_m=np.mean(velocities)

        print "Calculated %i waves" % N_ow
        print "u_max: %.2f" % u_max
        print "u_m: %.2f" % u_m

        # write values to 1 matrix
        N_ow_all.append(N_ow)
        u_max_all.append(u_max)
        u_m_all.append(u_m)

        # write velocties to csv to make graph
        velocities_df = pd.DataFrame(velocities, columns=['velocity'])
        velocities_df.to_csv('Results/velocities_C%s_%s.csv' % (configuratio


        print "\n"
    print "="*20

N_ow_all = pd.DataFrame(N_ow_all, columns=['N_ow'])
N_ow_all.to_csv('Results/N_ow_all.csv', index=False, header=False)

u_max_all = pd.DataFrame(u_max_all, columns=['u_max'])
u_max_all.to_csv('Results/u_max_all.csv', index=False, header=False)

u_m_all = pd.DataFrame(u_m_all, columns=['u_m'])
u_m_all.to_csv('Results/u_m_all.csv', index=False, header=False)
```

```
close all
clear all

per=0.02;
file = {'velocities_C1_I601219.csv','velocities_C1_I601421.csv',...
    'velocities_C1_I601624.csv','velocities_C2_I651016.csv',...
    'velocities_C2_I651218.csv','velocities_C2_I651421.csv',...
    'velocities_C2_I651623.csv','velocities_C3_I700814.csv',...
    'velocities_C3_I701016.csv','velocities_C3_I701218.csv',...
    'velocities_C3_I701420.csv','velocities_C4_I651013.csv',...
    'velocities_C4_I651215.csv','velocities_C4_I651417.csv',...
    'velocities_C4_I651618.csv','velocities_C5_I651022.csv',...
    'velocities_C5_I651225.csv','velocities_C5_I651429.csv',...
    'velocities_C6_I651016.csv','velocities_C6_I651218.csv',...
    'velocities_C6_I651421.csv','velocities_C6_I651623.csv',...
    'velocities_C7_I651016_new.csv','velocities_C7_I651218.csv',...
    'velocities_C8_I651016.csv','velocities_C8_I651218.csv',...
    'velocities_C8_I651421.csv','velocities_C9_I650814.csv',...
    'velocities_C9_I651016.csv','velocities_C9_I651218.csv',...
    'velocities_C10_I651016.csv','velocities_C10_I651218.csv',...
    'velocities_C10_I651421.csv','velocities_C11_I650814.csv',...
    'velocities_C11_I651016.csv','velocities_C11_I651218.csv'};

filen = {'velocities_C1_I601219','velocities_C1_I601421',...
    'velocities_C1_I601624','velocities_C2_I651016',...
    'velocities_C2_I651218','velocities_C2_I651421',...
    'velocities_C2_I651623','velocities_C3_I700814',...
    'velocities_C3_I701016','velocities_C3_I701218',...
    'velocities_C3_I701420','velocities_C4_I651013',...
    'velocities_C4_I651215','velocities_C4_I651417',...
    'velocities_C4_I651618','velocities_C5_I651022',...
    'velocities_C5_I651225','velocities_C5_I651429',...
    'velocities_C6_I651016','velocities_C6_I651218',...
    'velocities_C6_I651421','velocities_C6_I651623',...
    'velocities_C7_I651016_new','velocities_C7_I651218',...
    'velocities_C8_I651016','velocities_C8_I651218',...
    'velocities_C8_I651421','velocities_C9_I650814',...
    'velocities_C9_I651016','velocities_C9_I651218',...
    'velocities_C10_I651016','velocities_C10_I651218',...
    'velocities_C10_I651421','velocities_C11_I650814',...
    'velocities_C11_I651016','velocities_C11_I651218'};

Nw = [1358,1061,981,1322,1319,1311,1169,1138,1514,1078,579,1147,...
    1037,1152,1149,1056,1097,359,1076,1034,1010,325,1088,428,1251,...
    1048,991,1077,1081,957,1057,1018,...
    1038,1205,1234,938];

    u_2per_all = [];
    N_ow_all =[];
    u_mean_all = [];

for i = 1:length(file);
    A = importdata(file{i});
    filename1=strcat('graph_',filen{i},'.fig');

    % Histogram
    hist(A);
    ylabel('occurency')
    xlabel('velocity [m/s]')
    savefig(filename1);
```

```
    Nw_extra = zeros(Nw(i)-length(A),1);
    u = [Nw_extra; A];

    % Calculate u_2%
    B = sort(u);
    remove = ceil(size(u,1)*per);
    C = B(1:length(B)-remove);
    u_2per = C(length(C));


    N_ow=length(A);
    u_mean=mean(u);

    % Save parameters to one file
    u_2per_all = [u_2per_all, u_2per];
    N_ow_all = [N_ow_all, N_ow];
    u_mean_all = [u_mean_all, u_mean];
end

