Additional thesis report

Damage on rock slopes under wave attack

"Investigation of the accuracy margins for the determination of the damage level S"

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Preface

Undoubtedly, the construction of a breakwater or even a protection (bed bank or on the shore) is considered to be a rather expensive project. Therefore, the accurate computation of the materials needed for the construction is of major importance since undesired overestimations will risk the financial feasibility of the project. On the other hand, safety regulations and operational margins demand a precise approach of every individual situation.

Furthermore, the development of a general formula that expresses all the different cases is a very difficult job which needs years of experiments and progress, and introduces uncertainties concerning the experimental plan, upon which is based. Therefore, this study is considered to be an insight on the limitations that occur in this kind of experimental plans, and can form the basis upon which further research can be established in order to optimize the procedure and the processing of the recorded data.

Firstly, I would like to thank Remon Kik, for the innumerous hours of work and discussions, concerning the subject of our projects, at the Laboratory of Fluid Mechanics at TU Delft. Kik was conducting his graduation project and our sterling cooperation was indispensable for the completion of our projects.

Finally, for the accomplishment of this additional thesis special thanks should be addressed to my supervisors ir. J.P. van den Bos and ir. H.J. Verhagen for their valuable advice, guidance and hours spent to read and point out the errors on my report.

Abstract

The aim of this study is the particularisation of the accuracy margins for the determination of the damage level in the experimental plan proposed by Remon Kik at his thesis for the study of Notional Permeability of breakwaters “The experimental research of the permeability factor P”.

At KIK [2011] six tests were conducted for each of the three examined structures. Out of these test cases and by using logical and operational criteria, two test cases for every structure were selected in order to be reproduced. For the first structure eight repetition tests (three for the first test case and five for the second) were executed, while for the rest structures six repetition tests were conducted (three for every test case). Therefore, for this study 20 tests were executed and for each of the tests, profile measurements took place every 5cm and every 10cm, before and after the application of the wave spectrum.

The evaluation of the proposed technique took place by means of comparisons between different test cases in order to specify the existence of similarities in the statistical behaviour of original tests and their repetitions. Therefore, statistical tests are used to examine the behaviour of the individual tests not only individually, but also in combination with the rest of the test components.

Firstly, all test samples were examined, in whether they are successively represented by the normal distribution. Comparisons took place with all the available statistical distributions (normal, uniform, exponential, Poisson) provided by the IBM statistical package SPSS using the *One Sample Kolmogorov-Smirnov test*. Indeed, for all tests, it was found that the normal distribution shows the highest probability of successfully representing the damage values distribution. As a result, all damage sequences were analyzed using the formulas applied for the case of normal distribution.

Afterwards, the two proposed computational approaches (*smooth/polyline* fit) for the quantification of damage, were compared, with the aim to determine which one is the most suitable to represent the damage resulted after the conduction of the tests. The analysis showed that despite *smooth fit* approach results in values 15-30% higher than the *polyline fit,* can more efficiently describe the occurring damage on the structure.

Thereinafter, was examined the statistical behaviour of the repetition tests (RTs) with respect to the original tests (OTs). The aim was to identify the statistical range of the measured damage values for every test case that representatively describe the level of damage for this particular case. In addition, extreme deviations of individual damage measurements were being considered and interpreted. For the accomplishment of this part of the study the *Kruskal-Wallis non parametric test for k-independent variables* was used. In

general the analysis showed good consistency between repetitions and original tests for the most of the test cases although there were few cases that showed considerable differences.

For the selected statistical and computational approaches the optimum measurement space step had to be specified. Therefore, a comparison took place between measurements every *5cm* and every *10cm*. The length of the confidence intervals was used to quantify the difference in accuracy and the two fundamental non parametric tests of *Mann-Whitney U/ Wilcoxon W* and *Kolmogorov-Smirnov* (theoretical explanation Appendix B) were applied in order to qualitatively investigate the magnitude of the behavioral change of the distribution due to the addition of the in-between measurements (profile measurements every *5cm*). The analysis showed that although the smaller measuring step increased the accuracy at about 10-30% the differences in absolute damage values were trivial.

Furtherupon, differences among tests that occur in the plunging and in the surging area were examined and tendencies were recorded. The outcome showed that an imperceptible difference occurs. The deviation was steadily bigger for the case of tests located in the plunging area (28% in contrast to 21.5% of the surging area), but this difference is considered to be trivial.

Finally, the accent was paid in the limitations of the available means and equipment. The observed higher damage values at the *sides* were investigated. The 13 cross sections of the structure were divided into two groups of *side* and *middle cross sections and* comparisons between them were accomplished. Then the influence of the boundary measurements was quantified in order to interpret any existing tendencies of higher damage values and local irregularities that may affect the output of the computations. In fact, the data analysis showed that the variation of damage values at the *side* cross sections was for all the cases larger than the *middle* ones. In half of the cases the difference was significant while for the other half, difference occurred, but with a lower magnitude.

By translating and interpreting the above mentioned comparisons a clear image about the accuracy and the validity of the proposed experimental technique was outlined. The convergence of the measured values and the relative small variations that occurred on average showed the consistent character of the method. The differentiation of the accuracy due to strategic changes (denser measurements, elimination of side measurements) displays that the method can be improved but the fact that the variations were on average among the margins of the statistical error contributes in the acceptance of the results.

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Notations

A_i = erosion area in a cross-section (indices 1, 2, 3) [m^2]
ARC=Reflection compensator
d = water depth [m]
D = Duration of a wave record [s]
D = Diameter [m]
D_{15} = Sieve diameter exceeded by 15% of the stones [m]
D_{50} = Sieve diameter exceeded by 50% of the stones [m]
D_{85} = Sieve diameter exceeded by 85% of the stones [m]
D_n = nominal diameter $(W/\rho_a)^{1/3}$ [m]
D_{n50} = nominal diameter exceeded by 50% of the stones [m]
f = Frequency [Hz]
g = gravitational acceleration [m/s^2]
H = Wave height [m]
H_s = (incoming) significant wave height [m]
$H_{2\%}$ = Wave height exceeded by 2% of the waves [m]
$H_{1/3}$ = average of the highest 1/3 of the wave heights in a wave record [m]
H_{m0} = 4 times the standard deviation of the surface elevation [m]
H_{rms} = root mean square wave height [m]
K-S = One sample Kolmogorov-smirnov test
K-W = Kruskal-Wallis test
L = Wave length [m]
L_0 = Deep water wave length ($=gT^2/2\pi$) [m]
m_0 = zero-th order spectral moment [-]
m_{-1} = first order negative spectral moment [-]
n = number of tests [-]
$N_{Iribarren}$ = dustbin factor in stability formula of IRIBARREN [1938] [-]
N = number of waves [-]
P = permeability coefficient defined in VAN DER MEER [1988] [-]
PM = Pierson Moskowitz
σ = standard deviation
μ = mean value
S = damage level as defined in VAN DER MEER [1988] ($=A_i/D_{n50}^2$) [-]
t = Time [s]
T = Wave period [s]
T_m = Mean wave period [s]
$T_{m-1,0}$ = spectral wave period m_{-1}/m_0 [s]
T_p = Peak wave period [s]
WWM = Whitney U test (also called the Mann–Whitney–Wilcoxon (MWW) or Wilcoxon rank-sum test)
α = Slope angle of construction [-]
ξ = Iribarren parameter calculated with T_p [-]
ρ = Mass density of stone [kg/m^3]
ρ_w = density of water [kg/m^3]

Chapter 1

Introduction

1.1 General

Apparently, all around the world innumerous constructions can be recognized that aim to protect the shoreline, bed and bank of special areas, against wave attack, erosion and sedimentation.

One of the most famous man-made interventions along the coastal areas is the breakwater which can be found in different types (mound type, monolithic, composite or special types) according to the demanding properties of every specific case. Most of the times it is mainly consisted of various layers, while for the design of the armour-upper layer the choice has to be made between two formulas; the Hudson and the Van der Meer formula.

On the one hand, the Hudson formula, as it is developed in the studies of 1953, 1959 and 1961, is a more general formula based on a dimension analysis and curve fitting where all the unknown factors (type of units, breaking/non breaking waves and acceptable damage) are included in a 'dustbin' factor k_D.

$$W \geq \frac{\rho_s g H_{10}^3}{K_D \Delta^3 \cot(\alpha)} \qquad (1.1)$$

H = mean value of the upper 10% of the wave heights	[m]
Δ = relative density (ρ_s- ρ_w/ ρ_w)	[-]
ρ_s = density of rock	[kg/m3]
ρ_w = density of water	[kg/m3]
α = angle of slope	[-]
K_D = dustbin factor of Hudson	[-]

On the other hand, the Van der Meer formula is the outcome of an extensive program that resulted into the thesis of VAN DER MEER[1988]. Besides, it is considered to be more detailed since it takes into account factors such as the period of the waves (Iribarren number), the storm duration (number of waves) and the damage level, which in the case of the Hudson formula are being neglected. Indeed, Van der Meer found that there is distinction between surging and plunging breakers and therefore the formula for surging and plunging waves read BREAKWATER AND CLOSURE DAMS [2009]:

$$\frac{H_s}{\Delta d_{n50}} = c_{pl} P^{0.18} \left(\frac{S}{\sqrt{N}}\right)^{0.2} \xi_m \text{ (plunging waves)} \qquad (1.2)$$

$$\frac{H_s}{\Delta d_{n50}} = c_s P^{-0.13} \left(\frac{S}{\sqrt{N}}\right)^{0.2} \xi_m{}^{P} \sqrt{\cot a} \text{ (surging waves)} \qquad (1.3)$$

The distinction between the two breaker types is being held by a transition formula that uses the critical value of the surf similarity parameter:

$$\xi_{cr} = \left[\frac{c_{pl}}{c_s} P^{0.31} \sqrt{\tan\alpha}\right]^{\frac{1}{P+0.5}} \qquad (1.4)$$

For $\xi_m < \xi_{cr}$ waves are plunging and equation (1.1) is used
For $\xi_m > \xi_{cr}$ waves are surging and equation (1.2) is used

In which:
H_s = Significant wave height
c_{pl} = Parameter for plunging waves μ = 6.2, σ = 0.4
c_s = Parameter for surging waves μ = 1.0, σ = 0.08
P = Notional permeability
S = Damage number
N = Number of waves
$\xi_m = \frac{\tan(\alpha)}{\sqrt{s_m}}$ Iribarren number or Breaker parameter
s_m = Wave steepness calculated with the mean wave period

Moreover, Van der Meer formulas contain a factor which describes the notional permeability of the structure in order to include in the computation, the notion of energy dissipation due to structure permeability. Notional permeability values P depend on the different layers of which the breakwater cross section is consisted. These values were empirically determined for three standard situations while for a fourth (filter layer and core, P=0.4) interpolation of the tested configurations is used.

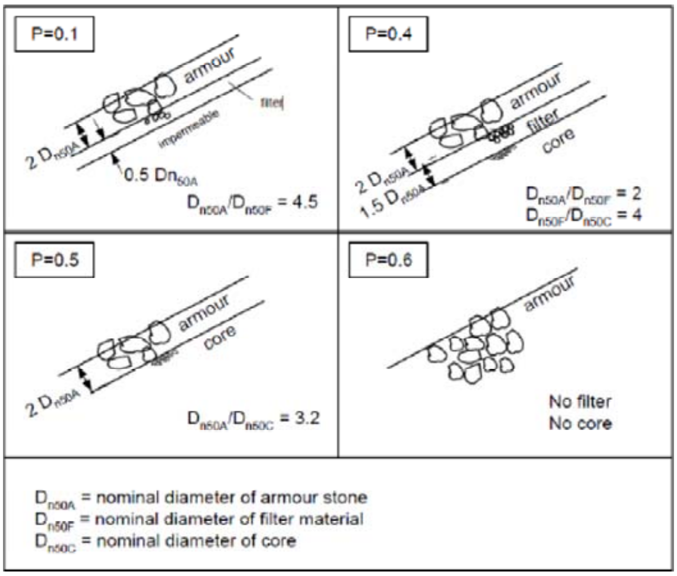


figure 1-1 Notional permeability configurations (source SCHIERECK[2001])

Unfortunately, in practice intermediate situations of the known configurations are used, introducing uncertainties, concerning the value of the notional permeability of the structure which plays a crucial role in the computation.

An attempt to cover this lack of experimental data takes place in the study of Notional Permeability of breakwaters "The experimental research of the permeability factor P" by R. KIK[2011]. During this study, an experimental plan has been established to determine the notional permeability for three different structures based upon the determination of the damage level due to specific wave incidents.

Specifically, the determination of the "notional permeability" factor P for every test case, takes place by fixing or measuring all the variables in the Van der Meer formula's 1-2 and 1-3 the permeability factor P. Indeed, damage level is being computed by measuring the structure profile and comparing it with the profile after the application of the wave incident. Afterwards, the only unknown, the value of P is computed by the Van der Meer equations.

For two out of the three tested structures, experimental data are available from VAN DER MEER[1988], and thus, reference cases occur. On the other hand, this is not the case for the third test structure. Nevertheless, every structure has been tested by means of six test cases which were established according to structural and environmental conditions that are described at the following Chapter.

Therefore, and in order to investigate the validity, accuracy and sensitiveness of the proposed experimental plan the above mentioned study is supplemented with this additional thesis study. During this study repetition tests of selected test cases took place and were accompanied with statistical analysis, in order to gain insight into the related limitations and drawbacks of the plan under consideration.

1.2 Problem description

Undoubtedly, the introduction of the experimental plan by KIK[2011] has risen several questions concerning the determination of the damage level. Mainly, these questions have to do with the statistical behaviour of the computed damage and its sensitiveness to various aspects that involve in both the used measurement technique and the processing of the acquired data.

More precisely, this study has attempted to answer the following questions:

1) *Which statistical distribution can describe best the distribution of the measured damage values?*
2) *Among the two proposed computational approaches, the smooth and the polyline fit approach, which one is more representative with respect to the damage values calculated using the Van der Meer equations?*
3) *What is the level of statistical consistency of the measured damage values between the initial tests and their repetitions? In case of substantial differences how can they be interpreted?*
4) *How sensitive are the measured damage values with respect to the space step (5cm/10cm) used for the conduction of the profile measurements?*
5) *Are there important differences among the variation of the measured damage values with respect to the breaker type (surging/plunging area)?*
6) *Does and at which extent, the cross section position (side/middle measurements) affect the spreading of the measured damage values?*
7) *Which aspects need further investigation and what can be done to improve the proposed experimental plan?*

1.3 Problem definition

Summarizing, the main scope of this study is to evaluate the proposed experimental procedure by answering the following ultimate question:

"How accurate is the proposed experimental plan for the determination of the damage level, by which factors is it being affected, which is the related sensitivity and what can be done in order to be improved?"

1.4 Research strategy & objectives

Taking into consideration the time needed for the execution of a single test with respect to the available time of such a study, two test cases were repeated for every structure. Mainly, every examined test case was followed by three repetition tests except from test case 6 where five repetition tests were conducted and added on the two original tests that were executed by KIK[2011]. The following table is an inventory of the executed test cases with information about original and repetition tests.

Test case	Kik [2011]	Papadopoulos [2011]
(TC)	(OT)	(RT)
3	3	3a, 3b, 3c
6	6, 6-2	6a, 6b, 6c, 6d, 6e
8	8	8a, 8b, 8c
11	11	11a, 11b, 11c
20	20	20a, 20b, 20c
26	26	26a, 26b, 26c

table 1-1 Test inventory

The selection of the TCs to be repeated was based on the following criteria:

- Test cases that showed extreme values such as significant or trivial amount of damage with respect to the computed damage values using the Van der Meer equations.
- Test duration, keeping in mind the time shortage for the accomplishment of this thesis.
- Equal distribution of TCs in the plunging and surging area.

Afterwards a research strategy was developed that aimed to answer, step by step, the questions described at section 1.2. In particular, for every question the evaluation plan is described above:

1) *Which statistical distribution can describe best the distribution of the measured damage values?*

   The determination of the statistical distribution that most efficiently describes the spreading of the computed damage values is based upon the application of the *One Sample Kolmogorov-Smirnov test*. Particularly, for every individual test (both OTs and RTs) the measured damage values are compared using different statistical distributions and then the most suitable distribution is selected and used for the proceeding statistical computations.

2) *Among the two proposed computational approaches, the smooth and the polyline fit approach, which one is more representative with respect to the damage values calculated using the Van der Meer equations?*

Two computational approaches, the *smooth* and the *polyline fit* were used in order to quantify the damage level. Afterwards, a statistical analysis takes place aiming in determining the most efficient computational approach that best describes the measured damage level with respect to the calculated damage values using the Van der Meer equations. In fact, the mean value of the damage level for every individual test is computed and is being compared to the corresponding value extracted by the formulas. In addition, the analysis is supplemented with standard deviation and 90% confidence intervals computations of the damage values to provide insight of their spreading around the mean values.

3) *What is the level of statistical consistency of the computed damage values between the initial tests and their repetitions? In case of substantial differences how can they be interpreted?*

At this part of the study, is being examined the statistical behaviour of the repetition tests (RTs) with respect to the original tests (OTs). The aim is to identify the statistical range of the measured damage values for every test case that representatively describes the level of damage for this particular case. In addition, extreme deviations of individual damage measurements are being considered and interpreted. For the accomplishment of this part of the study is being used the *Kruskal-Wallis non parametric test for k-independent variables* (number of tests for every case).

4) *How sensitive are the measured damage values with respect to the space step (5cm/10cm) used for the conduction of the profile measurements?*

The application of a smaller measurement step of *5cm* instead of *10cm* increases the level of detail but currently increases the duration for the execution of an individual test. Therefore, an investigation takes place to determine if denser measurements introduce additional information that leads in substantial deviation of the measured damage values. For that reason, firstly, two non parametric statistical tests, the *Mann-Whitney U/ Wilcoxon W and the Kolmogorov-Smirnov test* are applied to specify if there is statistical difference among the measured damage values when increasing the measurement step and afterwards, the measured damage values with the two measurement steps are being compared with the corresponding damage values extracted by the Van der Meer equations.

5) *Are there important differences among the variation of the measured damage values with respect to the breaker type (surging/plunging area)?*

For every structure two tests cases are being repeated; one at the surging and one at the plunging area. Then, takes place a comparison of the statistical characteristics of the damage values for the two test cases of every structure. The aim of this investigation is to identify the existence of higher spreading of damage values that depends on the type of wave breaking on the structure.

6) *Does and at which extent, the cross section position (side/middle measurements) affect the spreading of the measured damage values?*

For the case of the highest density measurements (profiles every *5cm*), the profile measurements are divided into two groups of *side* and *middle* measurements.

Afterwards, takes place a statistical analysis of the computed damage values that ends with the comparison of the damage value of the two groups with respect to the damage value of test. Therefore, any differences are quantified and a conclusion is drawn to whether and at which order the location of the profile measurement leads at the overestimation or underestimation of the measured damage values.

7) *Which aspects need further investigation and what can be done to improve the proposed experimental plan?*

The last question can be considered as a review for both the experimental plan and procedure, and therefore information and answers are extracted during the whole study by both the execution of the repetition tests and the processing of the data in order to answer the previous questions.

1.5 Outline

In Chapter 2 information is given about the theoretical background of the damage notion and the parameters, conditions and assumptions made by KIK[2011] in his experimental procedure. At the end, a detailed description of the three test structures is presented.

Chapter 3 contains the analytical description of the available laboratory equipment and the testing procedure. Also, information about the laser calibration, which was important for the execution of the profile measurements, can be found. Finally, the two computational approaches for the damage level estimation are being explained.

In chapter 4 all the comparisons for the evaluation of the experimental procedure are presented. In specific, the chapter starts with the presentation of the data set, proceeds with the statistical analysis of the measurements and end with comparisons for different test cases and influencing parameters such as measurements density, surging/plunging area, reflection compensator activation and *side*/*middle* measurements.

Chapter 5 consists of the conclusions for every case and the final conclusion concerning the practical/technical part of the experimental procedure.

Finally, Appendix A contains the tables with the individual measurements for every structure and test component, and the accompanied statistical computations (mean values, standard deviations and confidence intervals). In Appendix B the theoretical background of the executed statistical tests is discussed and finally in Appendix C the graphs from the normal distribution approach are being displayed.

Chapter 2

Information & background

2.1 Damage notion

The level of damage in the Van der Meer equations is expressed by the parameter “S” which can be written as $S = \frac{A}{d_{n50}^2}$ in which:

A= erosion area in the cross section	[m^2]
d_{n50}= $(\frac{W_{50}}{g\rho_s})^{1/3}$=$(\frac{M_{50}}{\rho_s})^{1/3}$	[m]
W_{50}= mean weight of armour stones	[N]
ρ_s= density of armour stone	[kg/m^3]

The erosion in the area A is the combination due to profile settlement and the dislocation of the unstable stones. The ratio of erosion area divided by the area of the armour stone represents the number of the stones which were being removed from the cross section (porosity and shape not taken into account).

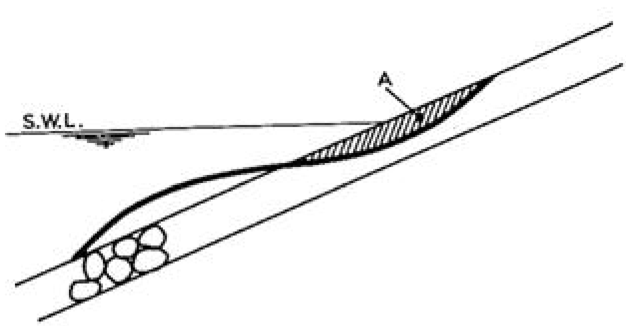


figure 2-1 Eroded area for the determination of damage level (source SCHIERECK[2001])

The following table contains the limits of the acceptable damage and failure for armour layers consisted of two layers of units:

slope	Initial damage (no repair needed)	Intermediate damage (repair needed)	Failure (core exposed)
1:1,5	2	3-5	8
1:2	2	4-6	8
1:3	2	6-9	12
1:4	3	8-12	17
1:6	3	8-12	17

table 2-1 Damage tolerances for different slopes (source SCHIERECK[2001])

In case of natural rocks, the damage level is simply determined by measuring the difference between the initial and the profile after the event, using different measuring rods at a certain distance with respect to each other.

2.2 Review of the experimental procedure Kik [2011]

The test procedure followed during this study is exactly the same with the one described by R. Kik at his thesis. At first, the design of the tested structures is described and then the selection of the environmental and structural parameters is being presented.

2.2.1 Description of test Structures

In total three structures are being examined. The first two structures have already been tested at the past and the corresponding notional permeability values P can be found in literature. These two structures are mainly used as reference cases for the proposed experimental plan, that later, at the case of structure 3, will be used to determine a P-value which has not been documented yet.

2.2.1.1 Structure 1

The first structure consists of a permeable core material and an armour layer and applies for the case of P=0.5.

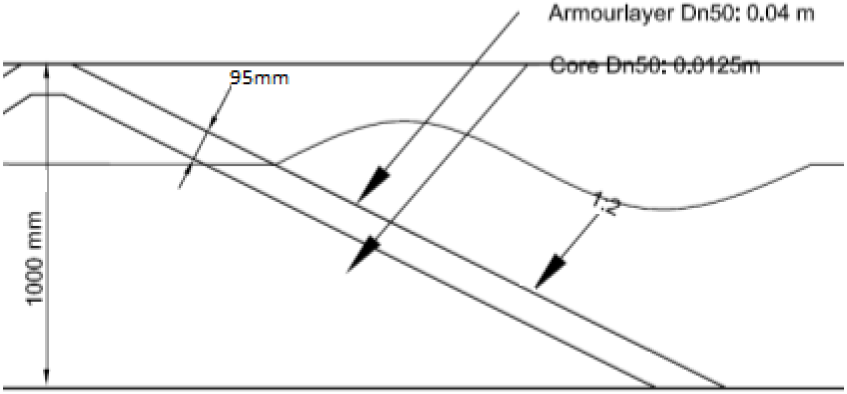


figure 2-2 test Structure 1, P=0.5 (source KIK[2011])

Structure 1	
	
armour layer	core material
d_{n50}=0.04m	d_{n50}=0.0125m

table 2-2 Material index for Structure 1

2.2.1.2 Structure 2

The second structure (second reference case) is the construction with an armour layer on a thin filter and an impermeable core as defined by Van de Meer and applies for the case of P=0.1.

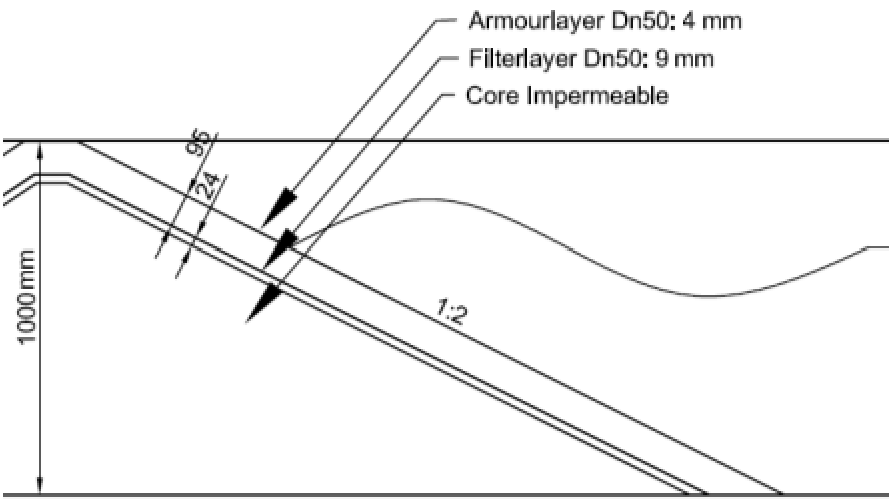


figure 2-3 test Structure 2, P=0.1 (source KIK[2011])

Structure 2		
		
armour layer	filter layer	impermeable core
d_{n50}=0.04m	d_{n50}=0.009m	-

table 2-3 Material index for Structure 2

Due to the very fine material of the filter layer, and in combination with the slope of 1:2, wooden sticks were placed in the transverse direction of the structure slope to keep the material from sliding down. The same sticks were also used in the case of Structure 3.