dlmwrite('output_N_overtopWaves.csv', N_ow_all, 'delimiter', ';');
dlmwrite('output_u_2per.csv', u_2per_all, 'delimiter', ';');
dlmwrite('output_u_mean.csv', u_mean_all, 'delimiter', ';');
```

I Individual overtopping wave volume

I.1 Method

The volume of the overtopping waves are measured in the third experiment. The test set-up is changed slightly compared to the first two experiments, in order to obtain the individual volumes (see figure I.1). An overtopping box is designed which collects the water during the test. A gauge in the box measures the amount of litres in the box during the test. The box is mounted on the frame of the flume to avoid floating or sinking. A box width of 0.25 metre is selected to limit the water spillage from the flume. Before every test, the gauge is calibrated by filling the box with a measured amount of water. This amount of water correlates to the voltage-difference and the factor between the volume and voltage is calculated.

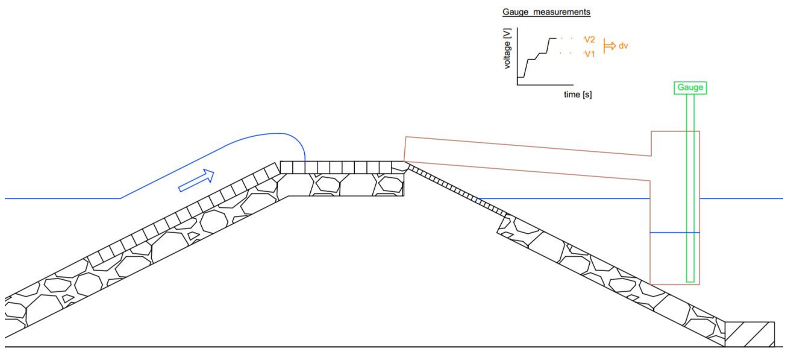

Figure I.1: *Sketch of overtopping volume measurements*

The data measured by the gauge in the box have to be processed in order to get the individual overtopping wave volume. The data processing is conducted by means of a Matlab-routine (see next pages). The steps carried out in this routine are:

- All data file names are given in the variable 'file' and are imported one by one. The five columns of the data file are assigned to five parameters; Time (t), Voltage (V) and three wave gauge measurements (H1, H2 & H3)

- First, the number of waves is calculated in the same way as shown in appendix F. This value is used later in the process.

- The voltage measurements consist of a lot of noise. A so called Moving Average Filter is used to reduce the noise. This filter smooths the data by replacing each data point with the average of the neighbouring data points. The number of neighbouring data points (N) is chosen as small as possible for every single test. The consequence of this method is a delayed output of N/2 samples which is corrected by shifting the time with the same value of N/2.

- The smoothed data are plotted against the time. The begin and end of every overtopping wave is selected in this graph manually. By subtracting the begin voltage of a wave by the end voltage, the difference in voltage is calculated.

- The difference in voltage per wave is translated to a volume in litre by using the calibration factor (lPerV). The total overtopping volume per metre, the mean individual overtopping volume per metre and average discharge per metre are be calculated with the obtained volumes. The two percent highest individual overtopping wave volume is calculated by adding zero values for the non-overtopping waves, sorting the volumes from low to high, removing the highest two percent and assigning the highest remaining volume to the $V_{2\%}$ parameter.

- Finally, the voltage in the box and the smoothed voltage are presented in a graph. The obtained output parameters are written to a csv-file.

- The steps above are repeated for the other data files with varying N-values.

It should be mentioned that in some of the tests the overtopping box could not collect all the overtopping water because the box was too small. Emptying the box during the test when no overtopping events occurred solved this problem. Within the emptying time no overtopping waves are recorded. The emptying period is ignored during the manually selecting of the overtopping waves.

```
clear all
close all
clc

%% Variables

N_w_all=[];
N_overtopWaves_all=[];
P_ow_all=[];
Volume_mean_all=[];
Volume_total_all =[];
q_all = [];
Vol_2per_all=[];
Nw_extra = [];

file = { 'C1_I601219','C1_I601421','C1_I601624v2',...
        'C2_I651016','C2_I651218_v2','C2_I651421',...
        'C3_I700814','C3_I701016v2','C3_I701218'...
        'C3_I701420','C4_I651013','C4_I651215',...
        'C4_I651417','C4_I651618','C5_I651022',...
        'C5_I651225v2','C6_I651016','C6_I651218',...
        'C6_I651421','C6_I651623','C8_I651016',...
        'C8_I651218','C8_I651421'};

N = [1500,500,500,500,500,500,500,500,500,150,2000,500,500,500,500,...
    500,500,500,250,250,500,250,250,500,500,500,500,500,500,250,250,...
    500,250,250];

%% Loop all files

for i = 1:length(file);
    close all

    % Import data from file
    filename1 = strcat(file{i},'.ASC');
    delimiterIn = ';';
    A = importdata(filename1,delimiterIn);

    % Reset parameters
    V_start = [];
    V_end = [];
    V_overtopWave = [];
    derivative = [];
    t_overtopWave = [];

    % Assign data to parameter
    t=A.data(:, 1);
    V=A.data(:, 5);
    H1=A.data(:, 2);
    H2=A.data(:, 3);
    H3=A.data(:, 4);

    % Constants
    t_test = length(t)/100;      % duration of the test [s]
    l_box=0.25;                  % width of the box [m]

    %% Number of waves

    ZeroCross1 = crossing(H1,t,mean(H1));
    ZeroCross2 = crossing(H2,t,mean(H2));
```

```
ZeroCross3 = crossing(H3,t,mean(H3));

% Number of wave per wave gauge
N_w1 = size(ZeroCross1,2)/2;
N_w2 = size(ZeroCross2,2)/2;
N_w3 = size(ZeroCross3,2)/2;

% Average of gauges
N_w=ceil((N_w1+N_w2+N_w3)/3);

%% A Moving Average Filter including delay correction

% Filter
N_used = N(i);
FilterN = ones(1, N_used)/N_used;
V_MovAvFil = filter(FilterN, 1, V);

% Delay
fDelay = (length(FilterN)-1)/2;
tDelay = t-fDelay/N_used;

% Remove first data
V_MovAvFil(1:N_used,:)=[];
tDelay(1:N_used,:)=[];

%% select begin and end of wave

% Plot figure
set(figure, 'name',file{i},'numbertitle','off')
plot(t, V, 'b', ...
     tDelay, V_MovAvFil, 'r');
axis tight;
ylabel('Voltage [V]');
xlabel('Time [s]');
title('Voltage in overtopping box');

% Select begin and end manually
[t_s, V_s] = getpts;
[t_e, V_e] = getpts;

dV=V_e-V_s;
dt=t_e-t_s;

% Translate difference in voltage to volume in liters per meter (dv-l/m)
lPerV = 3.0;
l = dV*lPerV/l_box;
l(l<0.005) = [];

% Some output parameters calculated
total_V = sum(dV);
total_V_raw = V(end)-V(1);

N_overtopWaves = length(l);
P_ow = N_overtopWaves/N_w;
Volume_total=sum(l);        %l/m
Volume_mean = mean(l);      %l/m
q = Volume_total/t_test;    %l/m/s

% 2 percent velocity
per = 0.02;
```

```
    Nw_extra = zeros(N_w-length(l),1);
    l2 = [Nw_extra; l];
    l3 = sort(l2);
    remove = ceil(size(l3,1)*per);

    Vol= l3(1:length(l3)-remove);
    Vol_2per = Vol(length(Vol));

    %% Plot raw and smoothed data
    set(figure, 'name',file{i},'numbertitle','off')
    plot(t, V, 'b', ...
         tDelay, V_MovAvFil, 'r');
    axis tight;
    ylabel('Voltage [V]');
    xlabel('Time [s]');
     title('Voltage in overtopping box');

%     for i = 1:length(V_s)
%         line('XData', [0 tDelay(length(tDelay))], 'YData', [V_s(i) V_s(i)],...
%             'LineStyle', '-', 'LineWidth', 0.5, 'Color','y');
%         line('XData', [0 tDelay(length(tDelay))], 'YData', [V_e(i) V_e(i)],...
%             'LineStyle', '-', 'LineWidth', 0.5, 'Color','m');
%     end

    legend('Raw data','Moving Average Filter', 'Start of overtopping wave', ...
        'End of overtopping wave', 'location','southeast');

    %% Output

    disp(file{i})
    disp(['The number of waves is N_w = ' num2str(N_w) ' [-]'])
    disp(['The number of overtopping waves is N_overtopWaves = ' ...
        num2str(N_overtopWaves) ' [-]'])
    disp(['The porbability of an overtopping wave P_ow = ' ...
        num2str(P_ow) ' [-]'])
    disp(['The mean volume per overtopping wave is Volume_mean = ' ...
        num2str(Volume_mean) ' [l/m]'])
    disp(['The total overtopping volume is Volume_total = ' ...
        num2str(Volume_total) ' [l/m]'])
    disp(['The average overtopping discharge q = ' num2str(q) ' [l/m/s]'])
    disp(['The largest 2 percent volume V_2% = ' num2str(Vol_2per) ' [l/m]'])

    filename2=strcat('output_',file{i},'.csv');
    dlmwrite(filename2, l, 'delimiter', ';');
    filename3=strcat('graph_',file{i},'.fig');
    savefig(filename3)
    filename4=strcat('graph_',file{i},'.jpg');
    saveas(gcf,filename4)

    % Save parameters to one file
    N_w_all=[N_w_all, N_w];
    N_overtopWaves_all=[N_overtopWaves_all, N_overtopWaves];
    P_ow_all = [P_ow_all,P_ow];
    Volume_mean_all=[Volume_mean_all, Volume_mean];
    Volume_total_all =[Volume_total_all, Volume_total];
    q_all = [q_all, q];
    Vol_2per_all=[Vol_2per_all, Vol_2per];