2.2.1.3 Structure 3

The third structure, which is often applied in practice but has no documented P-value, is a structure with an impermeable core, like sand + geo-textile, but with an extra thick (double) filter layer. The next layer is usually quarry-run to create the desired slope of the structure. On top of that layer the real filter layer is placed on which the armour layer will be situated. (KIK [2011]). A P-value of 0.3 is expected.

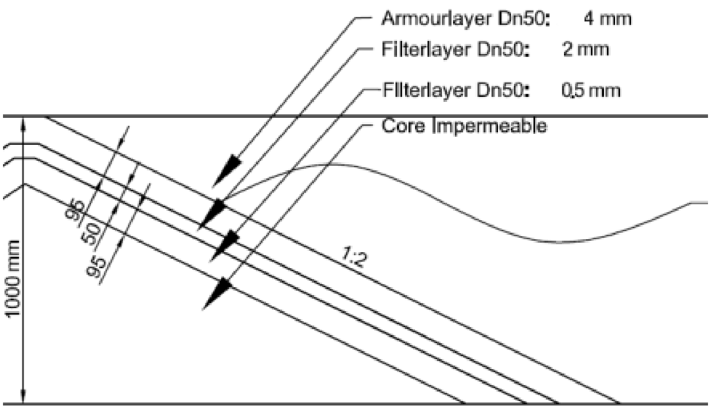


Figure 2-4 test Structure 3, P=0.3 (source KIK[2011])

Structure 3			
			
armour layer	filter layer	2nd filter layer	impermeable core
d_{n50}=0.04m	d_{n50}=0.02m	d_{n50}=0.009m	-

Table 2-4 Material index for Structure 3

2.2.2 Structural variations

Below, takes place a brief presentation of the assumptions, choices and conditions taken by R. Kik at his study concerning the environmental variations for building up the experiment. Thorough description is offered in KIK [2011].

Layer thickness

Double thickness armour layer is used as top layer. In his experiments VAN DER MEER [1988] also used a double armour layer which is common design technique, because in this way there is a better protection of the under layers. The thickness of the filter layer will be the same as specified in figure 1-1.

Slope angle

The slope angle selected for the structures to be tested is 1:2, like the one used by Van der Meer in the majority of his tests, in order to have a strong reference case.

Grading rock

As Van der Meer didn't find any relation between stability and the grading of the armour layer the usual grading of quarry rock for armour layers will be applied. This implies $d_{85}/d_{15} < 1.5$.

2.2.3 Environmental variations

The selection of the main environmental variations is based on the choices made by VAN DER MEER[1988] in order to provide a comparison background for the extracted results. The main parameters here are the type and the number of waves and spectral shape.

Type of waves: Surging/plunging

From the stability equations proposed by Van der Meer it can be concluded that, the influence of the permeability on the stability of the armour layer in the case of surging waves is larger than in the case of plunging waves. Consequently, in KIK[2011] accent was be paid on the surging region. On the other hand, during this study attention will be paid on the in both breaker types and therefore for every structure, one test case at every breaker type area will be repeated.

Duration

VAN DER MEER[1988] found that the influence of the number of waves was well represented by the factor $N/\sqrt{(S)}$ while he executed his experiments using up until 3000 waves which is also the value used in this study.

Spectral shape

Despite the fact that Van der Meer executed his tests using three different types of wave spectrums, he concluded that there is no distinction between them as long as the mean period is used. Therefore, during this study the structures will be attacked by a Pierson-Moskowitz wave spectrum which was the spectrum used by Van der Meer at the majority of his experiments.

Wave height/ period

In order to test the highest possible waves, as long as higher waves imply bigger armour stones, the maximum flume dimensions are taken into account. With respect to wave breaking and wave run-up the maximum wave height will be 0.27 m. The maximum wave height occurring in this spectrum is in the order of twice the significant wave height. In order to avoid wave breaking a water level of 0.65m is selected. The run up (2%) is about 0.45 m therefore the final height of the breakwater will be 1.1 m. During the repetition of a test the wave height and period will be kept constant and the level of damage will be determined.

Chapter 3

Measurements: equipment and procedure

3.1 Equipment

In the following pages the characteristics of the equipment used in the experimental procedure are being described. More information can be found in KIK[2011].

Wave flume: A wave flume 40m long, 0.8m wide and 1m deep, situated at the Laboratory of Fluid Mechanics at the Delft University of Technology was used. The selection of the water depth is done with respect to the allowed overtopping and is 0.65m.

Wave generator: The generation of the waves is succeeded with the use of a wave generator which is equipped with a reflection compensator to absorb the formation of the standing waves inside the basin. For the tests input, instead of regular waves a wave spectrum is given (Pierson Moskowitz spectrum).

figure 3-1 Wave generator with reflection compensator

Wave gauges/sensors: They are placed in three different places inside the flume. One device set is placed near the wave generator, to record measurements concerning the incoming wave spectrum; one is placed near the structure to record the reflected waves and finally one at the back side of the structure to measure the water-level variations behind the structure.

figure 3-2 Wave gauges for the incoming wave

Wave run up sensors: are placed in parallel with the slope of the structure and they are used to determine water-level fluctuations on the structure surface.

figure 3-3 Sensors measuring wave setup

Pressure gauges: Are used to measure the pressure differences inside the structure . In particular, four pressure gauges are used and are connected with five tubes in order to measure the pressure differences among three zones inside the structures. One tube is connected to the air and the other four are placed inside the structure 0.46m from the bottom of the flume and 0.25 m apart. In addition to the gauges inside the core, an extra pressure difference gauge is placed on the interface between the filter layer and the core.

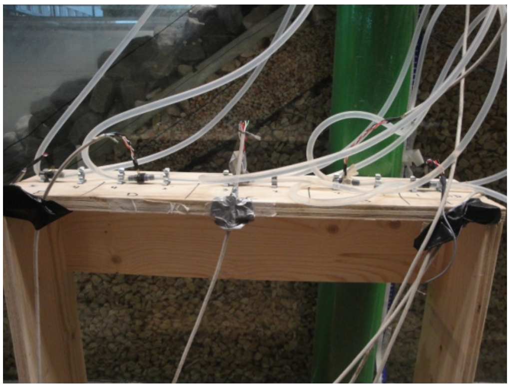
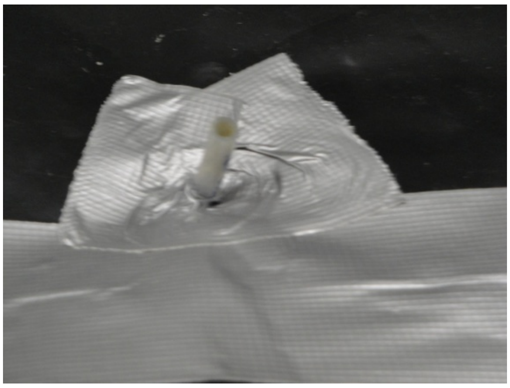
 

figure 3-4, 3-5 Pressure gauges and plastic tubes for the determination of the pressure gradient

Measuring equipment: Is consisted of two devices, a laser and an echo-sounder. The laser has the limitation that it starts measuring 15cm below its level and it has a range of 75cm. It can also measure below the water level with the appropriate calibration to take into account the deviation of the signal velocity due to the propagation into different mediums.

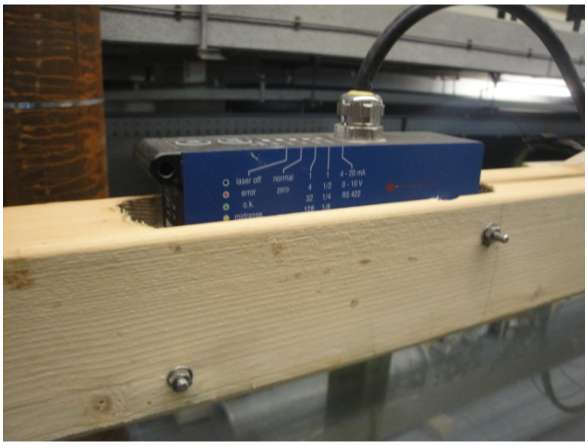


figure 3-6 The laser device used for the measurements

On the other hand the echo-sounder is measuring only below the water level. Therefore the area around the water level, which happens to be the most crucial with respect to damage, is a transition area where the measurement from the devices have to overlap. The careful calibration of their records is substantial for the validity of the measurements.

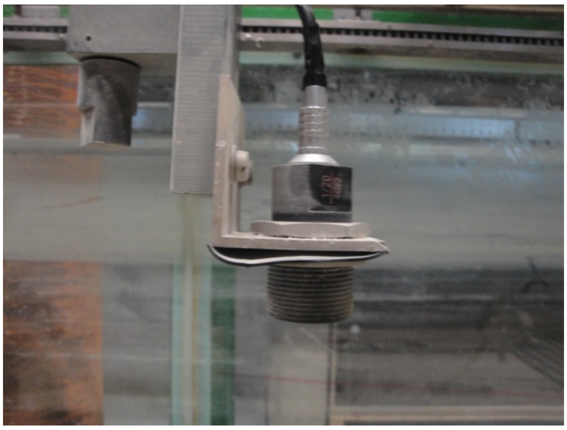


figure 3-7 Echo-sounder

Roller-wooden boom- wooden plates: The measuring devices are moving in the transverse direction simultaneously since they are installed on a wooden boom. Measurements are taken every 5 or 10cm with the use of wooden parallelepiped plates. The first and the last measurement are taken 0.1m from the sides of the flume. The device set is displayed in the following pictures.

figure 3-8, 3-9 wooden boom and 10cm wooden plate

3.2 Damage determination & profile measurements

At first, profile measurements of the tested structures have to take place. These measurements are being taken using both laser and echo-sounding equipment. Profiles are taken at thirteen cross sections, each 5 centimeters apart from each other. The first and the last measurement is taken 0.1 m from the side of the wave flume. The profile below the water level is measured using the echo-sounder and partly using the laser while, the area above the water level is measured with the laser.

The area around the water level is the most critical area because the most amount of damage is expected in that region. At the same time this is the area where the measuring equipment overlaps and therefore calibration of the instruments was needed in order to acquire correct data.

When the laser is measuring below the water level a correction factor has to be applied to the section below the water level accounting for the different speed the laser is travelling over that specific distance. The total distance measured is the distance through the air plus the distance through water. Since the position of the laser is fixed the distance from the device until the water surface can be considered constant. When the measured distance is larger than this constant distance the correction factor will be applied to that specific section. Resulting in a correctly measured height of the profile both below as above the waterline.

Calibration of the measuring devices: A metal block was placed inside the filled flume at a depth within the range of both devices and then, measurements were taken by both of them. Afterwards, the signal of the laser was manipulated in such way that both the devices plotted the metal block exactly at the same position (depth). From the calibration procedure a correction factor was computed and applied to represent the different propagation velocity of the laser signal in the air and in the water. Nevertheless, the correctness of the calibration is sensitive to the clarity of the water, which inevitably sometimes was changing due to dirt induced by the dust of the stones.

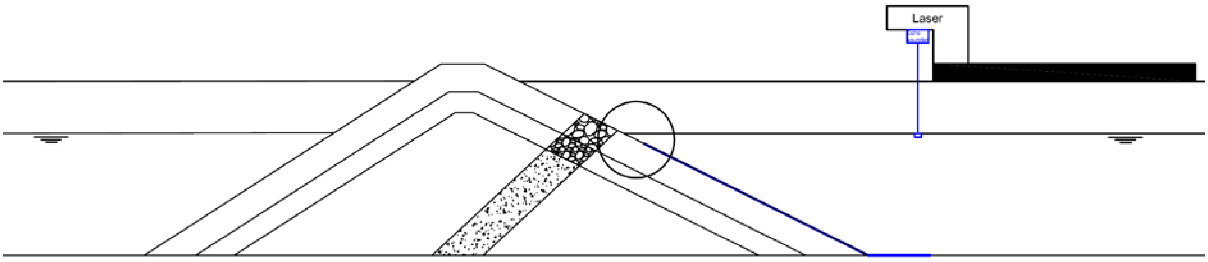


Figure 3-10 Measuring below water level with echo-sounder (source KIK[2011])

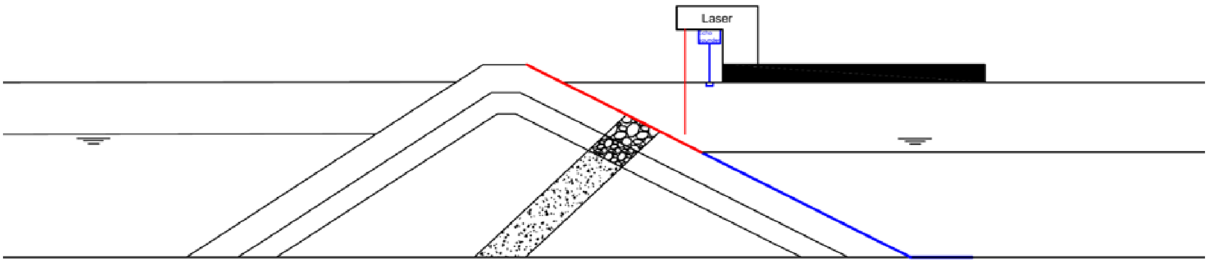


Figure 3-11 Measuring profile above water line with laser (source KIK[2011])

3.3 Testing procedure

When following an experimental procedure which will be repeated several times, it is indispensable to clearly describe it and then reproduce absolutely similar repetition conditions with the higher level of devotion. Any deviation from the pre-described conditions will cause a varying influence in the results and consequently it will lead in the disusing of the results.

The sequential steps of the measurement procedure are the following:

1. Initial test. Filling of the wave fume. Water level at 0.65cm.

2. Measurement of the initial profiles of the structure every *5cm* (or *10cm*) with the use of the laser device and the echo-sounder. Measurement of the initial water-level.
3. Photo-taking of the structure's side view and preparation of the video equipment.
4. Inspection of the pressure gauges indications on the computer screen and removal of air bubbles inside the tubes that connect the pressure gauges and specific locations inside the structure.
5. Start of the experiment. Activation of the wave generator via the computer using the corresponding input files containing the desirable wave spectrum and duration.
6. Supervision of the testing progression. Automatic finish of testing procedure, wave generator.
7. Photo-taking of the structure's side view and of special deformations of the initial profiles. (i.e. core or under-layer exposures).
8. Measurement of the final profiles of the structure every *5cm* (or *10cm*). Measurement of the final water-level.
9. Draining of the flume.
10. Removal of the armour layer stones and re-profiling of the under-layer.
11. Reset of the armour layer.
12. Starting of the new measurement procedure for the sequential test.

Remarks about the procedure:

1. After the installation of the equipment and the construction of structure 1, all the devices (i.e. pressure gauges, wave sensors, wave run up sensors etc.) were calibrated. Afterwards, recalibration of the devices was performed right after the construction of structures 2 and 3. Information about the calibration can also be found in the study of KIK[2011].
2. Assuming a testing duration 2 hours the total duration of the whole measuring cycle is about 330min (5.5 hours). Therefore, the execution of more than two tests per day was a very tough goal.
3. After the execution of every test, the top layer was removed and the first under-layer was re-profiled. The goal was to avoid any kind of initial dynamic stability conditions and physical interlocking of the stones caused by the previously executed test. These conditions are assured only by completely removing the top layer. Removal of only one layer of the top layer is not sufficient because deformations of under-layer cannot be treated and the penetration of stones from top layer inside the under-layer is contributing to the direction of safety.
4. Air bubbles that are trapped inside the tubes contaminate with errors the pressure distribution records.
5. The placement and removal of the stones is done as careful as possible. The reason is that, inevitably, after every test the stones are getting lighter and more rounded. Moreover, this phenomenon may result in the overestimation of the damage values

of the last experiments, due to the fact that the stones will be slightly lighter and will have weaker interlocking.

6. During the testing procedure, measurements of the wave run up, pressure distribution and wave spectrum are being taken automatically by the computer software used (Daisy Lab). The evaluation of these measurements is beyond the scope of this study.

3.4 Data processing & damage level computation

The recorded raw measurements, contain several errors(short duration, high peaks on the recorded signal) that occur, due to small waves and dirt on the water surface that lead to a bad reflection of the laser. Therefore, before the final stage of damage level computation, a filter has to be applied in the raw data, to erase the errors. In fact, this filter deletes the errors and fills in the deleted data points with interpolated values from adjacent correct measurements.

To accomplish that, two methods were proposed; the *smooth fit* and *the polyline fit* approach.

3.3.1 *Smooth fit approach*: A Matlab script (KIK[2011]), produces a smooth profile by replacing the errors with interpolated values from correct measurements in the vicinity of them.

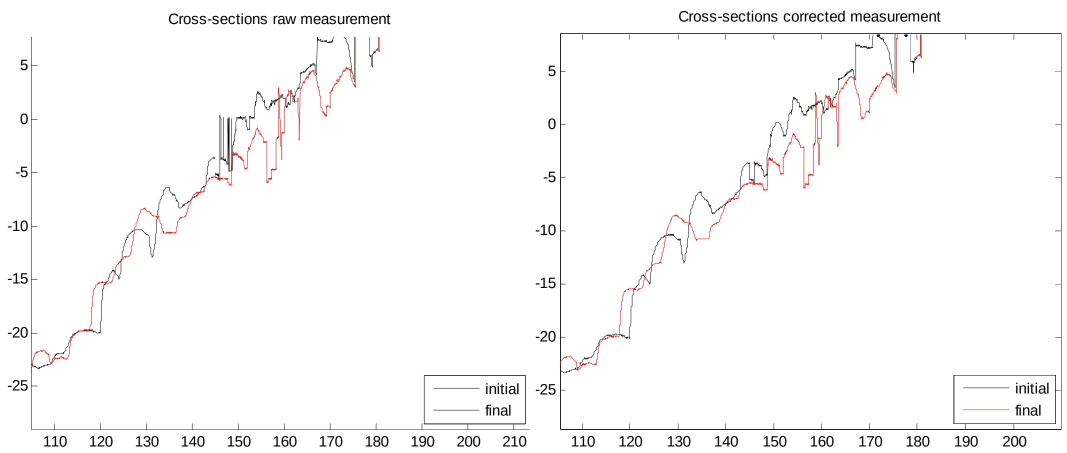


figure 3-12, 3-13 Initial/final profile measurements before and after the application of the *smooth fit* filter

Afterwards, the script computes the damage level for every pair of initial/final profile measurement, by subtracting the continuous final profile from the initial profile signal and then by dividing the eroded area (difference between initial and final profile) with d^2_{n50}.

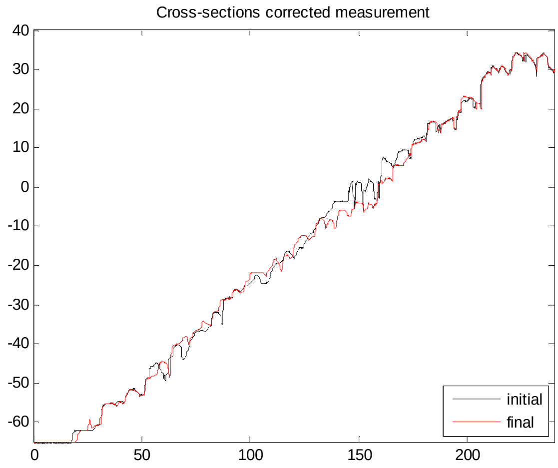


figure 3-14 damage level computation of the corrected cross section (source Kik[2011])

<u>Polyline fit approach:</u> Errors are treated similarly to the smooth fit approach, but afterwards the two continuous signals are averaged by using a 10-grade polynomial. The difference between the new averaged profiles express the eroded area, which is then divided by d^2_{n50}, to compute the damage value.

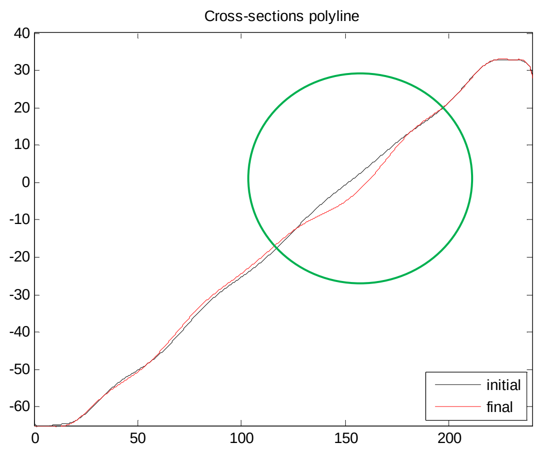


figure 3-15 Initial/final profile measurements before and after the application of the *polyline fit* filter

Remark 1: Various techniques can be used to specify the resulting damage level from the profile measurements. The important clue at this point is that the profile measurements taken for this study, are represented by a continuous signal. On the other hand, at the case of VAN DER MEER[1988], the profile measurements were discrete measurements, taken at cross sections every *10cm*, using measuring rods that were measuring every 4cm. Finally the all the profiles were averaged and used to compute the damage level.

Remark 2: since the laser beam was substantially smaller than the echo-sounder's, it had the opportunity to penetrate within the pores of the layer. Consequently, the continuous signal produced by the laser indicated more abrupt peaks while the corresponding signal from the echo-sounder was smoother.

Chapter 4

Statistical analysis-comparisons

This chapter contains the analysis and the comparisons used for the evaluation of the experimental procedure. At first, a statistical analysis of the computed damage levels takes place, in order to determine the statistical distribution that most efficiently represents the distribution of the computed damage levels. Afterwards, a computational approach (comparison *smooth*/*polyline* fit approach) is selected upon which are based the subsequent comparisons. In particular, for every test case several comparisons are being conducted in order to provide insight in the statistical behavior of the individual tests. Finally, the sensitivity of the computed damage values due to various aspects (measurements density, type of wave breaking, and influence due to measurements position) is being investigated by means of statistical analyses.

The different comparisons take place separately for every structure and afterwards a general conclusion is drawn. Below, is presented an analytical description of the total data set used in the analysis. More precisely, information is offered concerning the selected test cases the repetition tests and their characteristics.

4.1 Data set presentation

4.1.1Structure 1

Two test cases were selected (test case 3 and 6) while for structure 1 a notional permeability value of P=0.5 was used for the calculation of the damage values from the Van der Meer formulas. The tables below display the characteristics of the original and repetition tests of the test cases under consideration.

The particularity in test case 3 is that the original test, test 3, is executed with the reflection compensator activated while for all the repletion tests the reflection compensator was deactivated by accident (power cut off that reset the system adjustments). During repetition tests 3a, 3b, 3c the testing conditions were kept stationary, since the results displayed on the table below are almost identical to each other.

The mean wave height for tests conducted with the reflection compensator deactivated was 0.17m and were accompanied by a mean period of 2.83s. The wave steepness was 0.01 and the parameter ξ acquired a value of 4.24, dictating a surging breaking type of the waves on the structure since the critical Irribaren number was 3.54. The structure was tested for approximately 145min by 3000waves.

For the original test of test case 3, test 3, the mean wave height was slightly smaller (0.15m) and the mean wave period slightly higher (2.98s). These differences resulted in a higher Iribarren parameter of 4.76 and consequently the wave breaker type remained in the surging area. Finally the test duration was the same as in the other tests (145min).

structure 1/test case 3							
test	**H_s[m]**	**T_m[s]**	**T_p[s]**	**s**	**ξ**	**breaker type**	**calculated damage**
3	0,15	2,98	3,90	0,01	4,76	surging	6,91
3a	0,17	2,80	3,66	0,01	4,19	surging	18,71
3b	0,17	2,83	3,70	0,01	4,24	surging	17,90
3c	0,18	2,83	3,70	0,01	4,23	surging	18,42

table 4-1 Data inventory for test case 3

For test case 6 and for tests 6, 6-2, 6a, 6d, 6c the compensator was activated while the rest of the tests (6b, 6c) were conducted with the reflection compensator turned off (for the same reason as in test case 3). Consequently, for the tests without the contribution of the compensator, the structure had to suffer among others, the effect of the formation of standing waves.

structure 1/test case 6							
test	**H_s[m]**	**T_m[s]**	**T_p[s]**	**s**	**ξ**	**breaker type**	**calculated damage**
6	0,14	2,11	2,76	0,02	3,55	surging	8,70
6-2	0,15	2,08	2,72	0,02	3,36	plunging	11,55
6a	0,16	2,08	2,72	0,02	3,27	plunging	14,18
6d	0,16	2,10	2,75	0,02	3,31	plunging	14,35
6e	0,16	2,10	2,75	0,02	3,29	plunging	14,77
6b	0,16	2,14	2,8	0,02	3,31	plunging	17,03
6c	0,16	2,14	2,8	0,02	3,36	plunging	15,22

table 4-2 Data inventory for test case 6

Therefore, the components of testing case 6, can be divided into two groups, depending on the functioning of the reflection compensator. Despite that someone would expect differences in the characteristics of the wave climate (height, steepness and period) and maybe on the Iribarren number, the deviations were relatively trivial. The main difference can be found on the deviation of the shape of the wave spectrum applied on the flume. The considerably low value of computed damage for test 6 is determined by the fact that the test is in the transition area between surging and plunging and although the damage for the rest of the tests is calculated using the Van der Meer equation for the plunging area, this one is calculated using the equation for the surging area.

For the tests 6, 6-2, 6a, 6d, 6e, the mean wave height and period was around 0.15m and 2.1s respectively. The wave steepness was the same for all the tests s=0.02 and the Iribarren numbers were around 3.3, except from test 6 where a value of 3.55 was found. Consequently, the breaking type for the test case was located in the plunging area, except from test 6 which was in the transition boundary, from the surging side.

A slight increase of the mean wave height (0.16cm) and of the mean wave period (2.14s) was observed in the tests with the reflection compensator switched off. The ξ parameter remained more or less stable at approximately 3.33 and the type of wave breaking on the structure was plunging. For both tests the duration was 107 minutes.

4.1.2 Structure 2

For structure 2 a P value of 0.1 was used for the calculation of the damage values using the Van der Meer formulas and the two selected cases were test case 8 and test case 11.

The parameters concerning the test conditions and characteristics for test case 8 were kept exactly the same while for test case 11 a small deviation occurs between the original test 11 and the repetition tests.