end
```

```
%% Export parameters to csv-file
dlmwrite('output_N_w.csv', N_w_all, 'delimiter', ';');
dlmwrite('output_N_overtopWaves.csv', N_overtopWaves_all, 'delimiter', ';');
dlmwrite('output_P_ow.csv', P_ow_all, 'delimiter', ';');
dlmwrite('output_Volume_mean.csv', Volume_mean_all, 'delimiter', ';');
dlmwrite('output_Volume_total.csv', Volume_total_all, 'delimiter', ';');
dlmwrite('output_Discharge.csv', q_all, 'delimiter', ';');
dlmwrite('output_V_2per.csv', Vol_2per_all, 'delimiter', ';');
```

I.2 Results

The following graphs show the original and averaged signal in voltage against the time. These figures are used to select the start and end of the overtopping waves. Subsequently, the obtained data are edited to the overtopping volume parameters as presented in appendix E.

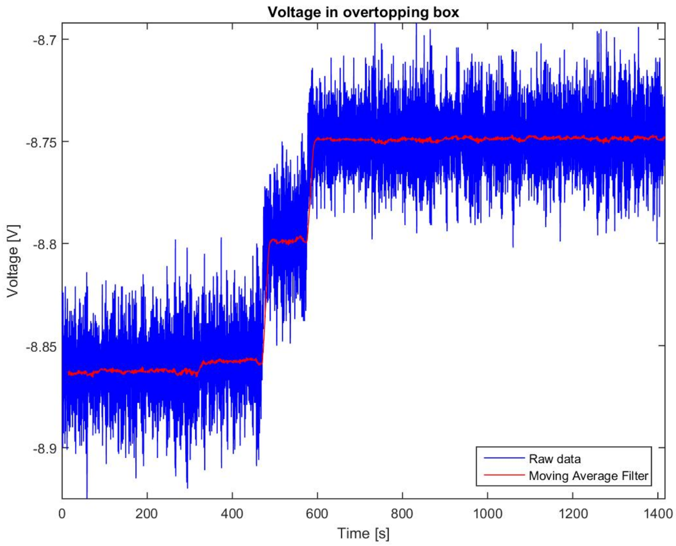

Figure I.2: $graph\_C1\_I601219$

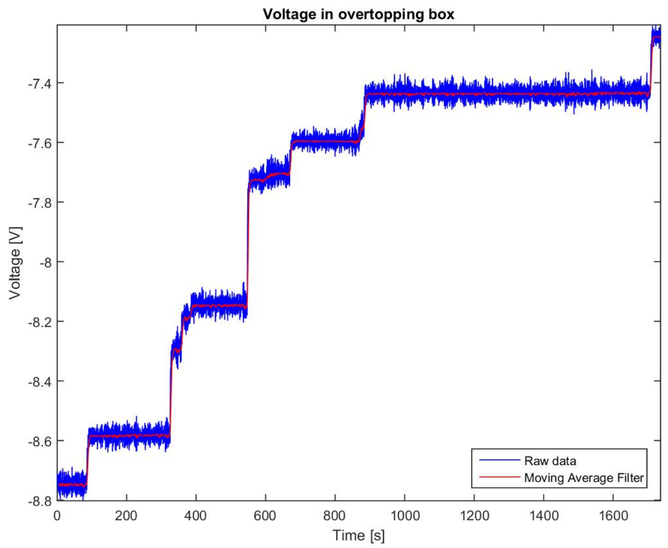

Figure I.3: $graph\_C1\_I601421$

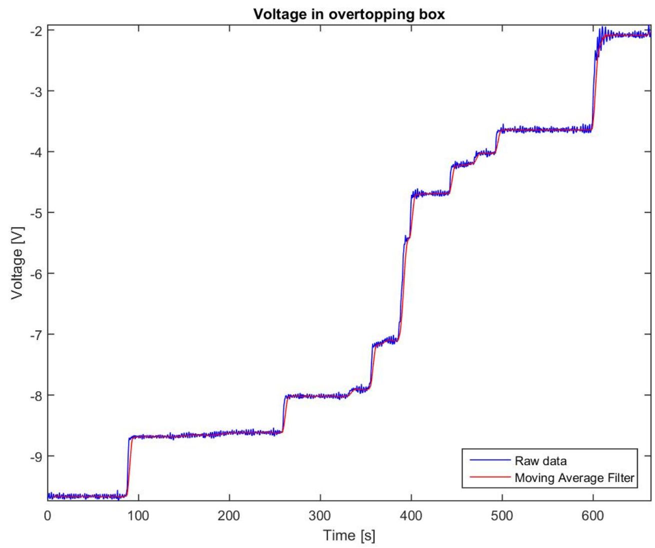

Figure I.4: $graph\_C1\_I601624v2$