For test case 8 the mean wave height was in the order of 0.1m accompanied by a mean period of 1.33s and a wave steepness of 0.03. The parameter ξ was 2.7 and the breaking type was in the area of surging since the critical Irribaren number counted 3.57. The duration was also the same for all the tests at 67min.

structure 2/test case 8							
test	**H_s[m]**	**T_m[s]**	**T_p[s]**	**s**	**ξ**	**breaker type**	**calculated damage**
8	0,09	1,33	1,74	0,03	2,76	plunging	2,48
8a	0,10	1,33	1,74	0,03	2,68	plunging	3,02
8b	0,10	1,33	1,74	0,03	2,68	plunging	3,08
8c	0,10	1,33	1,74	0,04	2,67	plunging	3,14

table 4-3 Data inventory for test case 8

The wave characteristics for the test case 11 are described by a mean significant wave height of 0.10m and a wave period of 3.46s for the test 11 and approximately 3.75s for the three repetition tests. Moreover, the wave steepness is identical for all the tests with a value of 0.01 while the parameter ξ is 6.71 for the first test and approximately 7.05 for the repetitions (critical value of 3.57). During the test duration of 173min for the original test and 188min for the repetitions, surging waves are attacking the 2nd structure.

structure 2/test case 11							
test	**H_s[m]**	**T_m[s]**	**T_p[s]**	**s**	**ξ**	**breaker type**	**calculated damage**
11	0,10	3,46	4,52	0,01	6,71	surging	6,70
11a	0,11	3,75	4,90	0,01	7,03	surging	9,20
11b	0,11	3,75	4,90	0,01	7,03	surging	9,20
11c	0,11	3,75	4,90	0,01	7,06	surging	8,77

table 4-4 Data inventory for test case 11

4.1.3 Structure 3

Test cases 20 and 26 were selected for further investigation. For the calculation of the damage values the notional permeability value was assumed P=0.3, since there is no reported value in the literature. The parameters concerning the test conditions and characteristics for test case 20 are exactly the same while for test case 26 there is a small deviation of the original test 26 with respect to the repetition tests.

The duration of the tests for test case 20 was about 111min and the wave characteristics were 0.13m and 2.22s for the mean wave height and mean period respectively. Consequently the Iribarren number fluctuated from 3.85 to 4.1, in the vicinity of the transitional area of surging and plunging waves (critical value 3.98).

structure 3/test case 20							
test	**H_s[m]**	**T_m[s]**	**T_p[s]**	**s**	**ξ**	**breaker type**	**calculated damage**
20	0,13	2,20	2,88	0,02	3,84	plunging	11,73
20a	0,14	2,30	3,01	0,04	4,06	plunging	11,13
20b	0,13	2,29	2,99	0,04	4,12	surging	9,34
20c	0,13	2,25	2,94	0,04	4,06	surging	9,10

table 4-5 Data inventory for test case 20

In test case 26 the input data had to be separated into the input in the original test 26, whereas the mean wave height and period was 0.11m and 1.18s respectively, with the values used for the repetition tests which were approximately 0.13m and 1.42s. Thereupon, differences occurred in the Iribarren number (minimum of 2.26 for test 26) and the wave steepness (about 0.04-0.05 for the repetition tests). These differences also explain the higher damage values found for the repetition tests. All tests, remained in the plunging area (critical Irribaren number counted 3.98) while the duration ranged from 57min to 70min.

structure 3/test case 26							
test	**H_s[m]**	**T_m[s]**	**T_p[s]**	**s**	**ξ**	**breaker type**	**calculated damage**
26	0,11	1,18	1,54	0,05	2,26	plunging	1,12
26a	0,13	1,42	1,86	0,02	2,41	plunging	4,46
26b	0,12	1,42	1,86	0,02	2,42	plunging	4,43
26c	0,12	1,41	1,84	0,02	2,43	plunging	4,18

table 4-6 Data inventory for test case 26

4.2 Statistical analysis of computed damage

Before applying any statistical approach for the evaluation and processing of the computed damage values, an investigation on their statistical behavior has to take place. The first characteristic that has to be determined is which distribution can most efficiently approach the distribution of the computed damage levels, due to the low sample population.

This can be done using the *One Sample Kolmogorov-Smirnov test*. The test is being executed using the IBM statistical package SPSS, and theoretical information about the test procedure are being presented in the Appendix II. All the measurement sequences (computed damage levels from the profile measurements) for every test and for the case of the *smooth fit* approach are being examined individually, under all the four possible statistical distributions (normal, uniform, exponential, Poisson).

For every group, a parameter (*asym.p sig.*) is determined that expresses the probability that a considered statistical distribution can represent the distribution of the damage values (null hypothesis). In case that, the value of *asymp. sig.* is lower than 0.05, then a different statistical distribution should be selected for the representation of the distribution of damage.

After the termination of data elaboration it was found, that the distribution with the higher effectiveness in approaching the measurement sequences, is the normal distribution. The following tables contain the output of the *One Sample Kolmogorov-Smirnov test* concerning the cases of Uniform and Normal distributions for the three different structures and for every case separately.

Apart from the normal distribution, which shows a strong consistency with the distribution of damage for test case 3, a uniform distribution could have been used, although for the cases of 3b/5cm and 3c/5cm the probability acquires low values.

structure 1/case 3		Uniform distribution	normal distribution		
measurement step per cm	**test**	**asymp. Sig**	**asymp.sig**	**μ**	**σ**
10	**3**	0,500	0,888	15,31	3,08
5	**3a**	0,231	0,917	20,69	3,04
10	**3a**	0,942	0,992	21,40	1,12
5	**3b**	0,272	0,889	19,39	3,92
10	**3b**	0,572	0,892	20,72	4,81
5	**3c**	0,245	0,989	21,24	3,20
10	**3c**	0,506	0,993	20,22	2,39

table 4-7 Statistical distribution test for test case 3

For test case 6, and for the case of uniform distribution problems might occur for test 6a/5cm while weak consistency can be found also in tests 6e/10cm and 6-2. Here, the selection of the normal distribution is much safer choice.

structure 1/case 6		Uniform distribution	normal distribution		
measurement step per cm	**test**	**asymp. Sig**	**asymp.sig**	**μ**	**σ**
5	**6**	0,575	0,977	8,16	3,29
10	**6-2**	0,176	0,873	10,44	1,63
5	**6a**	0,057	0,693	11,35	2,04
10	**6a**	0,387	0,610	11,95	2,33
5	**6d**	0,539	0,848	9,51	2,81
10	**6d**	0,695	0,994	9,51	3,09
5	**6e**	0,607	0,864	11,06	2,61
10	**6e**	0,141	0,494	10,71	2,60
5	**6b**	0,593	0,912	11,18	3,63
10	**6b**	0,847	0,952	11,68	2,78
5	**6c**	0,562	0,994	8,86	3,43
10	**6c**	0,488	0,956	9,59	3,18

table 4-8 Statistical distribution test for test case 6

Except from test 8b/5cm the rest original and repetition tests can be efficiently represented by the uniform distribution. However, all tests of test case 8, gave a higher *asymp. sig.* value for the case of normal distribution, instead of the uniform one.

structure 2/case 8		Uniform distribution	normal distribution		
measurement step per cm	test	asymp. Sig	asymp.sig	μ	σ
5	8	0,892	0,996	5,11	1,31
10	8	0,780	0,880	5,03	1,37
5	8a	0,970	0,991	5,44	1,74
10	8a	0,947	0,999	6,03	1,51
5	8b	0,147	0,412	5,99	1,81
10	8b	0,580	0,817	5,70	1,68
5	8c	0,973	0,830	5,38	1,68
10	8c	0,831	0,896	5,59	1,75

table 4-9 Statistical distribution test for test case 8

For the second test case of structure 2, test case 11, the uniform distribution is unsuitable for test 11/5cm and causes high uncertainty for test 11a/5cm. Therefore, for all tests, the normal distribution is a more reasonable choice.

structure 2/case 11		Uniform distribution	normal distribution		
measurement step per cm	test	asymp. Sig	asymp.sig	μ	σ
5	11	0,001	0,658	11,87	3,39
10	11	0,660	0,916	12,72	2,12
5	11a	0,117	0,566	14,23	2,16
10	11a	0,478	0,881	14,95	1,53
5	11b	0,059	0,647	13,84	2,82
10	11b	0,320	0,806	15,10	3,14
5	11c	0,817	0,995	16,27	3,07
10	11c	0,911	0,998	16,39	3,58

table 4-10 Statistical distribution test for test case 11

For test case 20, even normal distribution gave low values of *asymp. sig.* However, it was found that for test 20c the uniform distribution failed to satisfy the zero-condition hypothesis since the possibility that uniform distribution can describe the damage distribution is lower than 0.05. Consequently, normal distribution is also selected for test case 20.

structure 3/case 20		Uniform distribution	normal distribution		
measurement step per cm	test	asymp. Sig	asymp.sig	μ	σ
5	20	0,894	0,994	6,01	1,75
10	20	0,971	0,993	6,67	1,19
5	20a	0,706	0,893	5,73	1,31
10	20a	0,710	0,986	5,45	1,42
5	20b	0,893	0,952	5,80	1,44
10	20b	0,417	0,546	6,13	1,59
5	20c	0,022	0,365	8,25	1,95
10	20c	0,224	0,644	8,22	2,56

table 4-11 Statistical distribution test for test case 20

Finally, for test case 26 and for tests 26/10cm, 26/5cm and 26b/10cm the hypothesis for the uniform distribution is nearly rejected. In addition, two more tests, 26a/5cm and 26c/10cm showed very low values of *asymp. sig.*for the uniform distribution and therefore the selection of normal distribution is inevitable.

structure 3/case 26		Uniform distribution	normal distribution		
measurement step per cm	test	asymp. Sig	asymp.sig	μ	σ
5	26	0,060	0,851	3,61	1,84
10	26	0,082	0,552	3,61	2,34
5	26a	0,200	0,909	5,80	2,37
10	26a	0,679	0,982	5,22	2,55
5	26b	0,533	0,940	6,40	2,38
10	26b	0,103	0,446	5,74	2,20
5	26c	0,201	0,735	6,69	1,67
10	26c	0,811	0,976	6,25	1,31

table 4-12 Statistical distribution test for test case 26

Summarizing, the distribution of the damage values would have been expected to be an oscillation between a mean value with two extremes, an upper and a lower value. Therefore, a uniform distribution would have been a good approach for the distribution of the damage values. Nevertheless, for some cases the *asymp. sig.* variable of the uniform distribution takes values less than 5%(one in structure 3 and one in structure 2), which is the significant level and below this limit the selected distribution is unsuitable for the examined variable. Moreover, several cases are in the vicinity of this subjective limit, increasing the uncertainty in selecting the uniform distribution. Consequently, the selection of the normal distribution seems to be reasonable since it is located for all the cases between the acceptable margins.

All the individual measurement sequences for every test case, structure, measurement space step and computational method approach (*smooth* or *polyline* fit) are being presented in the Appendix I.

4.3 Comparison *smooth/polyline* fit approach

At this section of the study, the two computational methods used for the quantification of damage levels are being examined. The aim is to determine which one is the most suitable for the damage level representation. Afterwards the selected computational approach is used for the conduction of the subsequent computations at the following sections of the study.

At first, for the evaluation of the two approaches, the mean value and the standard deviation of the damage level is used, in order to estimate the confidence intervals for every test, individually. By that way, the order of magnitude and the spreading of the computed damage values are determined. Afterwards, for every test, the average damage values for the *polyline* and the *smooth* fit approach are compared and their difference is expressed as percentage of the *smooth* fit average damage value. This percentage indicates the magnitude of difference between the two computational methods.

Finally, the difference between calculated values from the Van der Meer equations and the mean damage values from the two approaches is being computed. At this point it should be noted that Van der Meer used the smooth fit approach for the analysis of his data. Afterwards, it is being expressed as percentage of the calculated value in order to indicate the deviation from the calculated values extracted by the Van der Meer formulas. The smaller this percentage is, the more the measured damage value converges to the output of the Van der Meer equations.

For the two computational approaches, analytical description of their characteristics is offered in paragraph 3.4 "Data processing & damage level computation".

4.3.1 Structure 1

A detailed picture of the confidence intervals for the case of structure 1 with respect to the computational method used is shown in the following table. The table contains the computations for the repetition tests 3a, 3b, and 3c because the original test 3 was executed with the reflection compensator turned on and therefore its contribution on the computed damage has to be investigated. In addition, the opposite holds for test case 6 where repetition tests 6b and 6c (reflection compensator turned off) were not included in this part of the analysis.

comparison measurement smooth fit/polyline fit							
Structure 1/test case 3				90% confidence interval			
Test	**μ**	**σ**	**n**	**Lower Bound**	**Upper Bound**	**interval length**	
3a	20,69	3,04	13	19,31	22,08	2,78	**smooth**
3b	19,39	3,92	13	17,60	21,18	3,58	
3c	21,24	3,20	13	19,78	22,70	2,92	
3a	19,04	3,27	13	17,55	20,53	2,98	**polyline**
3b	17,77	3,68	13	16,09	19,45	3,36	
3c	19,98	3,38	13	18,44	21,52	3,08	

table 4-13 Structure 1, smooth/polyline fit approach comparison for test case 3

comparison measurement smooth fit/polyline fit							
Structure 1/test case 6				90% confidence interval			
Test	**μ**	**σ**	**n**	**Lower Bound**	**Upper Bound**	**interval length**	
6	8,16	3,30	6	5,95	10,37	4,43	**smooth**
6-2	10,44	1,63	6	9,35	11,54	2,19	
6a	11,35	2,04	13	10,42	12,28	1,86	
6d	9,51	2,81	12	8,17	10,84	2,67	
6e	11,06	2,61	13	9,87	12,25	2,38	
6	6,19	3,63	6	3,75	8,63	4,87	**polyline**
6-2	8,42	2,27	6	6,89	9,95	3,05	
6a	8,37	1,99	13	7,46	9,28	1,82	
6d	7,53	3,36	12	5,94	9,12	3,19	
6e	8,45	2,99	13	7,09	9,82	2,73	

table 4-14 Structure 1, smooth/polyline fit approach comparison for test case 6

The differences among the two methods are small in the case of structure 1. Nevertheless, for all the cases, the extracted results from the *smooth* fit approach were larger than the corresponding output of the *polyline* fit. Specifically, the difference in the case of test series 3 is 8% while for test series 6, counts 22.6%. On average, the difference between the two computational approaches for the case of structure 1 is approximately 15.5%.

Moreover, a comparison is made between the calculated values from the Van der Meer equations and the computed ones after they were manipulated by the two methods. This comparison is displayed in the table below.

smooth/polyline fit approach							
Test	**Calculated S**	**Measured S smooth fit**	**difference**	**percentage %**	**Measured S polyline**	**difference**	**percentage %**
3a	18,71	20,69	1,98	10,57	21,33	2,62	13,97
3b	17,90	19,39	1,49	8,32	23,60	5,70	31,85
3c	18,42	21,24	2,82	15,33	18,30	0,12	0,65
6	8,70	8,16	0,54	6,16	9,93	1,24	14,24
6-2	11,55	10,44	1,11	9,62	11,12	0,43	3,71
6a	14,18	11,35	2,83	19,95	12,85	1,33	9,38
6d	14,35	9,51	4,84	33,76	10,49	3,86	26,89
6e	14,77	11,06	3,71	25,10	3,06	11,70	79,26

table 4-15 Structure 1, comparison between van der Meer equations output and computational methods

According to the table above, for half of the tests that were conducted in structure 1, the deviation from the calculated values (Van der Meer equations) was higher for the *smooth* fit approach. The opposite case holds for the other half were the *polyline* fit approach deviated more.

Partially, the average deviation for the *smooth* fit is approximately 11.4% for test case 3 and 19% for test case 6, while for the *polyline* approach the corresponding values hold 15% and 27% respectively.

4.3.2 Structure 2

The following table contains the computations for the estimation of the statistical characteristics of the computed damage levels with respect to the computational approach, in the case of structure 2.

In series test 8, the processing of the data showed that the mean damage level of in case of the *polyline* fit approach is 42% lower than the corresponding values of the *smooth* fit approach.

comparison measurement smooth fit/polyline fit							
Structure 2/test case 8				90% confidence interval			
Test	**μ**	**σ**	**n**	**Lower Bound**	**Upper Bound**	**interval length**	
8	5,11	1,31	13	4,52	5,71	1,19	**smooth**
8a	5,44	1,74	13	4,65	6,24	1,59	
8b	5,99	1,81	13	5,17	6,82	1,65	
8c	5,41	1,61	12	4,65	6,18	1,53	
8	3,07	1,36	13	2,45	3,69	1,24	**polyline**
8a	2,97	1,97	13	2,07	3,87	1,80	
8b	3,67	1,47	13	3,00	4,35	1,35	
8c	3,09	1,42	12	2,42	3,76	1,34	

table 4-16 Structure 2, smooth/polyline fit approach comparison for test case 8

For the case of test series 11 the difference was 18%. The average difference of the damage levels between the two methods, for this structure is 30%.

comparison measurement smooth fit/polyline fit							
Structure 2/test case 11				90% confidence interval			
Test	**μ**	**σ**	**n**	**Lower Bound**	**Upper Bound**	**interval length**	
11	12,90	1,86	13	12,05	13,75	1,70	**smooth**
11a	14,47	1,86	12	13,58	15,35	1,77	
11b	13,84	2,82	13	12,55	15,13	2,57	
11c	16,27	3,07	12	14,82	17,73	2,92	
11	9,57	1,90	13	8,70	10,44	1,74	**polyline**
11a	12,44	1,99	13	11,53	13,35	1,81	
11b	11,18	3,36	13	9,65	12,71	3,06	
11c	14,26	3,42	12	12,63	15,89	3,25	

table 4-17 Structure 2, smooth/polyline fit approach comparison for test case 11

Afterwards, the relation of the computed damage values with respect to the calculated from the Van der Meer equations is presented in the following table.

smooth/polyline fit approach							
Test	**Calculated S**	**Measured S smooth fit**	**difference**	**percentage %**	**Measured S polyline**	**difference**	**percentage %**
8	2,48	5,11	2,63	106,04	3,07	0,58	23,52
8a	3,02	5,44	2,42	80,06	2,97	0,05	1,61
8b	3,08	5,99	2,91	94,45	3,67	0,59	19,21
8c	3,14	5,41	2,27	72,21	3,09	0,05	1,70
11	6,70	12,90	6,20	92,50	9,57	2,87	42,84
11a	9,20	14,47	5,27	57,24	12,44	3,24	35,22
11b	9,20	13,84	4,64	50,42	11,18	1,98	21,53
11c	8,77	16,27	7,50	85,50	14,26	5,49	62,55

table 4-18 Structure 2, comparison between Van der Meer equations output and computational methods

Surprisingly, the smooth fit approach computations showed the higher difference with respect to the calculated damage values. In specific, they varied with an average of 80%. On the other hand, the *polyline* fit approach showed a better convergence, and has deviated with a mean value of 26%. The deviation for test case 8 was 88% for the *smooth* fit and 11% for the *polyline* fit, while for test case 11 the percentages were 71% and 41%. Finally, all the values computed with the *smooth* fit approach had individually bigger deviations than the *polyline* fit with respect to the calculated values.

4.3.3 Structure 3

The following tables present the output of the statistical analysis held for the structure 3 and for test cases 20 and 26.

For test case 20 the average damage was constantly higher for the case of *smooth fit* approach. Indeed, the average difference was in the order of 26%. Further upon, despite the higher order of damage level, the *smooth fit* approach was accompanied with lower standard deviation values and thus it showed narrower spreading.

comparison measurement smooth fit/polyline fit							
Structure 3/test case 20				90% confidence interval			
Test	**μ**	**σ**	**n**	**Lower Bound**	**Upper Bound**	**interval length**	
20	6,01	1,75	13	5,21	6,81	1,59	**smooth**
20a	5,73	1,31	13	5,13	6,33	1,20	
20b	5,80	1,44	13	5,14	6,46	1,31	
20c	8,25	1,95	13	7,37	9,14	1,78	
20	4,30	1,86	13	3,45	5,15	1,70	**polyline**
20a	3,95	1,64	13	3,20	4,70	1,50	
20b	4,17	1,67	13	3,41	4,94	1,53	
20c	5,99	2,11	13	5,03	6,95	1,93	

table 4-19 Structure 3, smooth/polyline fit approach comparison for test case 20

For test case 26 the mean damage level was on average 29% higher for the *smooth fit* approach. On the other hand, the spreading of the damage values was narrower for the *polyline fit* approach.

comparison measurement smooth fit/polyline fit							
Structure 3/test case 26				90% confidence interval			
Test	**μ**	**σ**	**n**	**Lower Bound**	**Upper Bound**	**interval length**	
26	3,61	1,84	12	2,74	4,49	1,75	**smooth**
26a	5,80	2,37	13	4,72	6,88	2,17	
26b	6,40	2,38	12	5,27	7,53	2,26	
26c	6,69	1,67	13	5,92	7,45	1,53	
26	2,79	2,20	13	1,78	3,79	2,00	**polyline**
26a	4,58	2,58	13	3,40	5,76	2,36	
26b	4,91	1,89	12	4,01	5,81	1,79	
26c	5,09	1,67	13	4,33	5,85	1,52	

table 4-20 Structure 3, smooth/polyline fit approach comparison for test case 26

Then, the situation with regard to the calculated values is being investigated. Analytical information about every case individually is shown in the following table.

smooth/polyline fit approach							
Test	**Calculated S**	**Measured S smooth fit**	**difference**	**percentage %**	**Measured S polyline fit**	**difference**	**percentage %**
20	11,73	6,01	5,72	48,76	4,30	7,43	63,34
20a	12,13	5,73	6,41	52,81	3,95	8,18	67,43
20b	9,34	5,80	3,54	37,87	4,17	5,16	55,31
20c	9,10	8,25	0,84	9,25	5,99	3,11	34,17
26	1,12	3,61	2,49	223,11	2,79	1,67	149,20
26a	4,46	5,80	1,34	29,94	4,58	0,11	2,57
26b	4,43	6,40	1,97	44,54	4,91	0,48	10,84
26c	4,18	6,69	2,50	59,91	5,09	0,91	21,79

table 4-21 Structure 3, comparison between Van der Meer equations output and computational methods

In the case of the third structure, the situation seems to be more balanced. For test case 20 all individual values for the case of *smooth* fit differed less than the corresponding ones from the *polyline* fit. On average, the differences were 33% and 55% respectively. The opposite situation holds for test case26. Indeed, on average the difference here is 89% for the *smooth* fit and 46% for the *polyline* fit. Therefore, the overall deviation for the *smooth* fit was 63% and for the *polyline* 51%.

4.3.4 Conclusion

A visual and aggregated expression of the above mentioned can be found in the graph below.

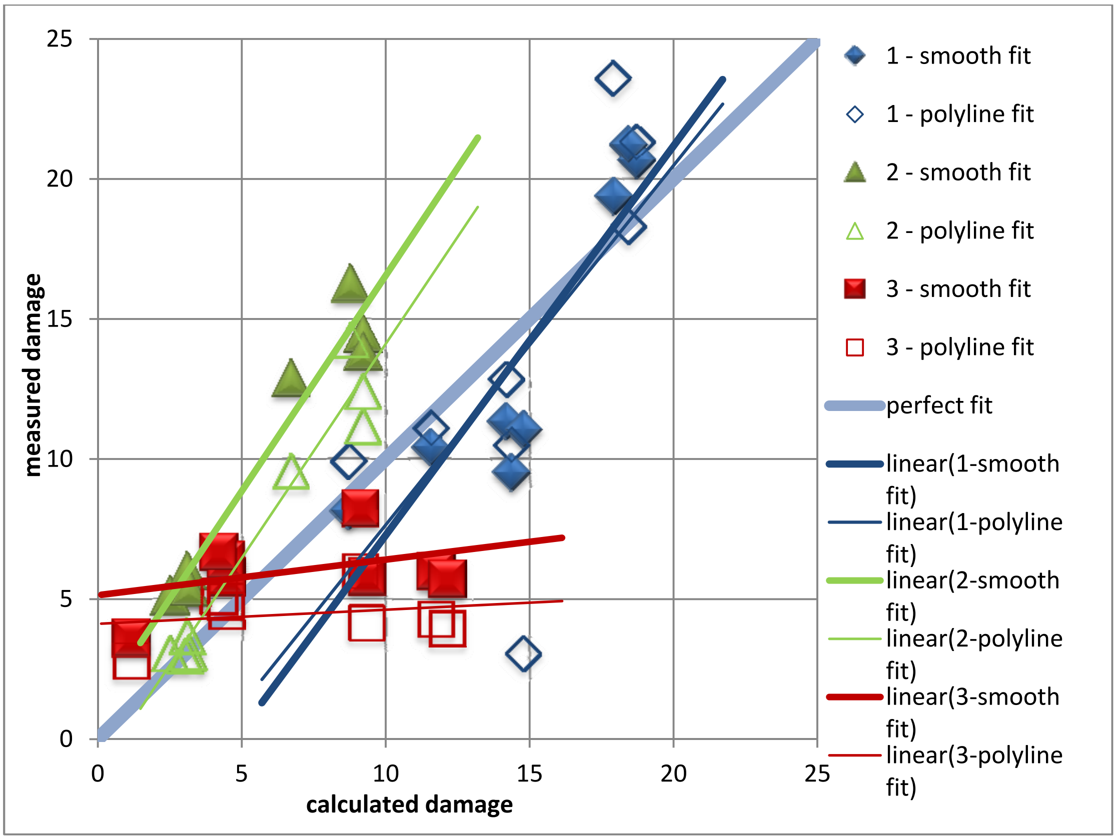


figure 4-1 aggregated damage values for all tests-case of *smooth-polyline* fit comparison

In general, for structures 2 and 3 (especially for structure 2) the *smooth* fit approach resulted in damage values 15% higher than the *polyline* fit. However, this was not the case for structure 1 were the situation is more balanced between the two test cases.

Finally, attention has to be paid on the fact that the computed damage values from test structure 3 are not in line with the calculated values according to Van der Meer formulas. Nevertheless, this is reasonable since this structure is the one tested for the first time (not reported notional permeability value).

Therefore, what is important is that the suggested intervals of the proposed evaluation contain the possible range of damage values and also are in the side of safety. These conditions are successively described when using the *smooth* fit approach (which is the one chosen by Van der Meer), although the issue of the computational approach needs further investigation and optimization. Consequently, the smooth fit approach will be used for the conduction of the subsequent analyses of this study.