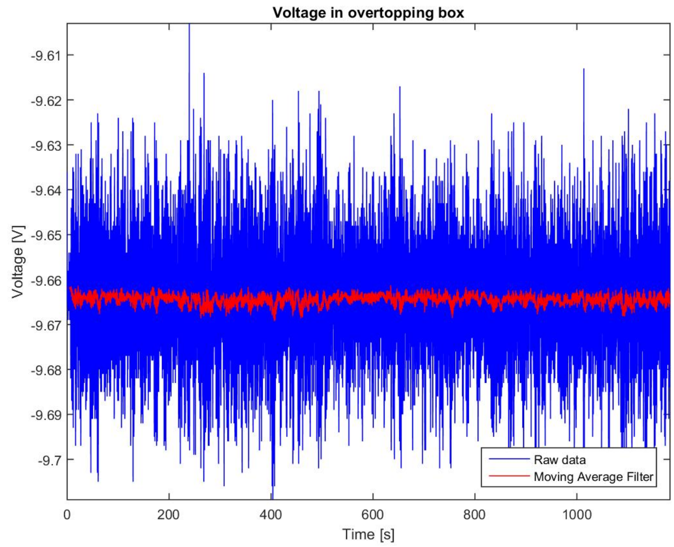

Figure I.5: $graph\_C2\_I651016$

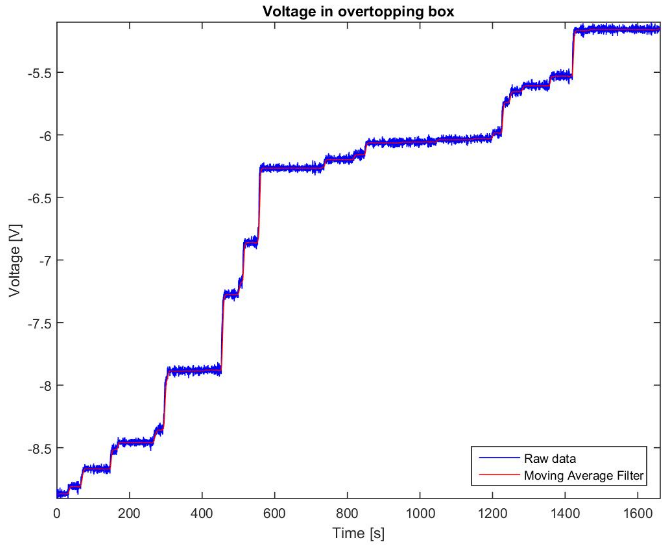

Figure I.6: $graph\_C2\_I651218_v2$

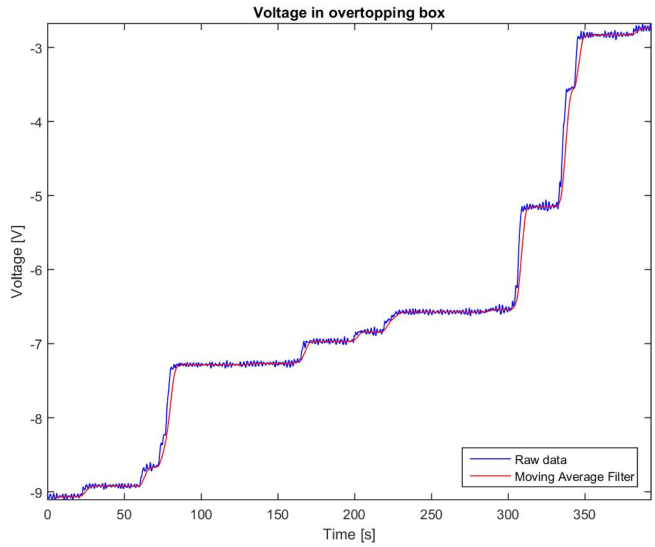

Figure I.7: $graph\_C2\_I651421$

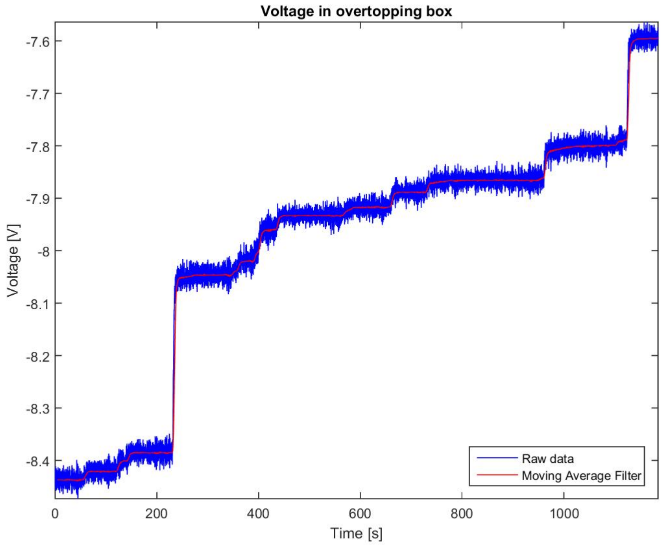

Figure I.8: $graph\_C3\_I700814$

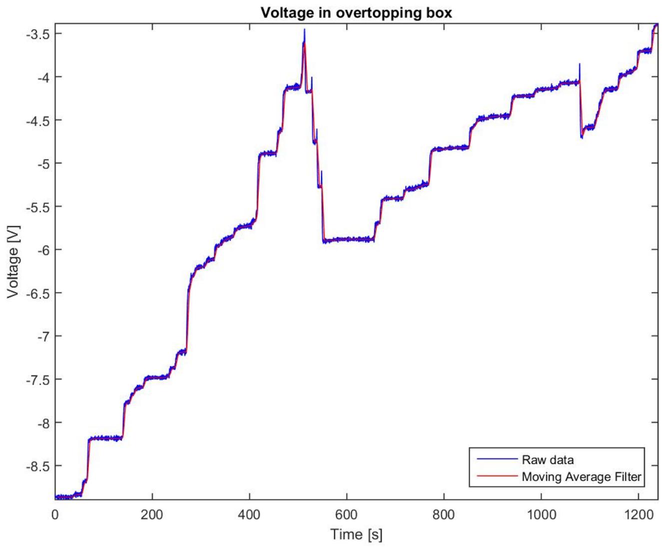

Figure I.9: $graph\_C3\_I701016v2$

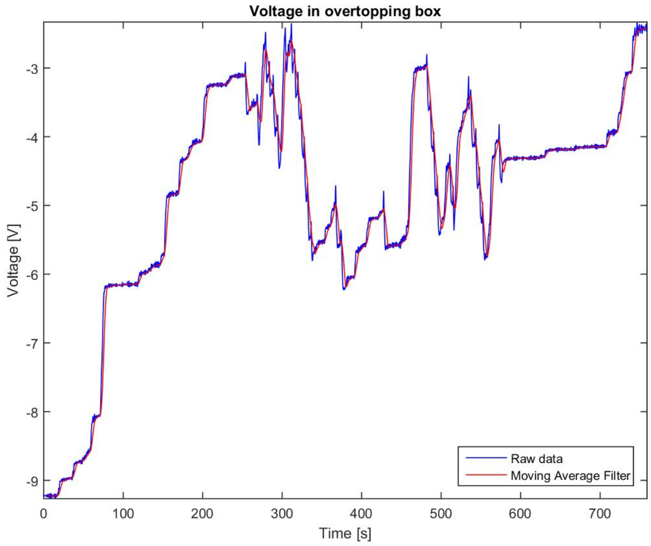

Figure I.10: $graph\_C3\_I701218$

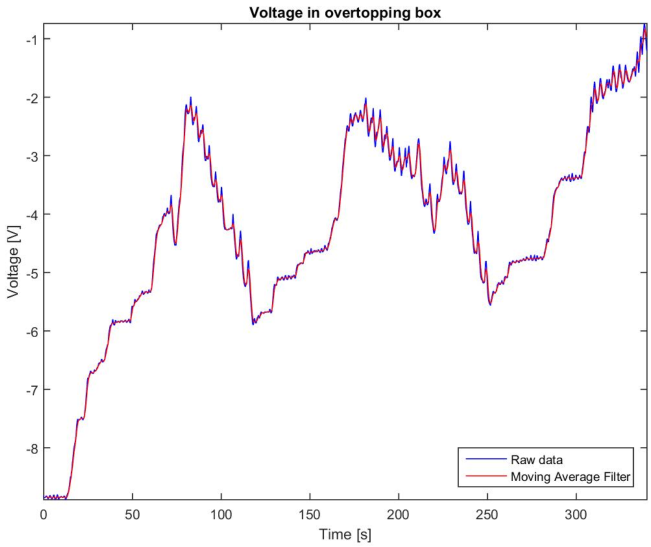