4.4 Comparison of individual tests

At this section of the study takes place an attempt to gain insight in the behavior of individual tests. More precisely, for every test case original and repetition tests are treated either individually, or separated into groups according to mutual characteristics and, afterwards a statistical analysis is applied with the aim to identify and explain the occurrence of behavioral deviations among the computed damage values.

In particular, the comparison takes place using the *Kruskal-Wallis non parametric test for k-independent variables* (number of tests), with the null-condition hypothesis that the distribution of damage among the different components of a test group is the same. The comparison does not include quantitative information about the differences among the tests, something that is not the goal of this study, but adequate qualitative indications about the differing test(s). The analysis focuses on the *smooth fit* approach, which is the one selected from the previous section, for the execution of the rest of the analysis.

Information about the theoretical background of the *Kruskal-Wallis test* can be found in Appendix II.

For test cases 3 (3a, 3b, 3c) and 6 (6b, 6c) some of the tests were conducted with the reflection compensator turned off. Subsequently, the analysis for these test cases was done separately for tests with the reflection compensator turned on, with the reflection compensator turned off and finally all tests of a test case where compared to each other in order to gain a general overview for the two test cases of structure 1. Moreover, for the analysis of the two remaining structures, every test case was treated separately by comparing the damage values the corresponding tests that consist of the particular test case.

4.4.1 Structure 1

Two test cases, test case 3 and 6 are investigated.

4.4.1.1 Test series 3

At first, the tests conducted with the reflection compensator turned off are being examined and then all tests of test case 3 are compared to each other.

4.4.1.1.1 Tests 3a, 3b, 3c Arc off

The computed damage values, fluctuated from 19.5 to 21.5, and although they seem to converge to a value of 21.5, they were also accompanied by large standard deviations in the order of 3.2-4. Indeed, for some cases (profile measurements) the computed damage was in the order of 27. However, the occurring deviations were in the same magnitude for all tests.

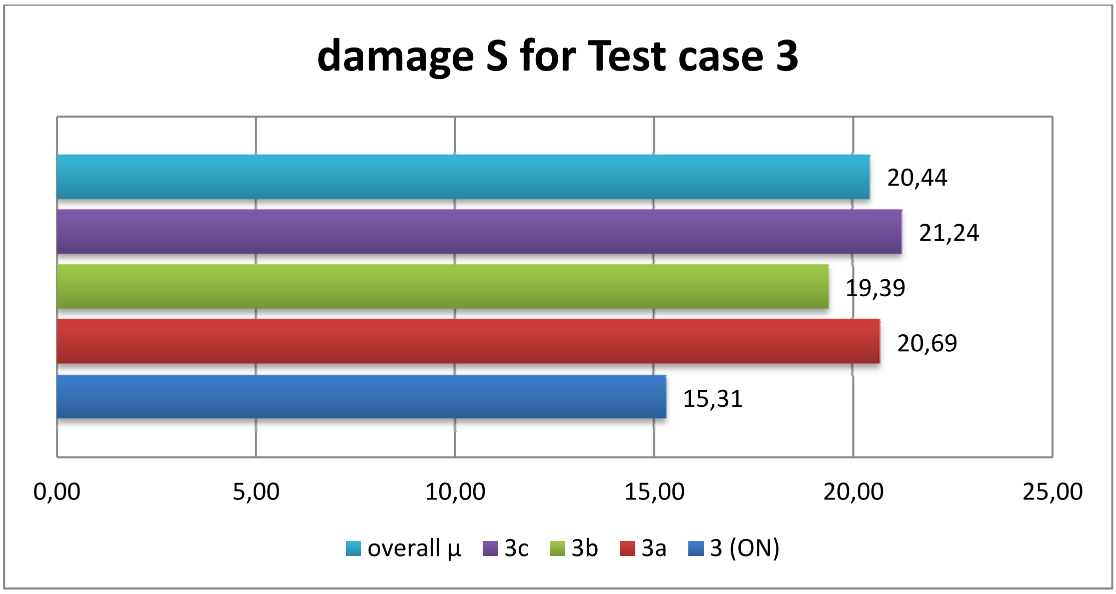


figure 4-2 mean damage values for test case 3

The previously described tendency is visualized by the output of the Kruskal-Wallis test. Firstly, a low probability (0.261) was found, for the hypothesis that the distribution of damage among the three repetition tests is the same. This means that despite there are resemblances among the damage distribution of the repetition tests, these resemblances are weakened by the existence of extreme values and by the systematically lower damage values that occurred at test 3b.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of damage S is the same across categories of test series 3 arc off.	Independent-Samples Kruskal-Wallis Test	.261	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

figure 4-3 Kruskal-Wallis hypothesis test for tests 3a, 3b, 3c

For this part of the comparison the computed damage values of the three tests are ranked in an ascending order and then the mean rank of the damage values of every test was determined. As a result the higher the rank the higher the mean damage level of the considered test. Indeed, test 3b ranked sensibly lower that the other two tests which seem to show identical distributions and identical magnitude of damage.

Ranks

	test series 3 arc off	N	Mean Rank
damage S	3a	13	21.38
	3b	13	15.85
	3c	13	22.77
	Total	39	

figure 4-4 Kruskal-Wallis test, ranks for tests 3a, 3b, 3c

Furthermore, the following figure displays the distribution of damage values for the three repletion tests, and verifies that although most of the damage values for the three tests are gathered at the same magnitude, the tail of test 3b is substantially lower than the other two tests and therefore is responsible for the low degree of resemblance between the tests.

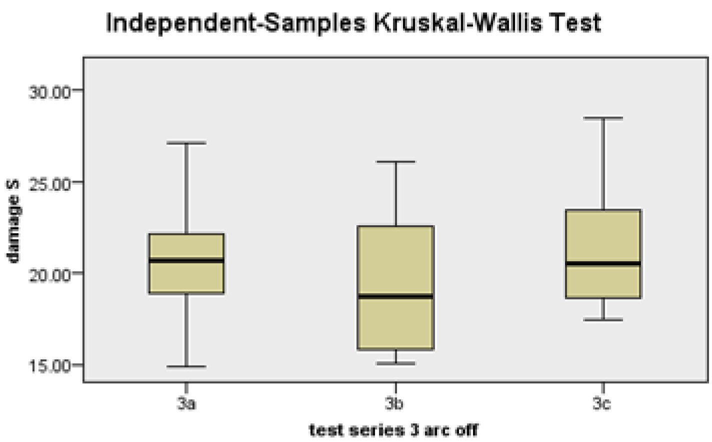


figure 4-5 Kruskal-Wallis test, distribution of damage values for tests 3a, 3b, 3c

4.4.1.1.2 Test series 3 all group components

For original test 3 a mean damage value of 15.31 with a standard deviation of 3.08 (figure 4-1 "mean damage values for test case 3") was found. Undoubtedly, the computed damage levels were lower with regard to the repetition tests, something that is explained by the absence of standing waves, since the reflection compensator was activated. On the other hand, the spreading of the damage values was in the same order as in the repetition tests which were executed without the aid of the reflection compensator.

As a result, the spreading of damage along the original test 3 was similar to the other three tests, but in much lower magnitude. Consequently, the zero condition hypothesis of the *Kruskal-Wallis* test was rejected.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of damage S is the same across categories of test series 3 arc comparison.	Independent-Samples Kruskal-Wallis Test	.011	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

figure 4-6 Kruskal-Wallis hypothesis test, test case 3 all tests

Prospectively, the mean rank of test 3 was approximately the one third of the mean ranks of the other three tests since the majority of the computed damage values of original test 3 were much lower than the corresponding ones from the repetition tests.

Ranks

	test series 3 arc comparison	N	Mean Rank
damage S	3a	13	26.92
	3b	13	20.77
	3c	13	28.15
	3	6	8.17
	Total	45	

figure 4-7 Kruskal-Wallis test, test case 3 ranks for all tests

In addition, the distribution of damage for original test 3 seems identical to the distribution of damage for repetition test 3b, but of course in different magnitudes. Therefore, and in order to sum up the usage of the reflection compensator had a decisive influence on the damage level distributions.

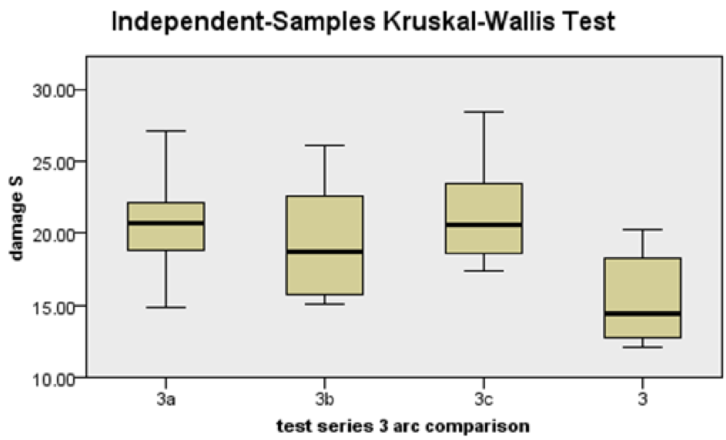


figure 4-8 Kruskal-Wallis test, distribution of damage values for test case 3 all tests

4.4.1.2 Test series 6

At first, the tests conducted with the reflection compensator turned on are being examined and the analysis proceeds with the investigation of the tests executed with the reflection compensator turned off. The analysis ends with comparison of all the original and repetition tests of test case 6.

4.4.1.2.1 Tests 6, 6-2, 6a, 6d, 6e ARC ON.

The average measured damage in the five tests with the reflection compensator switched on, varied from 9 till 11.3 apart from test 6 where a value of 8.16 was found. Moreover, among the five components of this testing group, test 6 was the one that showed the wider spreading of the measured values (σ=3.3). Moreover, there were two individual damage values that were very low values and had a decisive influence in the final outcome of the *Kruskal-Wallis* comparison. The influence was strengthened by the fact that the measurements population of test 6 was considerably small. On the other hand, the standard deviations values of the rest of the tests were in the order of 1.5-2 which is among the margins of statistical error, and therefore are considered acceptable.

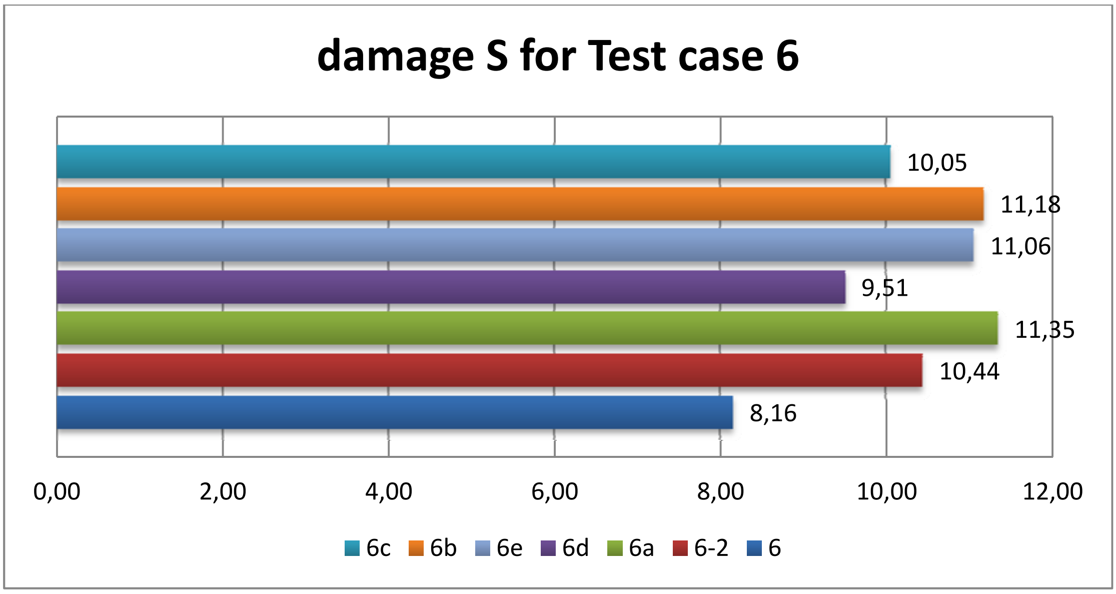


figure 4-9 mean damage values for test case 6

According to the outcome of the *Kruskal-Wallis test* the resemblance of the damage distribution among the examined tests was relatively weak. The tests that were mainly responsible for the occurring deviations are original test 6 and repetition test 6d. For these two tests the level of damage was much lower as a result it weakened the order of consistency between the tests.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of damage S is the same across categories of test series 6 arc on.	Independent-Samples Kruskal-Wallis Test	.173	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

figure 4-10 Kruskal-Wallis hypothesis test for tests 6, 6-2, 6a, 6d, 6e

To visualize the differences in the level of damage the following figure can be used. Here, the difference between the maximum (repetition test 6a) and the minimum (original test 6) rank of the tests was almost two times the latter. In addition the two lower values were as expected the ones from tests 6 and 6d. However, the rest of the tests ranks were evenly distributed between the two extremes.

Ranks

	test series 6 arc on	N	Mean Rank
damage S	6	6	15.17
	6-2	6	25.75
	6a	13	30.12
	6d	12	21.17
	6e	13	29.54
	Total	50	

figure 4-11 Kruskal-Wallis test, ranks for tests 6, 6-2, 6a, 6d, 6e

Finally, when examining the visual representation of the damage distribution of the tests, it can be easily observed that the tests can be divided into two groups. The first one contain the tests 6-2, 6a and 6e and is characterized by narrower spreading and higher damage values, and the second that consists of tests 6, 6d with wider spreading and lower damage values.

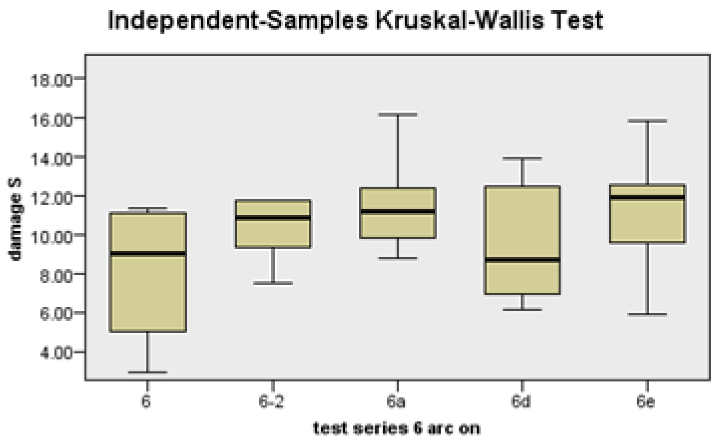


figure 4-12 Kruskal-Wallis test, distribution of damage values for tests 6, 6-2, 6a, 6d, 6e

4.4.1.2.2 Tests 6b, 6c ARC OFF.

For test 6b the average damage value measured was 11.18, while for test 6c it was slightly lower, at 10.05 (figure 4-8 "mean damage values for test case 6"). The wider spreading of the individual damage values resulted in larger standard deviation values in the order of 3.5.

The *Kruskal-Wallis test* showed a high probability of resemblance between the distributions of damage along the two tests.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of damage S is the same across categories of test series 6 arc off.	Independent-Samples Kruskal-Wallis Test	.446	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

figure 4-13 Kruskal-Wallis hypothesis test for tests 6b, 6c

Moreover, the ranks from the *Kruskal-Wallis test* are very close to each other, while the shape of the distributions shown on the following figure has many similarities.

Ranks

	test series 6 arc off	N	Mean Rank
damage S	6b	13	14.08
	6c	12	11.83
	Total	25	

figure 4-14 Kruskal-Wallis test, ranks for test components 6b, 6c

Indeed, the damage distribution for test 6b is more even than test 6c. However, apart from the mean and the standard deviations of the computed damage, even the extreme values coincide to each other, verifying the consistency that occurs among the two tests.

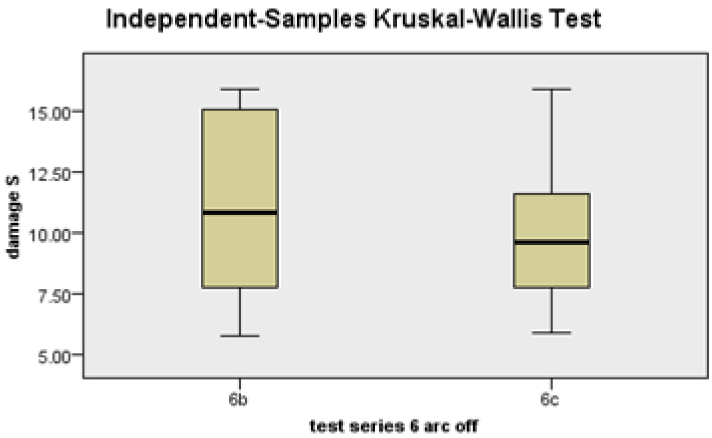


figure 4-15 Kruskal-Wallis test, distribution of damage values for tests 6b, 6c

4.4.1.2.3 Test series 6 all group components

In the following plots the difference in wave spectrum is indicated for the tests with and without the reflection compensator. In specific and as a representative example, the case of tests 6e(ARC ON) and 6b (ARC OFF), is considered although the rest of the investigation containing the *Kruskal-Wallis test* takes place for all the individual tests of test case 6.

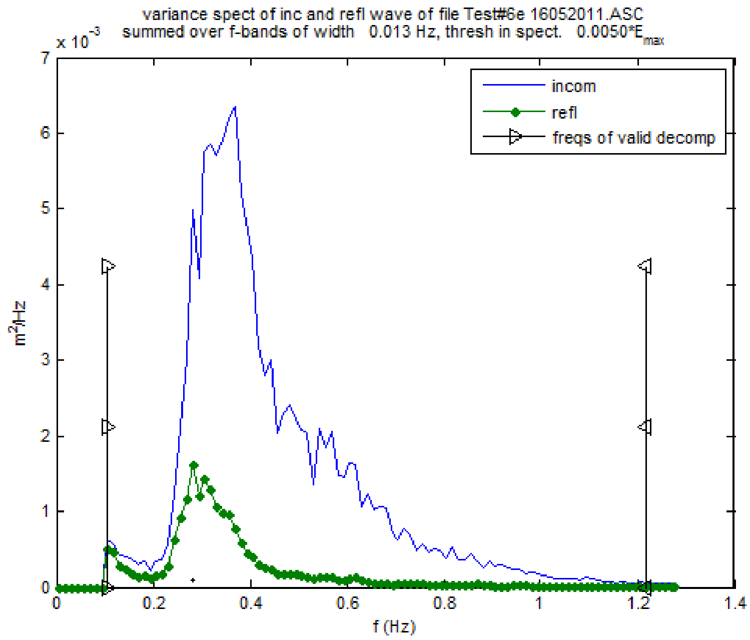


figure 4-16 Test 6e, incoming/reflecting wave spectrum, reflection compensator switched on

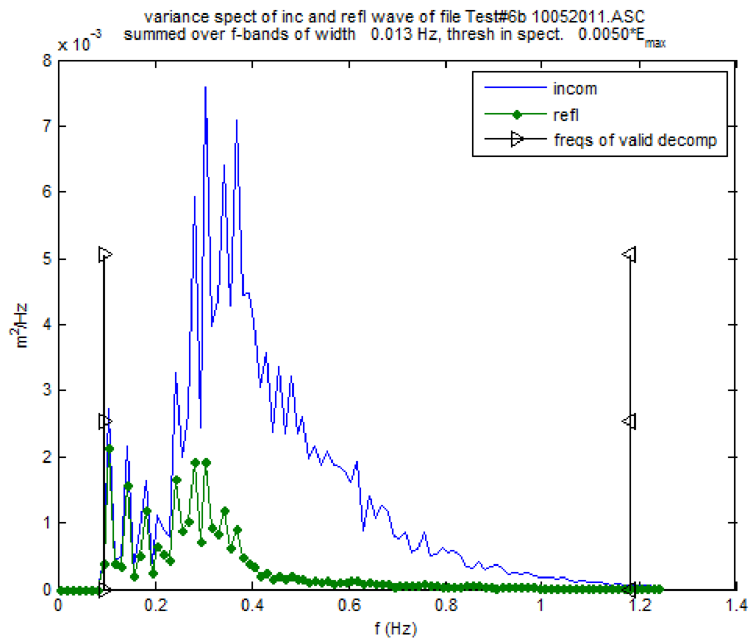


figure 4-17 Test 6b, incoming/reflecting wave spectrum, reflection compensator switched off

As it is displayed above, the deactivation of the reflection compensator has modified the shape of the wave spectrum in the area of the low frequencies, introducing a more abrupt distribution of energy. The excess local peaks (higher energy density in lower frequencies) indicate that the wave spectrum of the incoming wave is contaminated with the standing waves that occur in the basin. In addition, the difference is also noticeable in the wave spectrum of the reflecting wave as it was recorded by the wave gauges in front of the structure.

In specific, for the two cases presented by the figures above, no difference occurs between the significant wave heights, which were 0.16cm on both occasions. Differentiation holds for the values of the mean (2.1s 2.14s) and the peak period (2.75s 2.80s) of the spectrum and the wave length (6.89m 7.15m). The first value refers to test 6e-Arc ON and the second to test 6b-ARC OFF. In addition, the Iribarren numbers for the two tests are 3.29 and 3.31 respectively, both smaller than the critical Iribarren number, thus the type of wave breaking remained in the plunging area.

Furthermore, the outcome of the *Kruskal-Wallis test* showed a strong resemblance between the distributions of the tests with and without the reflection compensator.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of damage S is the same across categories of test series 6 arc comparison.	Independent-Samples Kruskal-Wallis Test	.991	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

figure 4-18 Kruskal-Wallis hypothesis test for test case 6 all tests

The ranks were almost identical, and the shape deviated only in tail of the distribution where the low damage values are located. Responsible for that is the contribution of extreme values due to individual damage values from test 6.

Ranks

	test series 6 arc comparison	N	Mean Rank
damage S	arc on	50	38.02
	arc off	25	37.96
	Total	75	

figure 4-19 Kruskal-Wallis test, ranks for test case 6 all tests

Conclusively, there is a convergence of the damage values in both the categories with respect to the contribution of the reflection compensator, in a specific range of damage values. Although, the variance of measurements sometimes weakens the certainty of the conclusion it is obvious that for testing group 6 the measured damage values were less influenced by the reflection compensator than the corresponding measurements of test 3

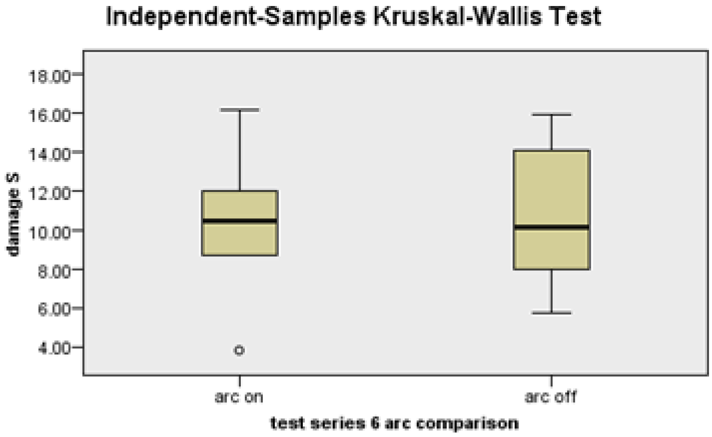


figure 4-20 Kruskal-Wallis test, distribution of damage values for test case 6 all tests

4.4.2 Structure 2

Test cases 8 and 11 are examined.

4.4.2.1 Test series 8

The mean damage values for the tests of test case 8 are oscillating around a value of 5.5. The minimum damage value was found at the original test 8, while the maximum damage was computed from test 8b. In addition, the standard deviation for all the tests was about 1.6 and acquired a maximum value of 1.81 for repetition test 8b. The existing damage differences between the original and repetition tests are between the margins of the accepted statistical error, a conclusion which is encouraged by the reasonable values of the standard deviations of all the tests.

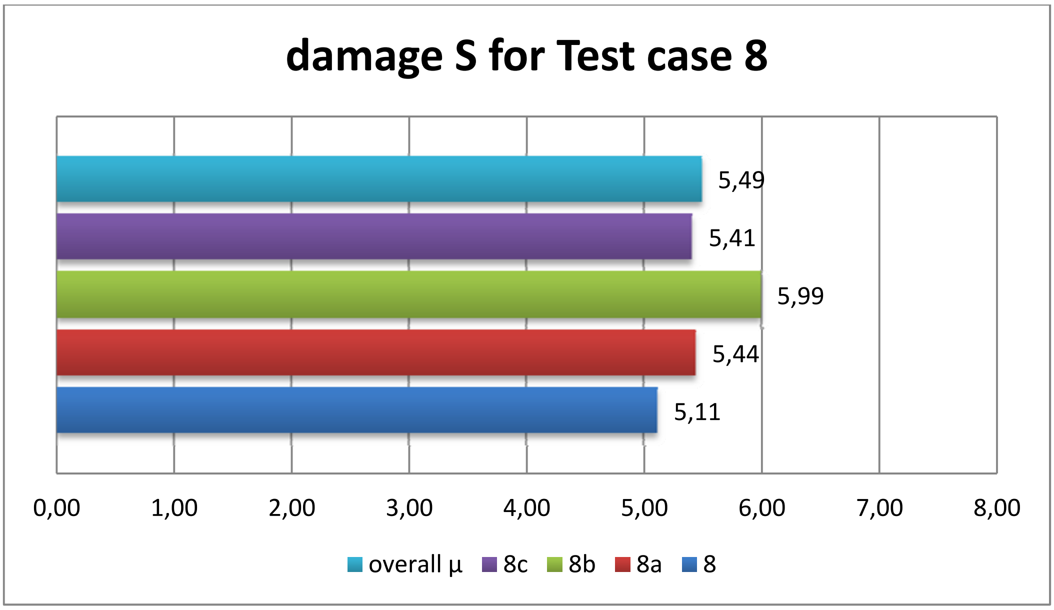


figure 4-21 mean damage values for test case 8

For the tests of test case 8 an extremely high probability of resemblance between the damage distributions was found. In specific, parameter *asymp.sig.* acquired a value of 0.761.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of damage S is the same across categories of test series 8.	Independent-Samples Kruskal-Wallis Test	.761	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

figure 4-22 Kruskal-Wallis hypothesis test for test case 8

Furthermore, the test ranks from the Kruskal-Wallis analysis were narrowly and evenly distributed showing the strong consistency that occurs between them. Indeed, the highest rank was found for repetition test 8c and as it was expected the lower one was for the original test 8.