Figure I.11: $graph\_C3\_I701420$

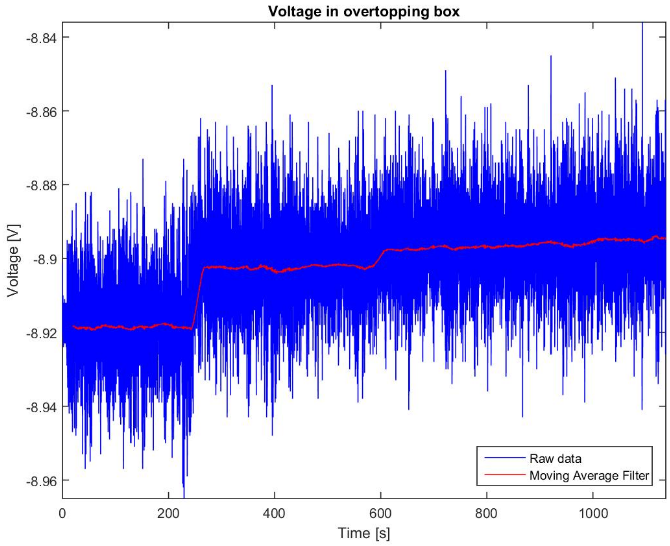

Figure I.12: $graph\_C4\_I651013$

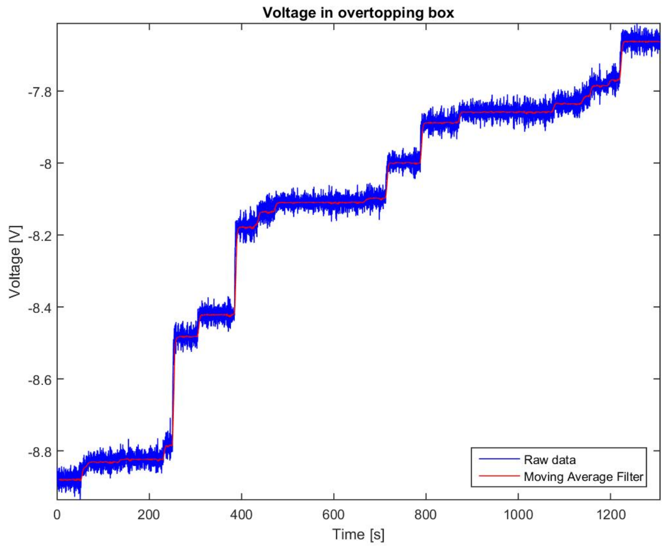

Figure I.13: $graph\_C4\_I651215$

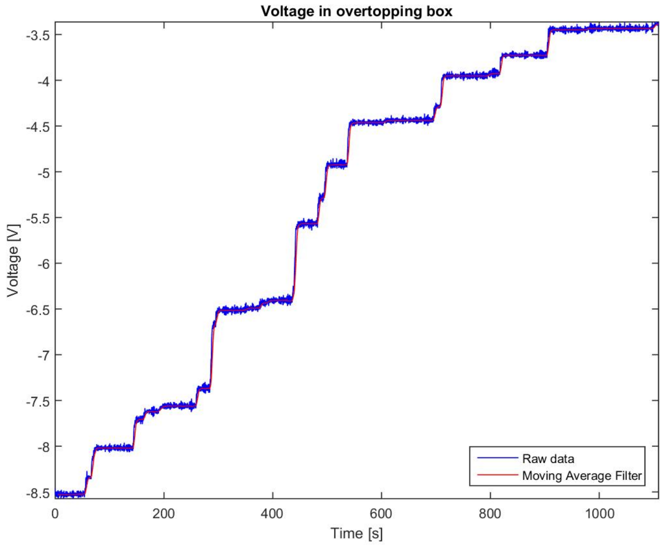

Figure I.14: $graph\_C4\_I651417$

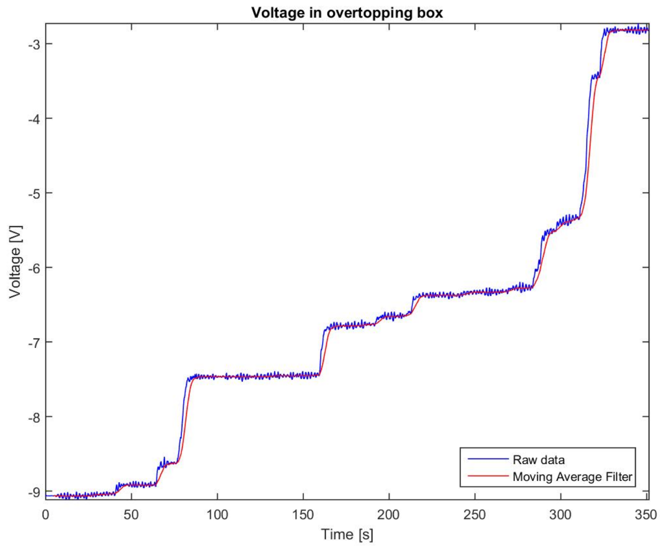

Figure I.15: $graph\_C4\_I651618$

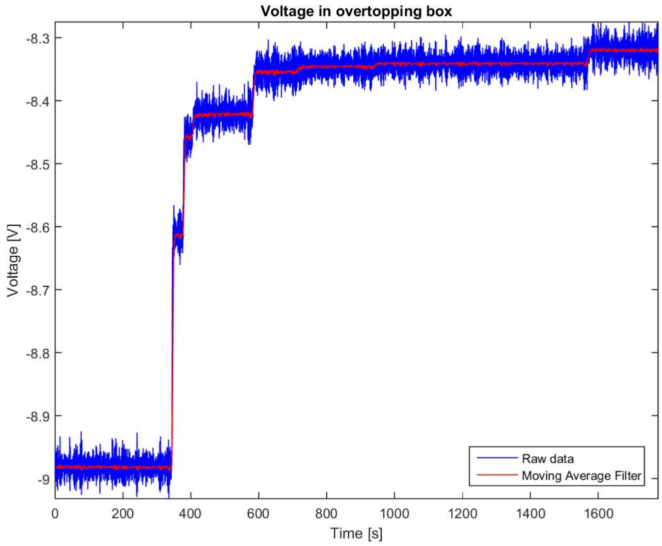

Figure I.16: $graph\_C5\_I651022$

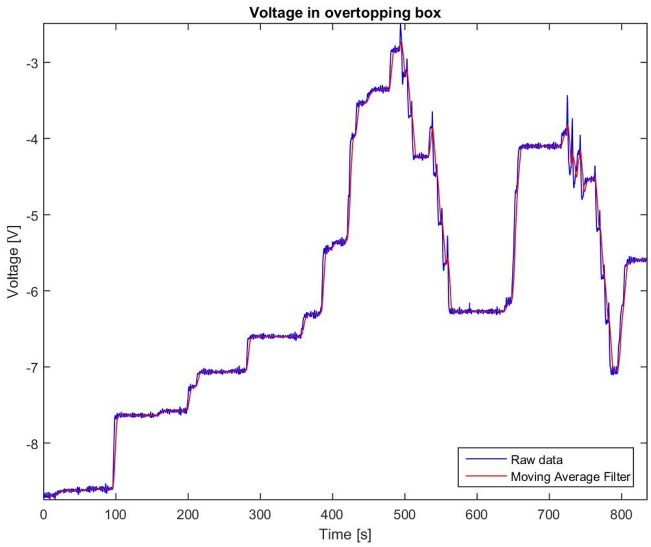

Figure I.17: $graph\_C5\_I651225v2$

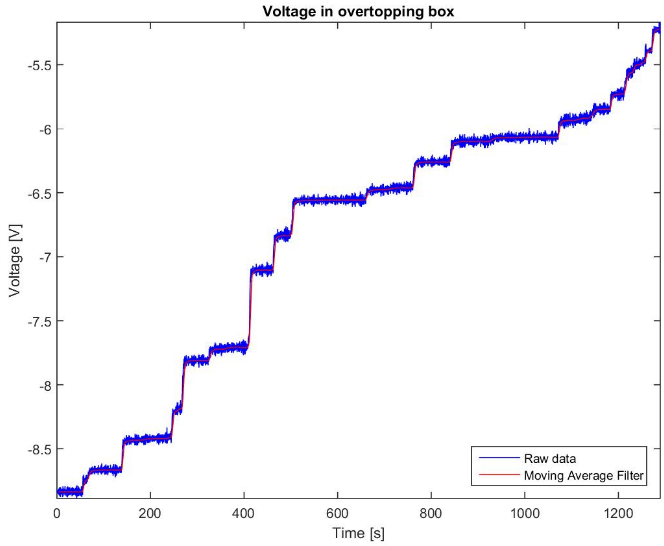