Ranks

	test series 8	N	Mean Rank
damage S	8	13	22.81
	8a	13	24.92
	8b	13	28.88
	8c	11	25.36
	Total	50	

figure 4-23 Kruskal-Wallis test, ranks for test case 8

At the end, the visual inspection of the damage distribution for the four examined tests verifies the conclusions drawn above. Especially, tests 8, 8a, and 8c are really close to each other with respect to the spreading of the damage values, while in repetition test 8b higher damage values can be found.

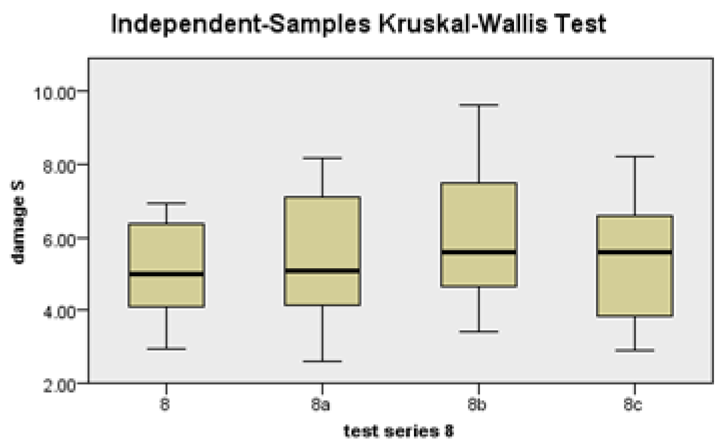


figure 4-24 Kruskal-Wallis test, distribution of damage values for test case 8

4.4.2.2 Test series 11

A variety of mean values were extracted by the tests and could be divided in three categories, with a maximum value of 16.27 for repetition test 11c, a minimum value of 12.90 which was found at original test 11 and a medium value at around 14 of the other two repetition tests. The very low values of test 11 are explained by the weaker wave load that was applied in the structure, while the large values of test 11c are a result of constructional imperfections, which are too difficult to predict.

For the first two tests (11, 11a) the standard deviation acquires very low values (σ=1.8) indicating a very smooth distribution of the damage along the transverse cross section of the structure. For the two remaining tests, the spreading of the damage values is bigger (σ=2.8-3), especially for test 11c. Nevertheless, the spreading magnitude could be characterized statistically acceptable.

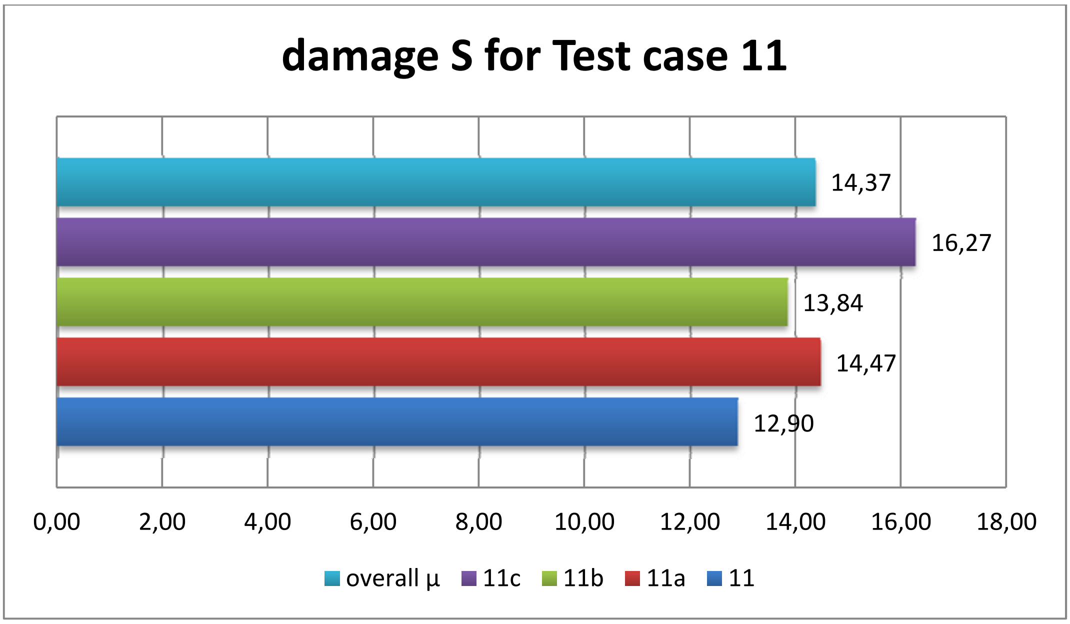


figure 4-25 mean damage values for test case 11

As a result of the above mentioned, the distribution of the damage along the four tests varies considerably. The ranks of tests 11 and 11b are in the same order while the distance between the ranks of test 11c and 11a is approximately the same with the distance between the ranks of test 11a and 11b. In addition, the score of test 11c is almost the double of the score done by test 11. Consequently, the zero-condition hypothesis was rejected by the Kruskal-Wallis test.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of damage S is the same across categories of test series 11.	Independent-Samples Kruskal-Wallis Test	.019	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

figure 4-26 Kruskal-Wallis hypothesis test for test case 11

Ranks

	test series 11	N	Mean Rank
damage S	11	13	18.38
	11a	12	27.29
	11b	13	21.65
	11c	12	35.58
	Total	50	

figure 4-27 Kruskal-Wallis test, ranks for test case 11

The difference among the distributions of the tests is clearly visible in the following figure, expressing the difficulty in placing a benchmark to compare the different distributions.

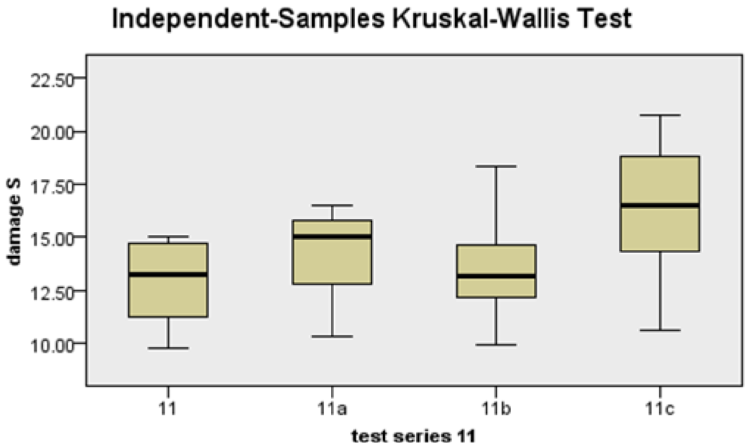


figure 4-28 Kruskal-Wallis test, distribution of damage values for test case 11

4.4.3 Structure 3

Two test cases, test case 20 and 26 are investigated.

4.4.3.1 Test series 20

Despite the fact that the test characteristics were kept stable in all the four tests, the last repetition test, test 20c, showed a significantly higher amount of damage. The mean damage values for the four tests of test case 20 are shown in the following graph. Nevertheless, the standard deviation of all tests was at the same magnitude, with a maximum of 1.95 for repetition test 20c.

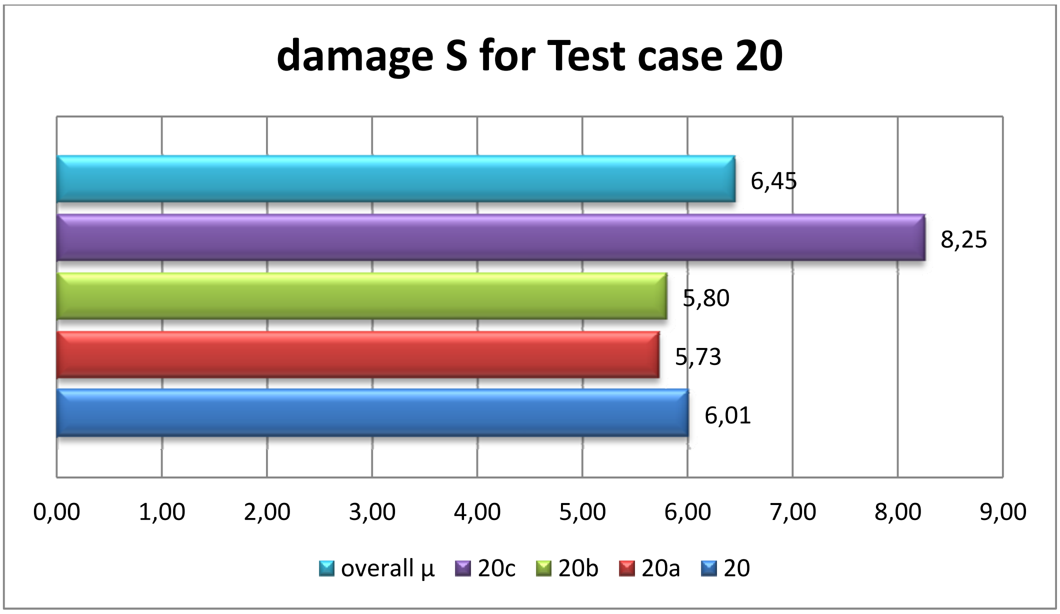


figure 4-29 mean damage values for test case 20

Additionally, the application of the Kruskal-Wallis test found that there is significant difference in the distribution of the damage S of repetition test 20c with respect to the other components of the group. In this case the value of the *asymp. Sig.* of the test was 0.2%, which is rather low.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of damage S is the same across categories of test series 20.	Independent-Samples Kruskal-Wallis Test	.002	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

figure 4-30 Kruskal-Wallis hypothesis test for test case 20

This difference is absolutely obvious on the ranking of the test which is doubled with respect to the other tests showing the higher magnitude of damage values that were computed. On the other hand, the original test 20 and the repetitions 20 and 20b show great consistency with almost identical mean damage values and rankings.

Ranks

	test series 20	N	Mean Rank
damage S	20	13	23.31
	20a	13	20.77
	20b	13	21.46
	20c	13	40.46
	Total	52	

figure 4-31 Kruskal-Wallis test, ranks for test case 20

The graphical representation of the damage distributions for the four tests displays the similarities between the first three tests and afterward the deviation of the fourth one towards damage values of higher order.

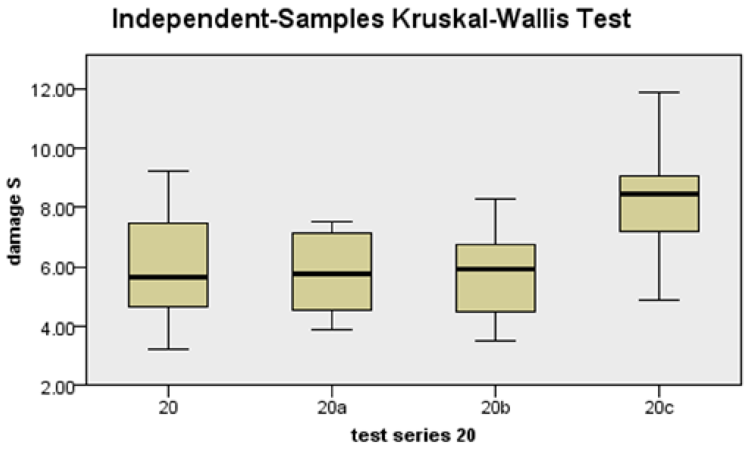


figure 4-32 Kruskal-Wallis test, distribution of damage values for test case 20

Further upon, among the four tests, test 20c is the one with the weaker correspondence, to the normal distribution approach, due to some extreme individual values (Appendix A table A-21) that are also indicated in the standard deviation of the test. The existence of these extreme values mainly depends on constructional imperfections, where the slightly incautious placement of the stones, results in easier displacements of the stones even by weaker than expected waves.

Besides, this test group is situated in the transition area between plunging and surging waves. Indeed, tests 20 and 20a are in the plunging area and tests 20b and 20c are in the surging area. This distinctiveness in combination with the measurements behavior with respect to the type of wave breaking on the structure will be discussed at a later section.

4.4.3.2 Test series 26

For the repetition tests of test case 26 the mean damage value fluctuates between 5.8 for test 26a to 6.7 for test 6c. Surprisingly, the standard deviation of the damage values is higher for test 26a (σ=2.37) and lower for test 26c (σ=1.67). On the other hand, the mean damage level for original test 26 was only 3.61 and was accompanied with a relatively high spreading of the individual damage values since the standard deviation was found σ=1.84. This fact is explained by the low values of H_s $T_{m,}$ and consequently Iribarren number ξ (Table 4-14). Apart from that, a probably more stable slope was constructed and contributed in this direction.

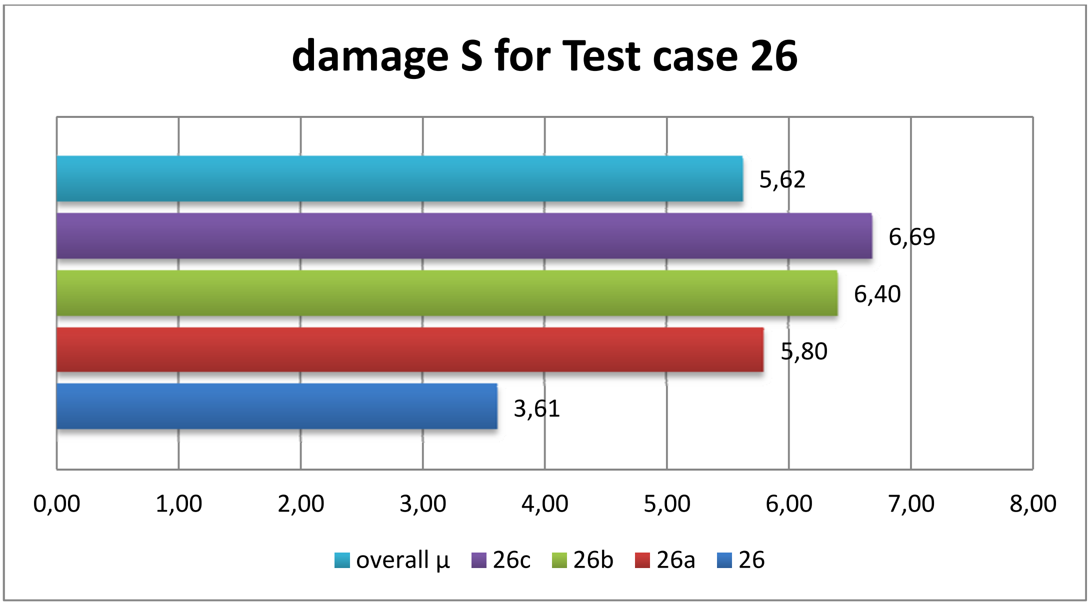


figure 4-33 mean damage values for test case 26

Consequently, the observed huge differences among the original test and the repetition tests were illustrated in the *Kruskal-Wallis* analysis. Indeed, the deviation was so large that the null-hypothesis was rejected.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of damage S is the same across categories of test series 26.	Independent-Samples Kruskal-Wallis Test	.007	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

figure 4-34 Kruskal-Wallis hypothesis test for test case 26

The difference in ranks is substantial and in absolute values it can be seen that the rank of original test 26 is almost the one third of the rank of any of the repetition tests.

Ranks

	test series 26	N	Mean Rank
damage S	26	12	12.92
	26a	13	27.31
	26b	12	29.83
	26c	13	31.31
	Total	50	

figure 4-35 Kruskal-Wallis test, ranks for test case 26

For the three repetition tests apart from the similar ranks from the *Kruskal-Wallis* test, the similarity can also be seen in the entire distribution of the computed damage values. Only the tail of test 26c differs, but this has to do mainly with the strong convergence of the damage values of test case 26c around the computed mean value.

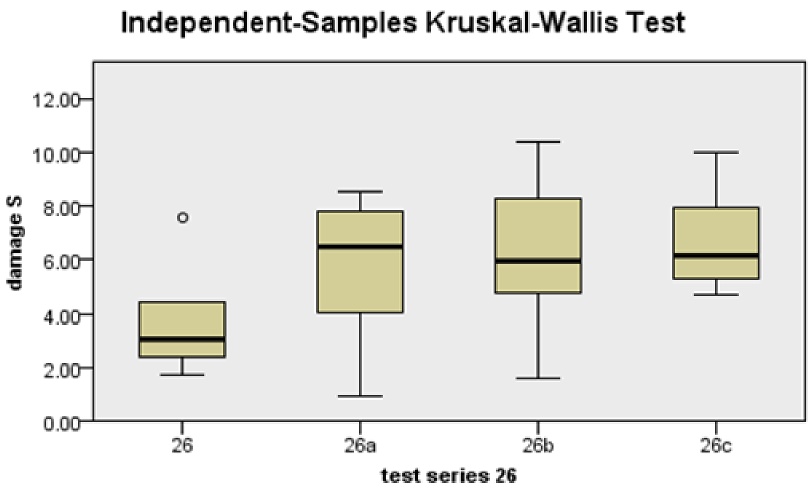


figure 4-36 Kruskal-Wallis test, distribution of damage values for test case 26

4.5 Comparison measurements per 5cm/10cm.

The goal of this comparison is to determine the influence of the measurement step, used for the conduction of the profile measurements, on the damage level computation. The measurements level of detail is important for the whole procedure since taking measurements every half the initial measurement step, substantially increases the test duration, and therefore less tests can be conducted for the same time. On the contrary, picking a wider measurement step may lead to non representative profile measurements since important profile deviations could be neglected and thus lower degree of confidence concerning the damage level computation could be achieved.

The selection of the two interval lengths for two sequential profile measurements (*5cm, 10cm*) is done with respect to the d_{n50} of the armour layer of the structure, which in this specific case was 4cm. Therefore, for every individual test, profile measurements were taken every *5cm,* and then they have been separated into two groups of measurements; every *5cm* and every *10cm*. Afterwards, a statistical analysis of the distribution of the corresponding computed damage values took place and was treated separately, for the three examined structures. Finally, a general conclusion is extracted concerning the sensitiveness of the damage level computation with respect to the step of the profile measurements.

More specifically, the above mentioned statistical analysis consists of two main procedures. At first, the two fundamental non parametric tests of *Mann-Whitney U/ Wilcoxon W* and *Kolmogorov-Smirnov* (theoretical explanation Appendix B) were applied in order to qualitatively investigate the magnitude of the behavioral change of the distribution due to the addition of the in-between measurements (measurements every *5cm*). In specific, for every individual test, a comparison of the measurements every *5cm* with the measurements every *10cm* has been made.

Thereupon, in order to illustrate these differences, a comparison of the computed mean damage values for every individual test was made, with the calculated damage values using the Van der Meer equations. Finally, and in order to quantify the spreading of the corresponding damage, the analysis is supplemented with computations of the standard deviation and 90% confidence intervals for every individual test.

4.5.1 Structure 1

The comparison, using the non parametric tests, for the test cases 3 and 6, showed that there is no significant difference in the distribution of damage among the corresponding individual tests regardless the measurement step.

structure 1	Mann-Whitney U/Wilcoxon W		Kolmogorov-Smirnov	
Test	asymptotic sig.	statistically significant difference	asymptotic sig.	statistically significant difference
3a	0,382	NO	0,782	NO
3b	0,634	NO	0,994	NO
3c	0,578	NO	0,953	NO
6a	0,578	NO	0,953	NO
6d	0,923	NO	1,000	NO
6e	0,525	NO	0,933	NO
6b	0,812	NO	0,969	NO
6c	0,925	NO	1,000	NO

table 4-22 Structure 1, summary of MMW and K-S test for test cases 3, 6

As a result, the distribution of damage has not been affected by the input of additional measurements on the sample. Apart from the test 3a, where the distribution resemblance seems a bit week (explained by some extreme values of median cross sections) for all the other measurement sequences the computed damage showed statistical consistency.

For the tests 3, 6 and 6-2, the comparison and the following ones are meaningless due to the fact that the cross section measurements were executed every *10cm* only.

When considering the comparison of computed damage values with the corresponding calculated ones, hardly any difference occurs. Of course there are cases where the decrease of measurement step was followed by smaller deviations but unfortunately when talking with absolute values these differences are only trivial. The situation gets clearer at the table below.

			measurements every 5cm			measurements every 10cm		
	Test	Calculated S	Computed S smooth fit	difference	percentage %	Computed S smooth fit	difference	percentage %
ON	3	6,91	15,31	8,40	**121,68**	15,31	8,40	**121,68**
OFF	3a	18,71	20,69	1,98	**10,57**	21,40	2,69	**14,36**
	3b	17,90	19,39	1,49	**8,32**	20,72	2,82	**15,77**
	3c	18,42	21,24	2,82	**15,33**	20,22	1,80	**9,77**
ON	6	8,70	8,16	0,54	**6,16**	8,16	0,54	**6,16**
	6-2	11,55	10,44	1,11	**9,62**	10,44	1,11	**9,62**
	6a	14,18	11,35	2,83	**19,95**	11,95	2,23	**15,72**
	6d	14,35	9,51	4,84	**33,76**	9,50	4,85	**33,79**
	6e	14,77	11,06	3,71	**25,10**	10,71	4,05	**27,44**
OFF	6b	17,03	11,18	5,85	**34,37**	11,68	5,35	**31,43**
	6c	15,22	10,05	5,17	**33,97**	9,59	5,63	**37,01**

table 4-23 test cases 3, 6: comparison between calculated values from Van der Meer equations and computed damage for measurements every 5cm/10cm

For test case 3 there is no clear image about the contribution of the additional measurements. For example, in test 3b the standard deviation of the damage values has decreased from 4.81, when measuring every *10cm,* to 3.92, when the measurement step is *5cm.* On the contrary, in test 3a an increase of the standard deviation of the computed damage from 1.40 to 2.78 was observed. For test 3c the spreading of the damage values is not affected by the measurement step.

comparison measurements per 5cm/10cm							
Structure 1				90% confidence interval			
Test	μ	σ	n	Lower Bound	Upper Bound	interval length	
3a	20,69	3,04	13	19,31	22,08	2,78	**per 5cm**
3b	19,39	3,92	13	17,60	21,18	3,58	
3c	21,24	3,20	13	19,78	22,70	2,92	
3a	21,40	1,12	7	20,70	22,10	1,40	**per 10cm**
3b	20,72	4,81	7	17,73	23,71	5,98	
3c	20,22	2,39	7	18,73	21,70	2,97	

table 4-24 test case 3: confidence intervals for measurements per 5cm/10cm

The same conclusion holds for the repetition tests of test case 6. For tests 6a and 6b the standard deviation was trivially decreased while for tests 6b and 6c the opposite happened. Due to the small magnitude of change the situation can be considered stable and therefore no additional information was introduced due to the decrease of the measurement step.

comparison measurements per 5cm/10cm							
Structure 1				90% confidence interval			
Test	μ	σ	n	Lower Bound	Upper Bound	interval length	
6	8,16	3,30	6	5,95	10,37	4,43	per 5cm
6-2	10,44	1,63	6	9,35	11,54	2,19	
6a	11,35	2,04	13	10,42	12,28	1,86	
6d	9,51	2,81	12	8,17	10,84	2,67	
6e	11,06	2,61	13	9,87	12,25	2,38	
6b	11,18	3,63	13	9,52	12,84	3,32	
6c	10,05	3,15	12	8,56	11,55	2,99	
6	8,16	3,30	6	5,95	10,37	4,43	per 10cm
6-2	10,44	1,63	6	9,35	11,54	2,19	
6a	11,95	2,33	7	10,50	13,40	2,90	
6d	9,50	3,09	6	7,43	11,58	4,15	
6e	10,71	2,60	7	9,10	12,33	3,24	
6b	11,68	3,04	7	9,79	13,57	3,78	
6c	9,59	2,60	6	7,84	11,34	3,49	

table 4-25 test case 6: confidence intervals for measurements per 5cm/10cm

In general, for the test cases of structure 1, the analysis showed that the conduction of measurements with a smaller measurement step has not provided any additional information concerning the computed damage levels. For half the tests the spreading of the values was decreased and for the other half it was increased, but the trivial magnitude of the differences describe a rather stable situation, which is characterized by statistical consistency.

4.5.2 Structure 2

When comparing the distribution of the computed damage levels for profile measurements every *10cm* and every *5cm* it can be seen that only insignificant statistical differences occur. Indeed, the statistical tests showed that for both the considered test cases (8, 11) of structure 2, the distribution of the computed damage level for measurements every *5cm* strongly resembles with the corresponding distribution for measurements every *10cm*.

structure 2	**Mann-Whitney U/Wilcoxon W**		**Kolmogorov-Smirnov**	
Test	asymptotic sig.	statistically significant difference	asymptotic sig.	statistically significant difference
8	0,94	NO	1,00	NO
8a	0,43	NO	0,93	NO
8b	0,69	NO	1,00	NO
8c	0,89	NO	1,00	NO
11	0,69	NO	1,00	NO
11a	0,47	NO	0,99	NO
11b	0,43	NO	0,99	NO
11c	1,00	NO	1,00	NO

table 4-26 Structure 2, summary of MMW and K-S test for test cases 8, 11

The comparison between computed and calculated damage values from the Van der Meer equations showed a rather balanced situation. In absolute values, the computed damage values were from 50% till 100% greater that the calculated values, regardless the measurement step.

Talking about test case 8, for the original test 8 and the repetition test 8c the computed damage values for both *5cm* and *10cm* measurements are almost identical. For repetition test 8a the transition from measurements every 10cm to measurements every 5cm decreased the deviation from the calculated values for almost 20%. The inversed happened for repetitions test 8b but in a lower magnitude (10%).