Figure I.18: $graph\_C6\_I651016$

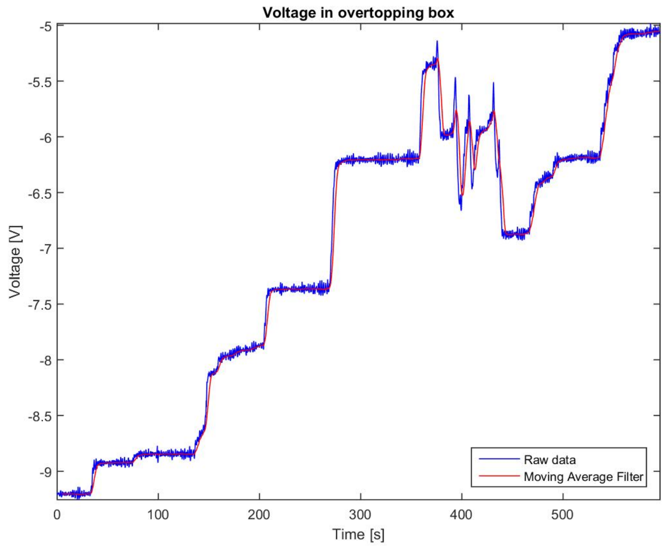

Figure I.19: $graph\_C6\_I651218$

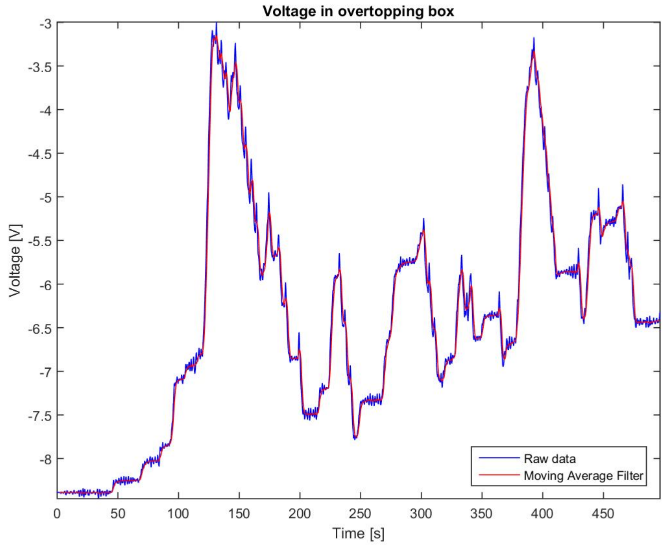

Figure I.20: $graph\_C6\_I651421$

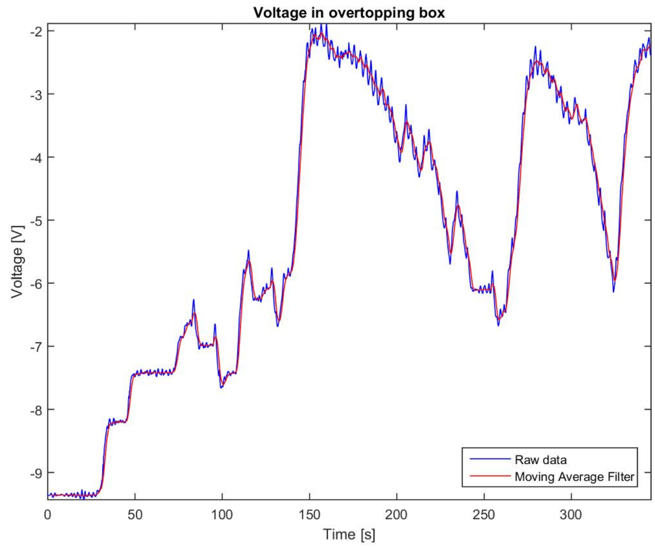

Figure I.21: $graph\_C6\_I651623$

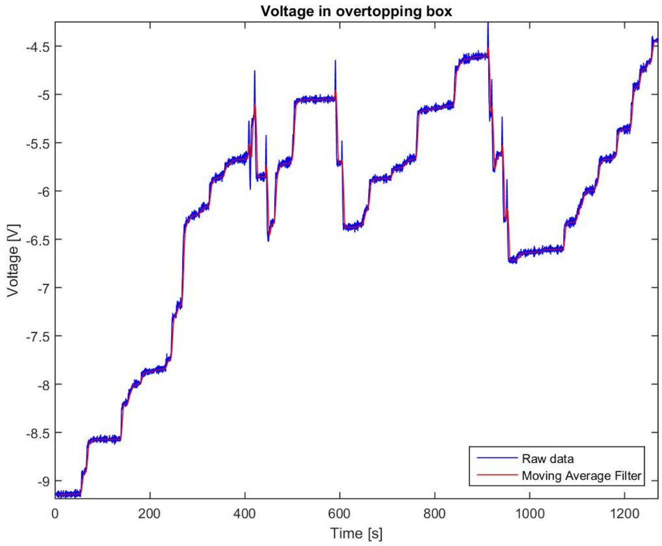

Figure I.22: $graph\_C8\_I651016$

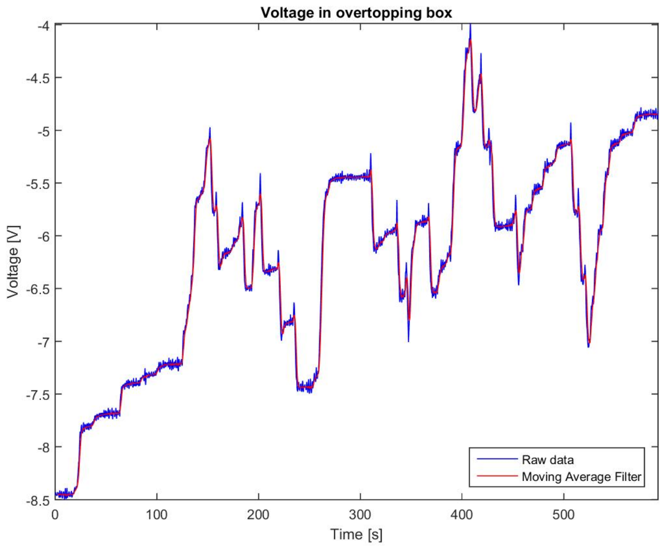

Figure I.23: $graph\_C8\_I651218$

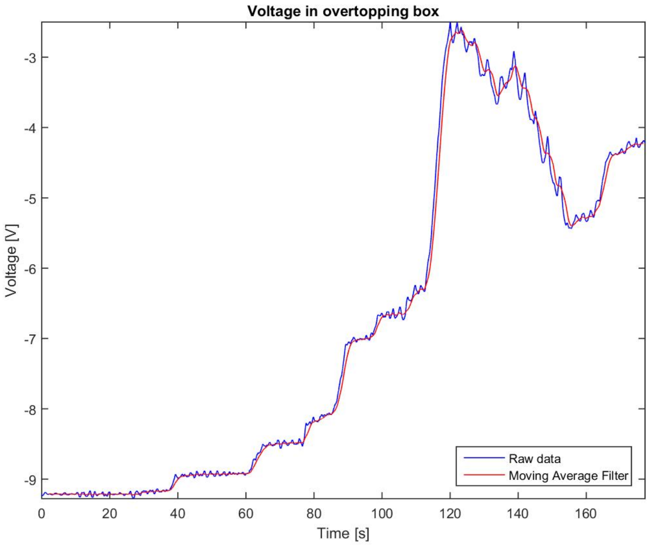

Figure I.24: $graph\_C8\_I651421$