In addition, for the three repetition tests of test case 11 the computed damage values for measurements every *5cm* displayed a slightly higher convergence to the corresponding calculated value, with respect to the damage value computed when measuring every *10cm.* On the contrary, this was not the case for original test 11, where a slight increase took place. Nevertheless, in absolute values all the differences are considered unimportant.

		measurements every 5cm			measurements every 10cm		
Test	Calculated S	Computed S smooth fit	difference	percentage %	Computed S smooth fit	difference	percentage %
8	2,48	5,11	2,63	**106,04**	5,03	2,54	**102,52**
8a	3,02	5,44	2,42	**80,06**	6,03	3,00	**99,37**
8b	3,08	5,99	2,91	**94,45**	5,70	2,61	**84,80**
8c	3,14	5,41	2,27	**72,21**	5,59	2,44	**77,80**
11	6,70	12,90	6,20	**92,50**	12,72	6,02	**89,83**
11a	9,20	14,47	5,27	**57,24**	14,95	5,75	**62,47**
11b	9,20	13,84	4,64	**50,42**	15,08	5,88	**63,92**
11c	8,77	16,27	7,50	**85,50**	16,39	7,62	**86,81**

table 4-27 test cases 8, 11: comparison between calculated values from Van der Meer equations and computed damage for measurements every 5cm/10cm

When taking into account the standard deviation of the computed damage values, it can be seen that for half the tests (original test 8 and repetition test 8c) of test case 8, the spreading of the values was decreased when profile measurements were taken every *5cm*, while for the other half (repetition tests 8a&8b) a wider spreading of damage was observed. Nevertheless, the accuracy of the computed damage values was increased since the length of the 90% confidence interval was decreased at around 25% for all the tests.

comparison measurements per 5cm/10cm							
Structure 2				**90% confidence interval**			
Test	μ	σ	n	Lower Bound	Upper Bound	interval length	
8	5,11	1,31	13	4,52	5,71	1,19	**per 5cm**
8a	5,44	1,74	13	4,65	6,24	1,59	
8b	5,99	1,81	13	5,17	6,82	1,65	
8c	5,41	1,61	12	4,65	6,18	1,53	
8	5,03	1,37	7	4,17	5,88	1,71	**per 10cm**
8a	6,03	1,51	7	5,09	6,96	1,88	
8b	5,70	1,68	7	4,65	6,74	2,09	
8c	5,59	1,75	7	4,50	6,67	2,17	

table 4-28 test case 8: confidence intervals for measurements per 5cm/10cm

A narrower spreading of the computed damage values was observed also for the tests 11, 11b and 11c of test case 11. The standard deviation of damage for the case of profile measurements every *5cm* was decreased at around 10%. On the other hand, for repetition test 8a the deviation of the damage values increased at approximately 20%.

Finally, the analysis of the confidence intervals showed a greater convergence of the computed damage values for both the original and repetition tests of test case 11. Indeed, the magnitude of the corresponding decrease of the interval length was approximately 35% for tests 11, 11b and 11c, but only 7% for test 11a.

comparison measurements per 5cm/10cm							
Structure 2				90% confidence interval			
Test	μ	σ	n	Lower Bound	Upper Bound	interval length	
11	12,90	1,86	13	12,05	13,75	1,70	per 5cm
11a	14,47	1,86	12	13,58	15,35	1,77	
11b	13,84	2,82	13	12,55	15,13	2,57	
11c	16,27	3,07	12	14,82	17,73	2,92	
11	12,72	2,12	7	11,40	14,04	2,64	per 10cm
11a	14,95	1,53	7	13,99	15,90	1,91	
11b	15,08	3,14	7	13,13	17,03	3,91	
11c	16,39	3,58	6	13,99	18,79	4,80	

table 4-29 test case 11: confidence intervals for measurements per 5cm/10cm

Likewise with structure 1, the contribution of the additional measurements was rather trivial. Despite the fact that for some tests the deviation of damage level decreased (when using measurements every 5cm), in absolute values the differences were insignificant.

4.5.3 Structure 3

Except from test 20, for the rest of the individual tests, the statistical analysis showed a strong resemblance between the distributions of the computed damage when measuring every *5cm* and every *10cm*. For test 20, despite the observed, weaker statistical resemblance, it is still rather clear that the damage levels computed from the profile measurements do not deviate substantially, and therefore are characterized by statistical consistency.

structure 3	Mann-Whitney U/Wilcoxon W		Kolmogorov-Smirnov	
Test	asymptotic sig.	statistically significant difference	asymptotic sig.	statistically significant difference
20	0,30	NO	0,75	NO
20a	0,63	NO	1,00	NO
20b	0,58	NO	0,93	NO
20c	0,63	NO	1,00	NO
26	0,71	NO	0,96	NO
26a	0,63	NO	1,00	NO
26b	0,78	NO	0,96	NO
26c	0,69	NO	1,00	NO

table 4-30 Structure 2, summary of MMW and K-S test for test cases 20, 26

For test case 20 the deviation from the calculated damage level (Van der Meer formulas) for each of the tests was almost identical, independently from the measuring step. In addition, all tests showed a computed damage level that was half the calculated damage value.

On the other hand, for test case 26 the intermediate computations increased the computed damage levels with respect to the calculated ones at around 12%. However, the computed damage was between the margins of statistical error, and therefore acceptable, for all the tests. Even for the case of test 26, where a deviation of 223% was found and which seems to be enormous, can be explained by the fact that very low levels of damage can be strongly affected by constructional imperfections, where stones roll due to bad placement and not due to test conditions.

		measurements every 5cm			measurements every 10cm		
Test	Calculated S	Computed S smooth fit	difference	percentage %	Computed S smooth fit	difference	percentage %
20	11,73	6,01	5,72	**48,76**	6,67	5,06	**43,11**
20a	12,13	5,73	6,41	**52,81**	5,45	6,68	**55,08**
20b	9,34	5,80	3,54	**37,87**	6,13	3,21	**34,37**
20c	9,10	8,25	0,84	**9,25**	8,22	0,88	**9,65**
26	1,12	3,61	2,49	**223,11**	3,61	2,49	**223,11**
26a	4,46	5,80	1,34	**29,94**	5,22	0,76	**16,96**
26b	4,43	6,40	1,97	**44,54**	5,74	1,31	**29,51**
26c	4,18	6,69	2,50	**59,91**	6,25	2,07	**49,43**

table 4-31 test cases 20, 26: comparison between calculated values from Van der Meer equations and computed damage for measurements every 5cm/10cm

When considering test case 20, the introduction of intermediate measurements resulted in a narrower spreading of the computed damage values at almost 10% for all the repetition tests. On the contrary, for test 20 the standard deviation of the damage values increased with approximately 45%. However, the magnitude of the corresponding mean damage remained more or less the same, despite the fact that almost for all the cases the 90% confidence intervals for measurements every *5cm* have shifted towards bigger damage values. Moreover, apart from test 20 the length of the confidence intervals has decreased at around 30%, and thus has strengthened the certainty towards the order of the expected damage level for every particular case.

comparison measurements per 5cm/10cm							
Structure 3				**90% confidence interval**			
Test	μ	σ	n	Lower Bound	Upper Bound	interval length	
20	6,01	1,75	13	5,21	6,81	1,59	**per 5cm**
20a	5,73	1,31	13	5,13	6,33	1,20	
20b	5,80	1,44	13	5,14	6,46	1,31	
20c	8,25	1,95	13	7,37	9,14	1,78	
20	6,67	1,19	7	5,93	7,41	1,48	**per 10cm**
20a	5,45	1,42	7	4,57	6,33	1,76	
20b	6,13	1,59	7	5,14	7,12	1,98	
20c	8,22	2,56	7	6,62	9,81	3,19	

table 4-32 test case 20: confidence intervals for measurements per 5cm/10cm

For test case 26, the analysis showed an equivalent behavior to the one displayed for test case 20. In particular, the slight changes that occurred in the standard deviation of the computed damage values do not affect the order of magnitude of the damage level. In addition, it was found that the length decrease of 90% confidence intervals, due to the smaller measurement step, is on average 30% for all tests. The latter shows a stronger convergence of the computed damage levels towards the mean damage values for every test, when intermediate measurements are added on the sample population and therefore increases the certainty over the expected damage.

comparison measurements per 5cm/10cm							
Structure 3				90% confidence interval			
Test	μ	σ	n	Lower Bound	Upper Bound	interval length	
26	3,61	1,84	12	2,74	4,49	1,75	per 5cm
26a	5,80	2,37	13	4,72	6,88	2,17	
26b	6,40	2,38	12	5,27	7,53	2,26	
26c	6,69	1,67	13	5,92	7,45	1,53	
26	3,61	2,24	6	2,11	5,12	3,01	per 10cm
26a	5,22	1,91	7	4,03	6,41	2,37	
26b	5,74	2,38	6	4,13	7,34	3,20	
26c	6,25	2,40	7	4,76	7,74	2,98	

table 4-33 test case 26: confidence intervals for measurements per 5cm/10cm

To sum up, for structure 3 the introduction of intermediate measurements insignificantly increased the level of confidence towards the expected damage levels. The additional profile measurements didn't deviate the statistical distribution of the computed damage levels and maintained the computed damage at the same order of magnitude. Therefore, also for this case measurements every 10cm could have been sufficient.

4.5.4 Summary

Summarizing the above, for all three structures the statistical analysis showed that the introduction of measurements every 5cm resulted in trivial differences on the distribution of damage levels. The corresponding decrease in the standard distribution of the damage values was also insignificant and therefore the gains from the additional measurements have been rather limited. To visualize the above conclusions graphs 4-37 & 4-38 are presented below.

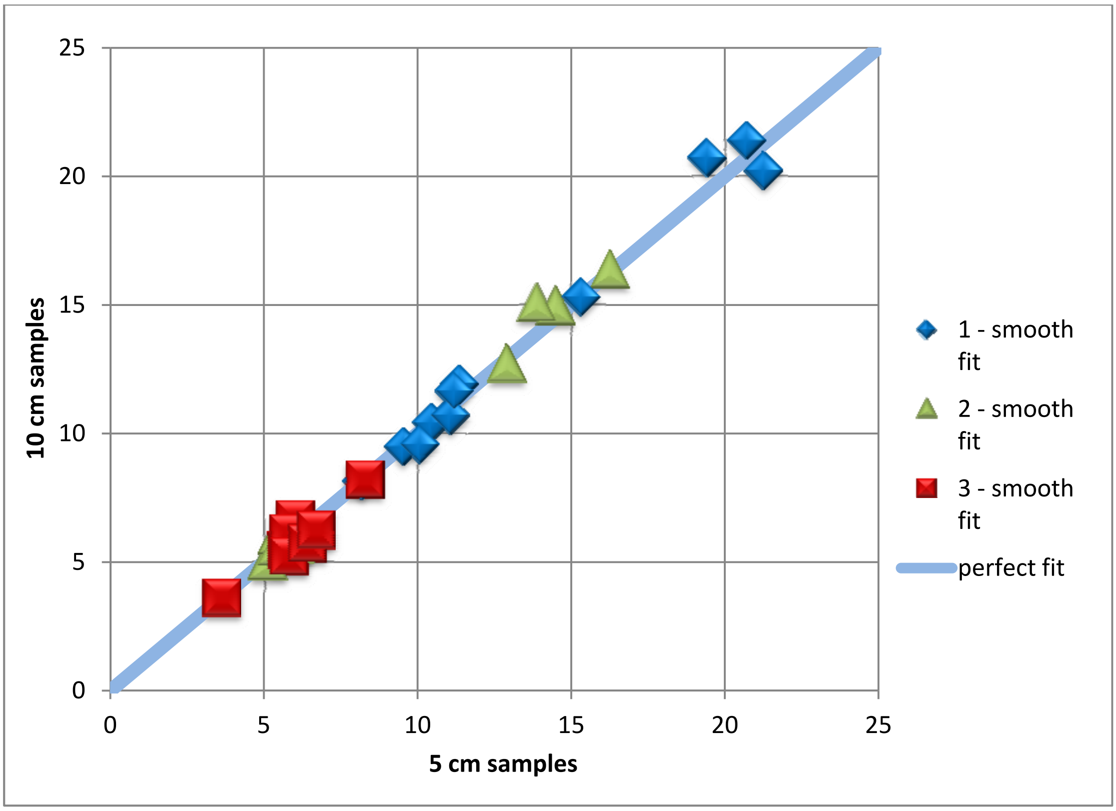


Figure 4-37 Direct comparison *5cm/10cm* for every test individually

The first graph shows the mean damage value for every test using the corresponding measurements every 5cm and every 10cm. Additionally, the 5cm sequences contain the values from the measurements every 10cm. By examining the graph it is rather obvious that the differences are really imperceptible since all measurements are really close or even on the line of perfect fit.

The second graph is a comparison of the computed damage values with the corresponding ones that are calculated using the Van der Meer formulas.

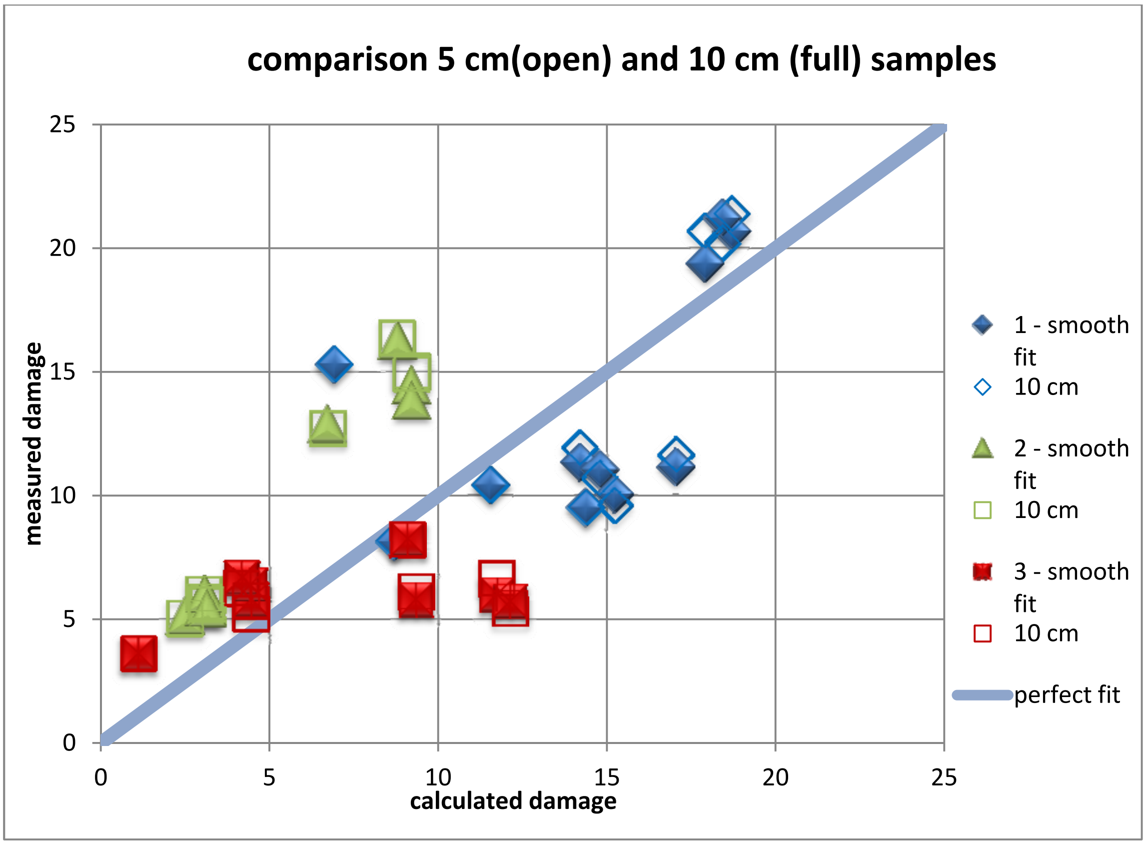


Figure 4-38 comparison 5cm/10cm measurements using all measurement sequences

Likewise, the deviation of the damage values using measurements every 5cm is equivalent to the one using measurements every 10cm. Indeed, the values are really close to each other and therefore measuring every 10cm would have been sufficient to obtain a valid image of the damage.

4.6 Comparison surging/plunging area

At this section of the study is being investigated the existence of a trend in the variation of the measured damage values with respect to the two different types of wave breaking. The tests were divided into two groups, one for the plunging and one for the surging area. Statistical computations took place for the determination of the mean , the standard deviation and the 90% confidence intervals.

For every case, the relation between the length of the confidence interval and the mean value of the measured damage, is considered. In specific, the interval length is expressed as percentage of the corresponding measured value, thus the magnitude of this percentage expresses the deviation with respect to the mean state. In addition the standard deviation of the measured damage values is expressed as percentage of the mean value for every test and then the mean value of these percentages for all the tests (original and repetitions) of a test case is computed and therefore for every structure two values are extracted; one at the plunging and one at the surging area.

Test case 20 is in the transition area, and therefore a comparison is also made between the components and their type of breaking. In addition, for test cases 3 and 6, only the tests with the contribution of the wave reflection compensator are taken into account, to avoid the inclusion of additional uncertainty due to the existence of standing waves in the flume. Nevertheless, analytical computations for all the test cases are being included in the following tables.

4.6.1 Structure 1

For the two test series of structure 1 analytical computation concerning the confidence intervals, with respect to the type of breaking, takes place.

comparison surging/plunging area							
Structure 1					90% confidence interval		
Test	breaking type	μ	σ	n	Lower Bound	Upper Bound	interval length
3	Surging	15,31	3,08	6	13,24	17,38	4,13
6	Plunging	8,16	3,30	6	5,95	10,37	4,43
6-2		10,44	1,63	6	9,35	11,54	2,19
6a		11,35	2,04	13	10,42	12,28	1,86
6d		9,51	2,81	12	8,17	10,84	2,67
6e		11,06	2,61	13	9,87	12,25	2,38

table 4-34 test cases 3, 6: comparison surging/plunging area

The evaluation for the two types of breaking showed that for test case 3 (only test 3 is considered) and for test case 6 (6, 6-2, 6a, 6d, 6e) the deviation is almost the same. More precisely, for the former counts 27%, and for the latter 26.77%. When considering the σ-values as percentage of the mean damage value of every test it is found that for the plunging area it counts 25% on average while for the surging area is 20%. Certainly, the absence of repetition tests under the same conditions (Arc on) for test 3, has to be accounted.

4.6.2 Structure 2

For structure 2 all repetition tests are taken into consideration. Test case 8 is located in the plunging area while for tests case 11 the wave breaking is surging. The following table gives an analytical image of the measured damage values and the confidence intervals for every case.

comparison surging/plunging area							
Structure 2					**90% confidence interval**		
Test	breaking type	μ	σ	n	Lower Bound	Upper Bound	interval length
8	Plunging	5,11	1,31	13	4,52	5,71	1,19
8a		5,44	1,74	13	4,65	6,24	1,59
8b		5,99	1,81	13	5,17	6,82	1,65
8c		5,41	1,61	12	4,65	6,18	1,53
11	Surging	12,90	1,86	13	12,05	13,75	1,70
11a		14,47	1,86	12	13,58	15,35	1,77
11b		13,84	2,82	13	12,55	15,13	2,57
11c		16,27	3,07	12	14,82	17,73	2,92

table 4-35 test cases 8, 11: comparison surging/plunging area

The results showed a noticeable difference in the deviation for the two breaking types. Test case 8, in the plunging area resulted in a value of 27% of the mean deviation from the mean value μ of the tests, while the corresponding deviation for series test case 11 (surging area) was only 16% (confidence intervals). The corresponding values when considering standard deviations are 30% for the plunging and 16% for the surging area. This difference, can be explained by the smoothness of the surging phenomenon, where the wave breaks in a more even way on the structure slope.

4.6.3 Structure 3

Structure 3 was tested by test cases 20 and 26. The former showed a distinctiveness so that half of the test components were located in the surging area and the rest were in the plunging area. On the other hand, original test 26 and the all the repletion tests were clearly in the plunging area. The results are shown in the table above.

comparison surging/plunging area							
Structure 3					90% confidence interval		
Test	breaking type	μ	σ	n	Lower Bound	Upper Bound	interval length
20	transition	6,01	1,75	13	5,21	6,81	1,59
20a		5,73	1,31	13	5,13	6,33	1,20
20b		5,80	1,44	13	5,14	6,46	1,31
20c		8,25	1,95	13	7,37	9,14	1,78
26	Plunging	3,61	1,84	12	2,74	4,49	1,75
26a		5,80	2,37	13	4,72	6,88	2,17
26b		6,40	2,38	12	5,27	7,53	2,26
26c		6,69	1,67	13	5,92	7,45	1,53

table 4-36 test cases 20, 26: comparison surging/plunging area

Indeed, the difference between surging and plunging wave breaking for test case 20, was trivial since the difference was 23% for the plunging and 21% for the surging components. Again, the difference is slightly bigger for the components in the plunging area. Finally, for test case 26 the deviation was in the order of 34% when using the comparison of confidence intervals, while for standard deviations the spreading approximates 38% of the mean damage value.

4.6.4 Summary

The following table contains a summary of the computations for the deviation of the confidence interval with respect to the mean value for all the cases concerning the breaking type variation.

type of breaking	Test series	μ	mean length of intervals	deviation from μ %	mean deviation from μ %
surging	3 (arc on)	15,31	4,13	27,00	21,53
	11,00	14,37	2,24	15,59	
	20 (20b-20c)	7,03	1,55	22,00	
plunging	20 (20b-20c)	5,87	1,40	23,79	27,98
	6 (arc off)	10,10	2,71	26,77	
	8,00	5,49	1,49	27,12	
	26,00	5,62	1,93	34,25	

table 4-37 summary of damage values deviation at surging/plunging area

As it was expected, between the two types of breaking an imperceptible difference occurs. The deviation was steadily bigger for the case of tests located in the plunging area (28% in contrast to 21.5% of the surging area), although this difference is considered to be trivial. The explanation for this difference stands in the character of the plunging wave breaking which is a more abrupt phenomenon than the surging wave breaking. As a result, the response of the structure armour layer becomes also more abrupt resulting in a wider spreading of the damage level.

4.7 Comparison *side/middle* measurements

During the experimental procedure, the visual inspection of the structure slope before and after the experiment, showed higher damage levels at the parts of the structure next to the flume walls with respect to the middle part. Therefore, at this section of the study, takes place an investigation in order to verify the existence of such difference and to quantify its magnitude.

As it was mentioned before, the structure was divided in 14 partitions and measurements took place every 5cm, thus in total 13 cross sections. Furthermore, the first measured cross section abstains 5cm from the flume wall. Afterwards, the cross sections were divided into two groups. The first one contains the *side* measurements which are the cross sections iia, ia, a, e, if and f. It is assumed that in a distance less than 15cm from the flume wall the stones are affected by its presence. In addition, the group of the middle measurements is consisted of the following cross sections: ib, b, ic, c, id, d, ie.

Firstly, for every testing group (i.e. test case 20) the mean damage value for each of the thirteen different cross sections is being computed and then, the average value among them is extracted. Afterwards, each of the individual mean values (from the thirteen cross sections) is compared to the general average value and the difference is expressed as percentage of the general average value. Finally, then mean value of the deviation for each of the two groups (*side* and *middle* measurements) is being computed. The procedure takes place for every structure and test case separately, and is displayed in the tables below.

4.7.1 Structure 1

Structure 1	μ per cross section													
Test	iia	ia	a	ib	b	ic	c	id	d	ie	e	if	f	μ per test series
3	22,73	20,69	16,42	21,11	19,93	18,74	19,71	22,3	18,47	20,35	18,56	17,09	21,94	**19,85**
6	13,49	13,73	10,96	11,69	9,92	10,24	9,08	8,55	9,88	7,46	9,40	11,60	11,12	**10,55**
difference 3	2,88	0,85	3,43	1,26	0,08	1,10	0,14	2,45	1,38	0,50	1,29	2,76	2,09	
difference 6	2,94	3,19	0,41	1,14	0,63	0,31	1,47	1,99	0,67	3,09	1,15	1,05	0,57	
percentage 3 (%)	14,50	4,26	17,27	6,34	0,40	5,56	0,72	12,3	6,97	2,53	6,48	13,91	10,53	
percentage 6 (%)	27,87	30,20	3,92	10,85	5,99	2,90	13,92	18,9	6,34	29,30	10,89	9,97	5,43	
3 (%)	**side**	**11,16**	**middle**	**4,98**										
6 (%)	**side**	**14,71**	**middl**	**12,60**										

table 4-38 test cases 3, 6: comparison between *side/middle* measurements

The analysis of test case 3 showed a higher deviation of damage values with respect to the mean, for the measurements at the *sides*. In specific, the difference from the mean value of the test series 3 (19.85) was 11%, while for the *middle* measurements was only 4%. In addition, the standard deviation for the *side* measurements was 2.61 while for the *middle* measurements, was 1.33.

The same holds also for test case 6, although it is rather trivial. The mean damage value was 10.55 and the deviation at the *sides* counted approximately 15% of that value, while the corresponding value for the *middle* measurements was 12.5%. In absolute values the standard deviation counts 1.64 for the *side* measurements and 1.35 for the *middle*.

Furthermore, the mean value of the damage level for the test case 3 was 19.57 for the *sides* and 20.08 for the *middle*. Despite that the difference is small, it shows a higher damage level in the *middle*. The converse situation holds for test case 6 where, the mean damage was significantly higher in the *sides* (11.72 to 9.55).

Finally, when neglecting the values from the cross sections iia and f (sides) the deviation from the mean values was decreased from 11.16% to 10.48% for test case 3 and 14.71% to 13.75% for test case 6. Moreover, for test case 6 the subtraction of the two lateral cross sections increased the convergence of the mean damage value at the *sides* (11.42% from 11.72%) to the mean damage value for all the cross sections (10.55). On the other hand, the converse situation in higher magnitude happened for test case 3 (19.57% to 18.19% when the mean counts 19.85).

4.7.2 Structure 2

Structure 2	**μ per cross section (damage)**													
Test	iia	ia	a	ib	b	ic	c	id	d	ie	e	if	f	μ per test series
8	5,75	4,44	6,59	6,00	5,68	5,50	4,71	5,16	6,03	6,10	5,15	4,84	5,19	**5,47**
11	14,45	13,35	13,96	14,76	15,17	14,70	13,68	13,4	14,07	13,18	14,70	13,59	16,99	**14,31**
difference 8	0,27	1,03	1,12	0,53	0,20	0,03	0,76	0,31	0,56	0,63	0,32	0,63	0,28	
difference 11	0,14	0,96	0,35	0,45	0,86	0,39	0,63	0,87	0,24	1,13	0,39	0,72	2,68	
percentage 8 (%)	4,99	18,80	20,39	9,70	3,71	0,56	13,88	5,7	10,16	11,44	5,93	11,55	5,10	
percentage 11 (%)	0,98	6,72	2,46	3,17	5,99	2,74	4,42	6,1	1,69	7,90	2,69	5,01	18,73	
8 (%)	**side**	**11,13**	**middle**	**7,88**										
11 (%)	**side**	**6,10**	**middle**	**4,57**										

table 4-39 test cases 8, 11: comparison between *side/middle* measurements

The average damage value for test case 8 is 5.47. The deviation from this value was noticeably higher in the *sides* (11.13%) in relation to the damage level at the *middle* (almost 8%). In absolute values the standard deviation for the *side* measurements was 0.75 and for the *middle* ones was 0,51. After neglecting the cross sections iia and f the deviation was decreased to the value of 10%. Nevertheless, the mean damage level for the *sides* was slightly decreased to the value of 5.25 from 5.37. This decrease is considered to be trivial.

For the test case 11 the situation was rather balanced. There is only slight difference between the deviation from the mean value in the sides and in the *middle* partitions (6.10% to 4.57% correspondingly). On the other hand, when considering standard deviations the spreading seems larger (1.31 at the *side* and 0.75 at the *middle*). Indeed, the deviation was strengthened when the elimination of the lateral cross sections took place (from 6.10% to 7.86%).

At this test case, the damage values at the boundary cross sections where dominant in the computation and by neglecting them the mean damage level was sensibly relegated from 14.50 to 13.90. Despite that, this relegation has trivial meaning in absolute terms of damage level.

4.7.3 Structure 3

Structure 3	μ per cross section													
Test series	iia	ia	a	ib	b	ic	c	id	d	ie	e	if	f	μ for test series
20	7,31	5,59	7,07	6,34	5,81	7,60	5,48	6,96	6,16	5,54	7,02	5,48	7,48	**6,45**
26	5,36	6,07	6,71	6,11	7,53	5,88	5,19	5,06	6,07	7,39	3,50	6,02	2,94	**5,68**
difference 20	0,86	0,86	0,62	0,11	0,64	1,15	0,97	0,52	0,29	0,91	0,57	0,97	1,03	
difference 26	0,32	0,39	1,03	0,43	1,85	0,20	0,49	0,62	0,39	1,71	2,18	0,35	2,74	
percentage 20 (%)	13,34	13,34	9,66	1,70	9,96	17,80	15,00	7,99	4,46	14,07	8,81	15,08	16,02	
percentage 26 (%)	5,68	6,91	18,19	7,57	32,63	3,48	8,67	10,9	6,86	30,16	38,44	6,08	48,22	
20 (%)	**side**	**12,71**	**middle**	**10,14**										
26 (%)	**side**	**20,59**	**middle**	**14,32**										

table 4-40 test cases 20, 26: comparison between *side/middle* measurements

In test case 20 hardly any difference occurs. The deviation is at the same level for both partitions (12.71% at the *side* to 10.14% at the *middle*) and furthermore the boundaries subtraction strengthens the convergence of the mean values (from 12.71 to 11.71). Moreover, the standard deviations hold 0.88 and 0.77 for the *side* and the *middle* measurements respectively. Finally, the new mean value for the *sides* is almost identical to the one for the *middle* (6.27 to 6.29 correspondingly).

A different situation occurs in test case 26. At first, the deviation from the mean value is important (20.59% to 14.32%) and is also reflected in standard deviation values (1.53 and 0.97 respectively), but after neglecting the boundaries (iia, f) a significant decrease of the deviation takes place (from 20.59% to 17.40%). In addition, the new mean damage level for the *sides* approximates the mean value for that holds for all the cross sections (5.57 to 5.68).

4.7.4 Summary

The data analysis showed that for all the structures the variation of damage values at the *side* cross sections (iia, ia, a, e, if, f) was for all the cases larger than the *middle* ones (ib, b, ic, c, id, d, ie). The magnitude of these differences also varied, but in general it could be said that for half of the cases the difference was significant while for the other half, difference occurred, but was relatively trivial.

However, no clear trend was found about whether this difference was higher at the side or the middle cross sections. Likewise, for half the tests the middle cross sections gave higher damage values while for the other half the situation was reversed.

Chapter 5

Conclusions-Research proposals

5.1 Statistical analysis of measured damage

The analysis of the *One Sample Kolmogorov-Smirnov test* showed, that for the 27 damage sequencies, the normal distribution approach is the most suitable choice. Specifically, for all the sequencies, the probability that the distribution of the measured damage values follow the normal distribution is higher than the corresponding probabilities of the alternative options, such as the uniform, the exponential and the Poisson distribution. For the majority of the cases the probability acquires very high values, while for only very few cases the normal distribution approach is ambiguous. Finally, the *One Sample Kolmogorov-Smirnov test* is considered to have a low probability of rejecting an hypothesis, that's why the comparison is made with respect to the other available distributions. The certainty of its result is strengthened by increasing the population of the sample.

5.2 Comparison *smooth/polyline* fit approach

The main difference between the two types of approach, is the level of detail. Specifically, *smooth* fit approach uses the continuous signal records without any manipulation apart from the error manipulation. This means that the examined signal contains among others the pores of the layer between the stones. In addition, this computational approach is the one used by Van der Meer for the analysis of his measurements. On the other hand, the *polyline* fit approach treats a modified signal which is the average expression of a profile measurement, and therefore cannot display local peculiarities, that may be important for concerning the under-layer exposal.

Undoubtedly, the *smooth* fit approach is more accurate method, but is very sensitive in overestimating the damage values due to the measurement high level of detail. Only a slight displacement of the measuring boom, or the coincidence where a stone moves and below a hole between the stones occur, will considerably increase the amount of damage that is being computed. Cases like the above mentioned, are definitely an inevitable problem, but in the case of *polyline* fit, the result is less affected by their influence. In general, the *smooth* fit approach resulted in damage values 15-30% higher than the *polyline* fit. The difference here is considered crucial because it leads to damage values of higher order and therefore higher damage levels.

Finally, the analysis with respect to the calculated values from the Van der Meer equations didn't show a very clear image about which of the evaluation methods deviates more, with respect to the calculated values. For structures 2 and 3 and in contrast to structure 1 the *smooth* fit approach deviated more, although it should be underlined that the results from structure 3 were not in line with the values extracted from the Van der Meer equations. Certainly, the output of the equations is not necessarily the most accurate solution approach, since there is not a specific seeking value but an interval of possible values. Therefore, what is important is that the suggested intervals of the proposed evaluation contain the possible range of damage values and also are in the side of safety. This conditions are successively described when using the *smooth* fit approach, although the issue of the computational approach needs further investigation and optimization.

5.3 Differences among the tests of a test case

In this part of the study, nine different cases were examined by the combination of the normal distribution analysis and the application of the *Kruskal-Wallis-one-way analysis of variance test*. More specifically, test cases 3, 6, 8, 11, 20 and 26 where tested, while particularly for test case 3 and 6 an extra comparison was made for the combination of repetition tests executed with and without the use of the reflection compensator. Moreover, for test case 6 three comparisons were made in total, one with the compensator, one without and one with both the original and the repetition tests in order to investigate the output of the different testing conditions.

The results indicated a strong consistency for five of the cases. Indeed, the test cases 8, 3 without the compensator and 6 without the compensator showed a convergence of the damage values in specific numerical ranges. From the computed confidence intervals, representative damage values with satisfying safety can be extracted. Test case 6 with the use of the reflection compensator, displayed a weaker similarity in the distributions among the repetition, but in order to increase its reliability additional tests should take place.

For the two test cases (20, 26) of structure 3, one of the repetition tests was significantly deviating with respect to the rest of the group. Responsible for this deviation were some individual measurements with extreme values, although in general the standard deviation of the test had reasonable values. The extreme values, especially when talking about maximums, may be due to constructional imperfections (misplacement of part of the armour layer stones), because the width of the flume is small and therefore a rolling stone can really make the difference. Also a small recklessness, which could be inevitable when talking about the human factor, in the measuring procedure can deviate strongly the result.

The interpretation of the results is more complicated in test case 11, where two tests converge and the other two strongly deviate into two different directions. For a more reliable conclusion about the damage level, the test case needs to be supplemented with additional repetition tests.

Finally, an especially interesting case was the one were all the tests of a test case were treated together independently from the use of the reflection compensator. In the test case 3, as it was expected, there was a substantial deviation between test 3 (arc off) and the rest of the tests which had significantly higher damage levels, due to the existence of higher waves. Surprisingly, in the test case 6 the tests (6b, 6c), without the compensator, the measured average damage converged strongly to the values of the rest of the repetitions (with arc on). Probably the type of the structure, the type of wave breaking and the wave steepness are responsible for this irregularity, but for a safer assumption further research has to take place.

Undoubtedly, for safety and certainty reasons and due to the fact that almost in every case some extreme values show up, the selection of the damage values should be done as close as possible at the upper boundaries of the confidence intervals, but also in accordance with economical criteria.

5.4 Comparison measurements every *5cm/10cm*

Although the low population of both the repetition tests and consequently the individual measurements hinders the certainty and safety of the conclusion, it was rather obvious that the additional measurements trivially decreased the standard deviation of the computed damage values. Their influence on the statistical distribution of the damage values was insignificant and therefore measuring every *10cm* would have been sufficient, while the resulting decrease in the test duration would offer the opportunity to conduct a bigger amount of tests.

On the other hand, the consistency of the measurements verifies that the actually observed damage oscillates between a range of values with low probabilities of unexpected extremes. This assumption is also encouraged by the fact that there was no significant change in the damage distribution among the tests because of the additional measurements. This behavioral normality is only threatened by the chaotic character of the constructional procedure that is responsible for causing the extreme damage effects (even a small wave can cause the slide of a big stone if the latter is not well placed in the structure).

In the end, the comparison with the estimated values strengthened the impression that the measured damage values abstain from the calculated value area with a range in the order of the accepted statistical error. This conclusion is proving the existence of a representative range of the expected damage magnitude among the range of the computed values, and independently from the measuring step. In order to further investigate these tendencies it would be really interesting to measure with a step smaller than the d_{n50} of the armour layer, in order to completely eliminate the possibility that there would be cross sectional lines with extreme damage magnitudes.

5.5 Comparison surging/plunging area

The analysis of the data showed a small but noticeable difference in the spreading of the data with respect to the type of breaking. The damage values for tests in the plunging area are characterized by a slightly larger deviation. Mainly responsible for this trend, is the character of the plunging breaking. During this type of breaking the wave crest becomes vertical, curls over and then drops onto the structure, causing a violent impact. The wave energy is released upon the structure in a more sudden and harsh way. Consequently, the structure reaction which is expressed by the damage is less even and is characterized by large diversity.

5.6 Comparison *side/middle* measurements

The data analysis showed a very interesting phenomenon in which the variation of damage values at the *side* cross sections (iia, ia, a, e, if, f) was for all the cases larger than the *middle* ones (ib, b, ic, c, id, d, ie). In half of the cases the difference was significant while for the other half, difference occurred, but was relatively trivial.

A possible explanation, is due to the fact that the friction between the stones in contact with the glass flume walls is smaller than the friction between stones. Therefore stones at the sides are more vulnerable to slide than stones being at a partition closer to the middle. Furthermore, due to domino effect, stones in the vicinity of the sensitive area can lose their stability easier than expected and therefore increase the damage level contaminating the output with additional values.

Moreover, the explanation would be uncontested if the mean damage values at the *sides* would be higher than those in the *middle*. However, this was not the case for half of the test series. Consequently, responsible for the uncertainty introduced in the sides is not only the lower friction but also other factors; among them the constructional imperfections where the local placement of bigger amount of stones in the middle together with thinner armour layer in the sides can deviate the distribution of damage.

5.7 Review of testing technique - optimization proposals

In general, the testing technique used, succeeded reasonable results that were characterized by consistency and convergence to specific criteria that were analytically described above. Certainly, there were measurements or even tests that were deviating largely or slightly from the other tests of a test case, but this was mainly due to constructional mistakes or uncertainties introduced by the implication of the human factor. Moreover, these deviations were among the boundaries of the acceptable statistical error. Unquestionably, the most efficient way to decrease their influence is to make a larger amount of repetition tests. On the other hand, there are parts in the procedure that could be improved in order to facilitate the procedure and increase the accuracy and certainty of the results.

Firstly, there were limitations introduced by the available measuring equipment. Specifically, the available laser device had a limited range and could measure only at a distance from its level (see also 3.1 "Equipment", 3-3 "Damage determination & profile measurements" & 3-4 "Data processing & damage level computation"). In order to perform the measurements under the water surface and beyond the range of the laser device, an echo-sounder was used. In addition the echo-sounder can only measure inside the water body and thus is useless outside of it. Therefore, a sensitive-transition area was formed around the water level which may have introduced errors in the profile measurements. Nevertheless, the area around the water-level is also the most crucial area for the damage determination.

A possible solution to quantify this influence and solve the problem is to repeat every measurement sequence after relegating the water-level for 5-10cm in case of final profile measurements. In case of initial profile measurements, measurements are taken, then the water level is heightened for 5-10cm and after that repetition measurements are taken again. The selection of the water level heightening-relegation will be done with respect to the slope of the structure in order to completely include the sensitive-transition area.

Undoubtedly, this procedure will largely increase the duration of the test cycle and the question holds here about what is the optimized relation between the application of this method, the number of the transverse profile measurements-measurement step (5.4 "Comparison measurements every 5cm/10cm") with respect to the d_{n50} of the top layer.

Another controversial issue of this technique is the measuring equipment which was used. Undoubtedly, the combination of the laser and the echo-sounder has disadvantages which were analytically presented, but also the alternatives have important drawbacks.

Specifically the use of a laser of wider range apart from the fact that it was not available and is more expensive is also sensitive in the clarity of the water. Indeed, the dust which is formed around the stones when they dry is then suspended in the water, causing undesired reflections on the laser beam and contaminating the measurements with errors. Especially, the initial profile measurements had to be repeated many times to decrease the signal errors, though in the final profile measurements the sediments were suspended over the full water body along the flume and thus the water was more clear. Consequently, the use of a stronger laser has to be accompanied with precautions concerning the clarity of the water, and the solution of replacing the water for every test is completely unacceptable for environmental and temporal reasons.

Furthermore, the replacement of the wooden plates used for the measurement steps, by metal ones will increase the weight of the roller, which is already heavy enough because it has to carry many instruments and devices.

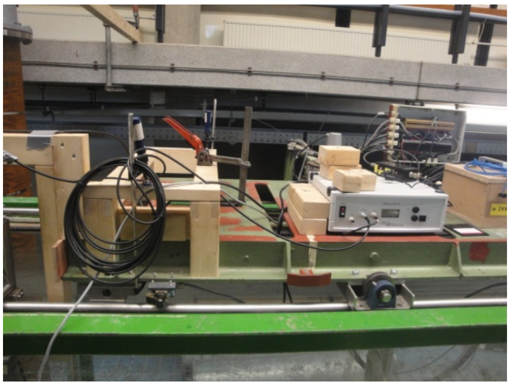


figure 5-1 Rolling metal car carrying the measurement equipment

Therefore, the wooden construction is considered a good solution due to low weight, and deformations. On the other hand the metallic plates will slide more easily along decreasing the time and effort needed to prepare the measurements.

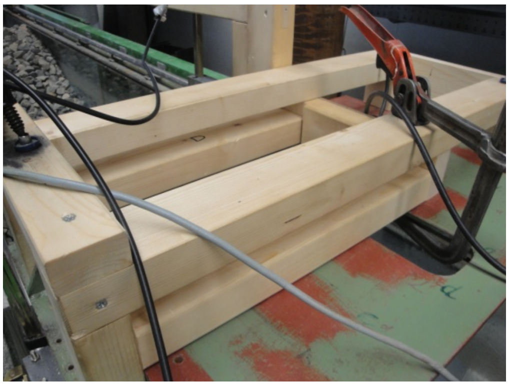


figure 5-2 Wooden construction and plates

Finally, a crucial question raises about the constructional consistency of the slope. As it is mentioned above, the local constructional imperfections have a substantial share in the spreading of the damage values and especially in cases where unexplained excess damage values were found. The short duration of the testing part of this thesis didn't allow the introduction of a system that would assure the elimination of such possibility. Furthermore, the small extent of the flume width and height increased the importance of every stone (every stone counts).

Accordingly, and by using only the available equipment, a different procedure could have been followed. In specific, after the re-profiling of every layer the laser device could be used to measure the slope. The laser has limitations mentioned above, but is adequate for the sensitive area from below the water level until the crest of the structure. Afterwards, the signal would be plotted and a mean slope line accompanied with accepted margins of deviation would be used to figure out and eliminate possible local irregularities. The disadvantage of this procedure is that the time duration of every test would be extended significantly.

Appendix A Individual damage values

Structure 1

Structure 1	cross section/measurements per 5cm (ARC OFF)													smooth fit	
Test	iia	ia	a	ib	b	ic	c	id	d	ie	e	if	f	mean value per test	standard deviation per test
3 (ON)	-	-	13,07	-	14,01	-	12,08	-	14,76	-	17,70	-	20,23	15,31	3,08
3a	22,09	19,08	19,99	27,82	21,34	17,73	20,70	21,00	23,10	18,68	20,38	14,89	22,22	20,69	3,04
3b	26,06	20,47	15,05	16,11	19,70	15,29	24,60	17,45	15,44	18,75	18,20	18,94	26,00	19,39	3,92
3c	20,03	22,53	17,57	19,39	24,66	23,21	21,44	28,44	20,56	23,62	17,97	17,43	19,30	21,24	3,20
μ cross section	22,73	20,69	16,42	21,11	19,93	18,74	19,71	22,30	18,47	20,35	18,56	17,09	21,94	overall μ	20,44
σ cross section	3,07	1,74	3,01	6,04	4,45	4,06	5,36	5,61	4,03	2,83	1,23	2,05	2,97	overall σ	0,95

table A-1 Structure 1, test series 3, smooth fit, measurements per 5cm

Structure 1	cross section/measurements per 5cm (ARC ON)													smooth fit	
Test	iia	ia	a	ib	b	ic	c	id	d	ie	e	if	f	mean value per test	standard deviation per test
6	-	-	9,84	-	2,96	-	5,65	-	8,18	-	11,36	-	10,97	8,16	3,30
6-2	-	-	10,28	-	7,50	-	11,71	-	11,50	-	9,95	-	11,71	10,44	1,63
6a	11,52	11,72	13,73	10,65	11,17	9,28	11,03	10,28	8,79	8,96	11,29	13,02	16,12	11,35	2,04
6d	13,92	12,67	10,21	8,84	-	7,50	6,43	7,93	6,09	6,77	8,48	13,35	11,88	9,51	2,81
6e	15,84	12,51	9,51	11,91	12,20	12,52	9,64	12,29	9,93	5,86	10,05	13,68	7,81	11,06	2,61
μ cross section	13,76	12,30	10,71	10,47	8,46	9,77	8,89	10,17	8,90	7,20	10,23	13,35	11,70	overall μ	10,10
σ cross section	2,17	0,51	1,71	1,54	4,18	2,55	2,72	2,18	2,02	1,59	1,18	0,33	2,97	overall σ	1,30

table A-2 Structure 1, test series 6 (ARC ON), smooth fit, measurements per 5cm

Structure 1	cross section/measurements per 5cm (ARC OFF)													smooth fit	
Test	iia	ia	a	ib	b	ic	c	id	d	ie	e	if	f	mean value per test	standard deviation per test
6b	12,67	15,86	15,58	15,19	14,91	13,18	10,80	6,40	9,35	5,75	8,34	7,18	10,10	11,18	3,63
6c	-	15,90	7,59	11,87	10,75	8,73	8,30	5,86	15,32	9,95	6,33	10,77	9,25	10,05	3,15
μ cross section	12,67	15,88	11,59	13,53	12,83	10,95	9,55	6,13	12,33	7,85	7,33	8,98	9,68	overall μ	10,61
σ cross section	#####	0,03	5,65	2,35	2,94	3,15	1,77	0,38	4,22	2,97	1,42	2,54	0,60	overall σ	0,80

table A-3 Structure 1, test series 6 (ARC OFF), smooth fit, measurements per 5cm

Structure 1	cross section/measurements per 10cm (ARC OFF)							smooth fit	
Test	**iia**	**a**	**b**	**c**	**d**	**e**	**f**	**mean value per test**	**standard deviation per test**
3 (ON)	-	13,07	14,01	12,08	14,76	17,70	20,23	15,31	3,08
3a	22,09	19,99	21,34	20,70	23,10	20,38	22,22	21,40	1,12
3b	26,06	15,05	19,70	24,60	15,44	18,20	26,00	20,72	4,81
3c	20,03	17,57	24,66	21,44	20,56	17,97	19,30	20,22	2,39
overall μ	22,73	16,42	19,93	19,71	18,47	18,56	21,94	**overall μ**	**20,78**
overall σ	3,07	3,01	4,45	5,36	4,03	1,23	2,97	**overall σ**	**0,59**

table A-4 Structure 1, test series 3, smooth fit, measurements per 10cm

Structure 1	cross section/measurements per 10cm (ARC ON)							smooth fit	
Test	**iia**	**a**	**b**	**c**	**d**	**e**	**f**	**mean value per test**	**standard deviation per test**
6	-	9,84	2,96	5,65	8,18	11,36	10,97	8,16	3,30
6-2	-	10,28	7,50	11,71	11,50	9,95	11,71	10,44	1,63
6a	11,52	13,73	11,17	11,03	8,79	11,29	16,12	11,95	2,33
6d	13,92	10,21	-	6,43	6,09	8,48	11,88	9,50	3,09
6e	15,84	9,51	12,20	9,64	9,93	10,05	7,81	10,71	2,60
μ cross section	13,76	10,71	8,46	8,89	8,90	10,23	11,70	**overall μ**	**10,15**
σ cross section	2,17	1,71	4,18	2,72	2,02	1,18	2,97	**overall σ**	**1,42**

table A-5 Structure 1, test series 6 (ARC ON), smooth fit, measurements per 10cm

Structure 1	cross section/measurements per 10cm (ARC OFF)							smooth fit	
Test	iia	a	b	c	d	e	f	mean value per test	standard deviation per test
6b	12,67	15,58	14,91	10,80	9,35	8,34	10,10	11,68	2,78
6c	-	7,59	10,75	8,30	15,32	6,33	9,25	9,59	3,18
µ cross section	12,67	11,59	12,83	9,55	12,33	7,33	9,68	overall µ	10,63
σ cross section	#######	5,65	2,94	1,77	4,22	1,42	0,60	overall σ	1,48

table A-6 Structure 1, test series 6 (ARC OFF), smooth fit, measurements per 10cm

Structure 1	cross section/measurements per 5cm (ARC OFF)													polyline fit	
Test	iia	ia	a	ib	b	ic	c	id	d	ie	e	if	f	mean value per test	standard deviation per test
3 (ON)	-	-	11,03	-	12,92	-	10,67	-	13,12	-	16,95	-	17,72	13,74	2,97
3a	19,75	17,27	18,40	25,66	20,11	16,40	19,56	18,27	22,40	17,26	19,29	11,87	21,33	19,04	3,27
3b	23,03	19,06	13,20	14,46	16,90	14,50	23,60	16,89	13,35	17,05	16,88	18,50	23,60	17,77	3,68
3c	17,83	20,47	16,54	17,06	24,28	21,67	21,26	27,40	19,26	22,60	16,49	16,63	18,30	19,98	3,38
µ cross section	20,20	18,93	14,79	19,06	18,55	17,52	18,77	20,85	17,03	18,97	17,40	15,67	20,24	overall µ	18,93
σ cross section	2,63	1,60	3,30	5,86	4,82	3,71	5,65	5,71	4,57	3,15	1,27	3,42	2,74	overall σ	1,11

table A-7 Structure 1, test series 3, polyline fit measurements per 5cm

Structure 1	cross section/measurements per 5cm (ARC ON)													polyline fit	
Test	**iia**	**ia**	**a**	**ib**	**b**	**ic**	**c**	**id**	**d**	**ie**	**e**	**if**	**f**	**mean value per test**	**standard deviation per test**
6	-	-	7,91	-	0,76	-	3,59	-	5,31	-	9,64	-	9,93	6,19	3,63
6-2	-	-	9,22	-	4,56	-	9,03	-	9,43	-	7,16	-	11,12	8,42	2,27
6a	7,15	8,03	11,08	8,40	7,80	5,19	9,19	7,47	7,08	6,38	9,08	9,07	12,85	8,37	1,99
6d	12,08	11,60	8,23	7,14	-	5,22	2,77	6,67	2,21	5,09	7,55	11,29	10,49	7,53	3,36
6e	14,42	8,83	7,56	8,00	10,04	10,49	7,02	10,47	7,92	3,63	7,80	10,66	3,06	8,45	2,99
µ cross section	11,22	9,49	8,80	7,85	5,79	6,97	6,32	8,20	6,39	5,03	8,24	10,34	9,49	**overall µ**	**7,63**
σ cross section	2,99	2,40	2,75	2,87	3,01	3,05	3,69	3,69	3,65	3,66	3,39	3,39	3,57	**overall σ**	**1,04**

table A-8 Structure 1, test series 6 (ARC ON), polyline fit measurements per 5cm

Structure 1	cross section/measurements per 5cm (ARC OFF)													polyline fit	
Test	**iia**	**ia**	**a**	**ib**	**b**	**ic**	**c**	**id**	**d**	**ie**	**e**	**if**	**f**	**mean value per test**	**standard deviation per test**
6b	11,32	14,74	14,23	13,25	13,67	12,68	8,23	4,33	7,80	3,72	5,15	5,21	8,04	9,41	4,07
6c	-	13,87	5,85	9,56	8,38	6,35	6,08	4,04	12,43	8,63	5,36	9,09	6,10	7,98	2,95
µ cross section	11,32	14,30	10,04	11,40	11,02	9,52	7,15	4,19	10,11	6,18	5,25	7,15	7,07	**overall µ**	**8,69**
σ cross section	######	0,61	5,93	2,61	3,74	4,47	1,52	0,20	3,27	3,47	0,15	2,74	1,37	**overall σ**	**1,02**

table A-9 Structure 1, test series 6 (ARC OFF), polyline fit measurements per 5cm

Structure 1	cross section/measurements per 10cm (ARC OFF)							polyline fit	
Test	iia	a	b	c	d	e	f	mean value per test	standard deviation per test
3 (ON)	-	11,03	12,92	10,67	13,12	16,95	17,72	13,74	2,97
3a	19,75	18,40	20,11	19,56	22,40	19,29	21,33	20,12	1,34
3b	23,03	13,20	16,90	23,60	13,35	16,88	23,60	18,65	4,69
3c	17,83	16,54	24,28	21,26	19,26	16,49	18,30	19,14	2,80
μ cross section	20,20	14,79	18,55	18,77	17,03	17,40	20,24	overall μ	19,30
σ cross section	2,63	3,30	4,82	5,65	4,57	1,27	2,74	overall σ	0,75

table A-10 Structure 1, test series 3, polyline fit measurements per 5cm

Structure 1	cross section/measurements per 10cm (ARC ON)							polyline fit	
Test	iia	a	b	c	d	e	f	mean value per test	standard deviation per test
6	-	7,91	0,76	3,59	5,31	9,64	9,93	6,19	3,11
6-2	-	9,22	4,56	9,03	9,43	7,16	11,12	8,42	2,94
6a	7,15	11,08	7,80	9,19	7,08	9,08	12,85	9,18	2,87
6d	12,08	8,23	-	2,77	2,21	7,55	10,49	7,22	3,52
6e	14,42	7,56	10,04	7,02	7,92	7,80	3,06	8,26	3,46
μ cross section	11,22	8,80	5,79	6,32	6,39	8,24	9,49	overall μ	7,75
σ cross section	3,03	1,42	4,04	3,00	2,77	1,06	3,76	overall σ	1,32

table A-11 Structure 1, test series 6 (ARC ON), polyline fit measurements per 10cm

Structure 1	cross section/measurements per 10cm (ARC OFF)							polyline fit	
Test	iia	a	b	c	d	e	f	mean value per test	standard deviation per test
6b	11,32	14,23	13,67	8,23	7,80	5,15	8,04	9,78	3,37
6c	-	5,85	8,38	6,08	12,43	5,36	6,10	7,36	2,69
μ cross section	11,32	10,04	11,02	7,15	10,11	5,25	7,07	overall μ	8,57
σ cross section	#######	5,93	3,74	1,52	3,27	0,15	1,37	overall σ	1,71

table A-12 Structure 1, test series 6 (ARC OFF), polyline fit measurements per 10cm

Structure 2

Structure 2	cross section/measurements per 5cm													smooth fit	
Test	iia	ia	a	ib	b	ic	c	id	d	ie	e	if	f	mean value per test	standard deviation per test
8	4,57	4,33	6,77	6,08	6,95	6,67	4,70	5,39	5,00	5,86	3,30	2,97	3,90	5,11	1,31
8a	6,78	4,22	4,42	8,06	7,38	2,62	5,86	5,08	8,16	3,55	4,06	5,04	5,52	5,44	1,74
8b	3,43	4,78	8,57	5,75	4,51	9,61	5,37	4,22	5,35	7,94	7,05	5,74	5,59	5,99	1,81
8c	8,20	-	6,59	4,12	3,86	3,11	2,92	5,95	5,60	7,04	6,18	5,61	5,76	5,41	1,61
µ cross section	5,75	4,44	6,59	6,00	5,68	5,50	4,71	5,16	6,03	6,10	5,15	4,84	5,19	**overall µ**	**5,49**
σ cross section	2,15	0,30	1,70	1,62	1,75	3,28	1,29	0,72	1,44	1,90	1,76	1,28	0,87	**overall σ**	**0,37**

table A-13 Structure 2, test series 8, smooth fit, measurements per 5cm

Structure 2	cross section/measurements per 5cm													smooth fit	
Test	iia	ia	a	ib	b	ic	c	id	d	ie	e	if	f	mean value per test	standard deviation per test
11	14,98	14,21	13,24	14,85	9,78	12,55	12,70	10,96	15,03	14,61	10,03	11,48	13,29	12,90	1,86
11a	16,41	14,94	13,11	13,03	14,59	16,27	16,50	14,37	12,71	-	15,54	10,35	15,77	14,47	1,86
11b	11,96	12,69	13,15	14,48	18,60	11,14	14,86	12,71	14,35	9,98	12,46	13,34	20,18	13,84	2,82
11c	-	11,55	16,33	16,70	17,70	18,85	10,65	15,71	14,18	14,95	20,75	19,20	18,72	16,27	3,07
µ cross section	14,45	13,35	13,96	14,76	15,17	14,70	13,68	13,44	14,07	13,18	14,70	13,59	16,99	**overall µ**	**14,37**
σ cross section	2,27	1,52	1,58	1,51	3,98	3,51	2,55	2,06	0,98	2,78	4,62	3,94	3,07	**overall σ**	**1,42**

table A-14 Structure 2, test series 11, smooth fit, measurements per 5cm

Structure 2	cross section/measurements per 10cm							smooth fit	
Test	iia	a	b	c	d	e	f	mean value per test	standard deviation per test
8	4,57	6,77	6,95	4,70	5,00	3,30	3,90	5,03	1,37
8a	6,78	4,42	7,38	5,86	8,16	4,06	5,52	6,03	1,51
8b	3,43	8,57	4,51	5,37	5,35	7,05	5,59	5,70	1,68
8c	8,20	6,59	3,86	2,92	5,60	6,18	5,76	5,59	1,75
μ cross section	5,75	6,59	5,68	4,71	6,03	5,15	5,19	overall μ	5,58
σ cross section	2,15	1,70	1,75	1,29	1,44	1,76	0,87	overall σ	0,42

table A-15 Structure 2, test series 8, smooth fit, measurements per 10cm

Structure 2	cross section/measurements per 10cm							smooth fit	
Test	iia	a	b	c	d	e	f	mean value per test	standard deviation per test
11	14,98	13,24	9,78	12,70	15,03	10,03	13,29	12,72	2,12
11a	16,41	13,11	14,59	16,50	12,71	15,54	15,77	14,95	1,53
11b	11,96	13,15	18,60	14,86	14,35	12,46	20,18	15,08	3,14
11c	-	16,33	17,70	10,65	14,18	20,75	18,72	16,39	3,58
μ cross section	14,45	13,96	15,17	13,68	14,07	14,70	16,99	overall μ	14,78
σ cross section	2,27	1,58	3,98	2,55	0,98	4,62	3,07	overall σ	1,52

table A-16 Structure 2, test series 11, smooth fit, measurements per 10cm

Structure 2	cross section/measurements per 5cm													polyline fit	
Test	**iia**	**ia**	**a**	**ib**	**b**	**ic**	**c**	**id**	**d**	**ie**	**e**	**if**	**f**	**mean value per test**	**standard deviation per test**
8	3,31	3,03	4,91	3,73	5,19	4,32	2,40	2,31	1,80	4,35	1,20	1,15	2,16	3,07	1,36
8a	2,86	3,80	1,53	7,06	5,93	0,89	4,44	2,45	3,23	0,30	0,92	2,82	2,43	2,97	1,97
8b	2,53	3,39	4,67	4,02	1,68	7,03	3,64	1,54	3,21	5,39	3,62	4,06	2,98	3,67	1,47
8c	5,52	-	4,86	1,60	2,49	1,47	1,10	2,44	3,56	3,99	4,22	3,63	2,19	3,09	1,42
μ cross section	3,56	3,41	3,99	4,10	3,82	3,43	2,90	2,19	2,95	3,51	2,49	2,92	2,44	**overall μ**	**3,20**
σ cross section	1,35	0,39	1,64	2,25	2,06	2,83	1,46	0,43	0,78	2,22	1,67	1,28	0,38	**overall σ**	**0,32**

table A-17 Structure 2, test series 8, polyline fit, measurements per 5cm

Structure 2	cross section/measurements per 5cm													polyline fit	
Test	**iia**	**ia**	**a**	**ib**	**b**	**ic**	**c**	**id**	**d**	**ie**	**e**	**if**	**f**	**mean value per test**	**standard deviation per test**
11	10,35	12,63	9,43	10,66	7,19	7,32	9,70	7,31	11,80	12,08	7,67	8,41	9,89	9,57	1,90
11a	13,88	13,31	11,33	10,48	12,19	12,57	14,35	11,78	11,26	16,59	13,23	8,44	12,31	12,44	1,99
11b	10,22	9,80	9,68	11,37	17,71	8,73	12,25	9,45	12,34	5,25	10,83	10,23	17,49	11,18	3,36
11c		8,96	14,67	14,69	16,36	17,31	8,84	13,35	10,57	12,94	19,32	16,91	17,20	14,26	3,42
μ cross section	11,48	11,18	11,28	11,80	13,36	11,48	11,29	10,47	11,49	11,71	12,76	11,00	14,22	**overall μ**	**11,86**
σ cross section	2,08	2,12	2,41	1,96	4,74	4,47	2,50	2,65	0,76	4,73	4,93	4,03	3,74	**overall σ**	**1,98**

table A-18 Structure 2, test series 11, polyline fit, measurements per 5cm

Structure 2	cross section/measurements per 10cm							polyline fit	
Test	iia	a	b	c	d	e	f	mean value per test	standard deviation per test
8	3,31	4,91	5,19	2,40	1,80	1,20	2,16	3,00	1,54
8a	2,86	1,53	5,93	4,44	3,23	0,92	2,43	3,05	1,71
8b	2,53	4,67	1,68	3,64	3,21	3,62	2,98	3,19	0,94
8c	5,52	4,86	2,49	1,10	3,56	4,22	2,19	3,42	1,58
μ cross section	3,56	3,99	3,82	2,90	2,95	2,49	2,44	overall μ	3,16
σ cross section	1,35	1,64	2,06	1,46	0,78	1,67	0,38	overall σ	0,19

table A-19 Structure 2, test series 8, polyline fit, measurements per 10cm

Structure 2	cross section/measurements per 10cm							polyline fit	
Test	iia	a	b	c	d	e	f	mean value per test	standard deviation per test
11	10,35	9,43	7,19	9,70	11,80	7,67	9,89	9,43	1,58
11a	13,88	11,33	12,19	14,35	11,26	13,23	12,31	12,65	1,21
11b	10,22	9,68	17,71	12,25	12,34	10,83	17,49	12,93	3,34
11c	0,00	14,67	16,36	8,84	10,57	19,32	17,20	12,42	4,04
μ cross section	8,61	11,28	13,36	11,29	11,49	12,76	14,22	overall μ	11,86
σ cross section	5,99	2,41	4,74	2,50	0,76	4,93	3,74	overall σ	1,63

table A-20 Structure 2, test series 11, polyline fit, measurements per 10cm

Structure 3

Structure 3	cross section/measurements per 5cm													smooth fit	
Test	iia	ia	a	ib	b	ic	c	id	d	ie	e	if	f	mean value per test	standard deviation per test
20	6,98	4,76	8,43	4,32	7,92	9,21	6,40	5,33	6,19	4,59	5,66	3,20	5,12	6,01	1,75
20a	7,23	4,91	4,68	6,56	3,94	4,44	3,87	7,51	6,24	7,12	7,10	5,75	5,09	5,73	1,31
20b	8,30	4,96	6,70	5,42	3,52	7,64	6,80	5,91	4,51	4,13	6,58	4,45	6,48	5,80	1,44
20c	6,72	7,72	8,47	9,05	7,84	9,09	4,85	9,10	7,70	6,32	8,72	8,50	13,23	8,25	1,95
μ cross section	7,31	5,59	7,07	6,34	5,81	7,60	5,48	6,96	6,16	5,54	7,02	5,48	7,48	overall μ	6,45
σ cross section	0,69	1,42	1,79	2,03	2,40	2,22	1,36	1,70	1,30	1,41	1,28	2,27	3,89	overall σ	1,21

table A-21 Structure 3, test series 20, smooth fit, measurements per 5cm

Structure 3	cross section/measurements per 5cm													smooth fit	
Test	iia	ia	a	ib	b	ic	c	id	d	ie	e	if	f	mean value per test	standard deviation per test
26	2,35	3,61	-	6,00	7,97	4,19	2,66	3,18	4,54	2,87	1,72	1,82	2,43	3,61	1,84
26a	5,20	7,30	6,70	8,44	8,16	5,15	4,97	2,89	7,50	8,56	0,95	6,51	3,06	5,80	2,37
26b	5,98	4,36	7,06	4,40	5,95	8,34	8,00	9,14	-	10,37	5,84	5,79	1,58	6,40	2,38
26c	7,89	9,01	6,37	5,59	8,04	5,82	5,11	5,03	6,16	7,76	5,47	9,97	4,69	6,69	1,67
μ cross section	5,36	6,07	6,71	6,11	7,53	5,88	5,19	5,06	6,07	7,39	3,50	6,02	2,94	overall μ	5,62
σ cross section	2,30	2,53	0,35	1,70	1,06	1,77	2,19	2,88	1,48	3,21	2,52	3,34	1,31	overall σ	1,39

table A-22 Structure 3, test series 26, smooth fit, measurements per 5cm

Structure 3	cross section/measurements per 10cm							smooth fit	
Test	iia	a	b	c	d	e	f	mean value per test	standard deviation per test
20	6,98	8,43	7,92	6,40	6,19	5,66	5,12	6,67	1,19
20a	7,23	4,68	3,94	3,87	6,24	7,10	5,09	5,45	1,42
20b	8,30	6,70	3,52	6,80	4,51	6,58	6,48	6,13	1,59
20c	6,72	8,47	7,84	4,85	7,70	8,72	13,23	8,22	2,56
µ cross section	7,31	7,07	5,81	5,48	6,16	7,02	7,48	overall µ	6,62
σ cross section	0,69	1,79	2,40	1,36	1,30	1,28	3,89	overall σ	1,18

table A-23 Structure 3, test series 20, smooth fit, measurements per 10cm

Structure 3	cross section/measurements per 10cm							smooth fit	
Test	iia	a	b	c	d	e	f	mean value per test	standard deviation per test
26	2,35	-	7,97	2,66	4,54	1,72	2,43	3,61	2,24
26a	5,20	6,70	8,16	4,97	7,50	0,95	3,06	5,22	1,91
26b	5,98	7,06	5,95	8,00	-	5,84	1,58	5,74	2,38
26c	7,89	6,37	8,04	5,11	6,16	5,47	4,69	6,25	2,40
µ cross section	5,36	6,71	7,53	5,19	6,07	3,50	2,94	overall µ	5,20
σ cross section	2,30	0,35	1,06	2,19	1,48	2,52	1,31	overall σ	1,14

table A-24 Structure 3, test series 26, smooth fit, measurements per 10cm

Structure 3	cross section/measurements per 5cm													polyline fit	
Test	**iia**	**ia**	**a**	**ib**	**b**	**ic**	**c**	**id**	**d**	**ie**	**e**	**if**	**f**	**mean value per test**	**standard deviation per test**
20	2,29	2,91	6,41	1,92	6,85	7,64	3,81	3,91	5,22	3,54	4,66	1,93	4,80	4,30	1,86
20a	5,75	2,93	2,57	5,08	1,38	3,13	2,14	5,82	5,40	4,90	5,86	4,49	1,94	3,95	1,64
20b	6,77	4,04	3,65	3,65	1,54	7,05	5,65	4,29	4,06	2,10	4,16	2,23	5,05	4,17	1,67
20c	4,99	6,23	5,95	6,16	4,71	7,67	3,33	6,87	4,30	3,48	5,77	6,92	11,47	5,99	2,11
µ cross section	4,95	4,03	4,64	4,20	3,62	6,37	3,73	5,22	4,75	3,50	5,11	3,89	5,82	**overall µ**	**4,60**
σ cross section	1,92	1,56	1,84	1,84	2,64	2,18	1,46	1,37	0,67	1,14	0,84	2,32	4,02	**overall σ**	**0,93**

table A-25 Structure 3, test series 20, polyline fit, measurements per 5cm

Structure 3	cross section/measurements per 5cm													polyline fit	
Test	**iia**	**ia**	**a**	**ib**	**b**	**ic**	**c**	**id**	**d**	**ie**	**e**	**if**	**f**	**mean value per test**	**standard deviation per test**
26	1,29	3,62	7,45	4,51	6,32	2,88	1,31	2,34	3,12	0,72	1,07	0,52	1,08	2,79	2,20
26a	4,01	7,30	6,46	8,27	7,35	3,91	3,57	0,69	6,41	4,29	0,21	5,27	1,77	4,58	2,58
26b	4,71	3,28	5,89	3,80	5,25	6,17	6,25	6,26	-	7,92	5,44	3,05	0,88	4,91	1,89
26c	5,33	6,96	5,20	4,19	6,76	3,84	3,98	3,26	4,84	6,03	3,58	8,83	3,39	5,09	1,67
µ cross section	3,83	5,29	6,25	5,19	6,42	4,20	3,78	3,14	4,79	4,74	2,58	4,42	1,78	**overall µ**	**4,34**
σ cross section	1,78	2,13	0,95	2,07	0,89	1,39	2,02	2,34	1,65	3,06	2,39	3,53	1,14	**overall σ**	**1,06**

table A-26 Structure 3, test series 26, polyline fit, measurements per 5cm

Structure 3	cross section/measurements per 10cm							polyline fit	
Test	**iia**	**a**	**b**	**c**	**d**	**e**	**f**	**mean value per test**	**standard deviation per test**
20	2,29	6,41	6,85	3,81	5,22	4,66	4,80	4,86	1,54
20a	5,75	2,57	1,38	2,14	5,40	5,86	1,94	3,58	1,99
20b	6,77	3,65	1,54	5,65	4,06	4,16	5,05	4,41	1,66
20c	4,99	5,95	4,71	3,33	4,30	5,77	11,47	5,79	2,66
μ cross section	4,95	4,64	3,62	3,73	4,75	5,11	5,82	**overall μ**	**4,66**
σ cross section	1,92	1,84	2,64	1,46	0,67	0,84	4,02	**overall σ**	**0,92**

table A-27 Structure 3, test series 20, polyline fit, measurements per 10cm

Structure 3	cross section/measurements per 10cm							polyline fit	
Test	**iia**	**a**	**b**	**c**	**d**	**e**	**f**	**mean value per test**	**standard deviation per test**
26	1,29	7,45	6,32	1,31	3,12	1,07	1,08	3,09	2,71
26a	4,01	6,46	7,35	3,57	6,41	0,21	1,77	4,25	2,65
26b	4,71	5,89	5,25	6,25	-	5,44	0,88	4,74	1,96
26c	5,33	5,20	6,76	3,98	4,84	3,58	3,39	4,73	1,18
μ cross section	3,83	6,25	6,42	3,78	4,79	2,58	1,78	**overall μ**	**4,20**
σ cross section	1,78	0,95	0,89	2,02	1,65	2,39	1,14	**overall σ**	**0,77**

table A-28 Structure 3, test series 26, polyline fit, measurements per 10cm

Appendix B

Theoretical background of the used statistical tests

K-S

Kolmogorov-Smirnov test (K-S test): is a non parametric test used to identify what kind of distribution does the examined continuous variable follow. There four options*, the normal, the uniform the exponential and the Poisson* distribution. It is an important test in order to determine the satisfying statistical distribution which dictates the character of the tests that could be performed for this variable. On the other hand, it is considered to have low power dictated by the population of the sum (low population=low power) and with a low probability to reject the Zero condition hypotheses.

For the test, the observations are ordered in an ascending order and then for every individual observation the percentage of observations smaller than that is compared with the expected percentage in the theoretical distribution.

The null hypotheses for the for the test is formulated according to the examined distribution although it is possible to test all the available options:

Ho:" the variable X follows the theoretical (i.e. normal, uniform)"

For the test output accent is paid to the values of Z, which represents *Kolmogorov-Smirnov* value Z and to the value of Asymp. Sig. which represents the probability that the Z value would be found if the zero condition hypotheses is true. If this probability is less or equal than 0,05, then the Zero hypotheses is rejected and therefore the variable does not satisfy the examined statistical distribution. Additionally, in order to decrease the uncertainty of the outcome, the scewness and the kurtosis of the variable could be checked and if their values are bigger than 1 or smaller than -1, means that their behavior significantly differs from the normal distribution.

MMW

The Mann–Whitney U test (also called the Mann–Whitney–Wilcoxon (MWW) or Wilcoxon rank-sum test), is a technique used to test two independent samples on a continuous measurement, with small population that a parametric test cannot be performed. Therefore, it is a non parametric hypothesis test to identify if there is statistical difference between two independent groups and how significant this difference is. More precisely:

Mann–Whitney U test: it actually, performs medians comparison. In order to do that, it merges the two samples and then assigns ranks on the values of the continuous variable (at this occasion “damage”). Afterwards, it computes the sum of the ranks (called U or W) which corresponds to each of the categorical or grouping variables (i.e. two different tests, or measurements every 5cm or 10cm). Finally, it compares the different sums and evaluates if there is significant difference between the two groups. In case of ties, half of the rank value is added to every sum.

Wilcoxon rank-sum test: at first, it arranges the continuous variable values of the different categorical values in ascending order and then it compares every value of the one group with all the values of the other(s) group(s). For every comparison, a score is kept, which shows how many times a value from the one group is bigger than the values of the other(s). Then, all the scores are added and the difference in sums (called Q or W) of every group is computed. In case of ties, half point is being added to each of the corresponding sums.

The zero condition hypotheses, which is being examined is the following:

Ho: ”The distribution of damage S, is the same across the categories of the categorical variable”

In order to interpret the output of the test, attention is paid to the *Z* value and to the significance level, represented by the *Asymp. Sig (2-tailed)*. If the value of the latter is less or equal than 0.05, then the zero hypothesis is rejected and the two samples are significantly different. Unfortunately, the direction of the difference (which group is higher or stronger) is not showed directly but needs further elaboration using a “means comparison”. In the end, the effect size statistics “*r*” is computed by dividing the value of “*Z*” with the total number of observations and not the cases of the grouping variable and by comparing it with the Cohen(1988) criteria.

The IBM statistical package SPSS was used to execute the tests which contemporaneously runs both the Mann-Whitney U and the Wilcoxon Rank-Sum test.

K-W

The Kruskal-Wallis test is a non parametric method for the one way analysis of variance between groups, by ranks. It is considered to be extension of *Mann-Whitney U test* because it compares the scores of the values of a categorical value on some continuous variable, but for three or more groups instead of two which is the case for *Mann-Whitney U test*. The scores are converted to ranks and the medians of each group are compared.

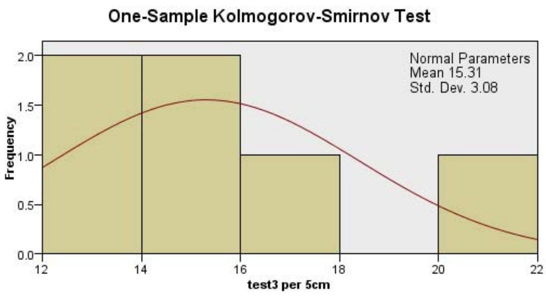
For the computation, all the data from the different groups are ranked together and in case that ties occur, then half of the rank they were about to receive is assigned to them. If all groups belong to the same population and do not show significant differences the averaged assigned rank for each group would be (N+1)/2, in case of equal group sizes. Therefore, this testing technique measures the difference or resemblance of the actual observed average ranks to the expected one.

The Zero condition Hypotheses is the same as the MMW test and the interpretation is based on the values of *Chi-Square*, the degrees of freedom *df* and the significance level which is represented by *Asymp. Sig.* If the latter is equal or less than 0.05, then there is statistically significant difference in the continuous variable among the different groups of the categorical value. In order to find which group had higher overall ranking the same procedure as the one in the MMW test should be followed, or to perform MMW tests between pairs of groups and also dividing the alpha level (significance criteria) by the number of tests that are going to take place (stricter alpha value).

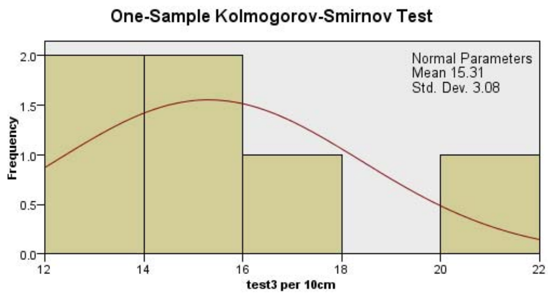
Appendix C

SPSS output for One sample Kolmogorov-Smirnov test

Test 3



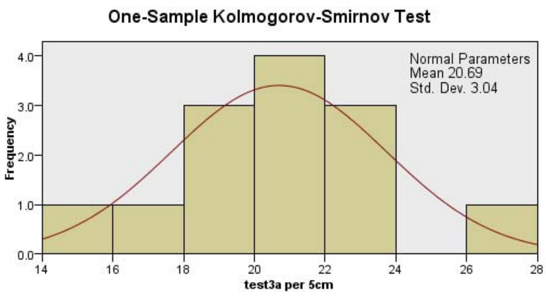
Total N		6
Most Extreme Differences	Absolute	.237
	Positive	.237
	Negative	-.147
Test Statistic		.581
Asymptotic Sig. (2-sided test)		.888



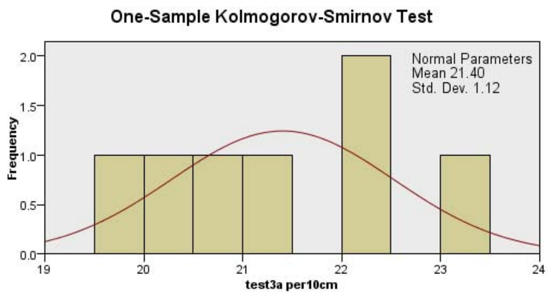
Total N		6
Most Extreme Differences	Absolute	.237
	Positive	.237
	Negative	-.147
Test Statistic		.581
Asymptotic Sig. (2-sided test)		.888

figure C-1 Structure 1, test 3, smooth fit

Test 3a



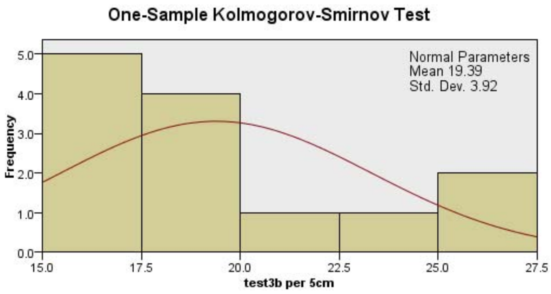
Total N		13
Most Extreme Differences	Absolute	.154
	Positive	.154
	Negative	-.101
Test Statistic		.556
Asymptotic Sig. (2-sided test)		.917

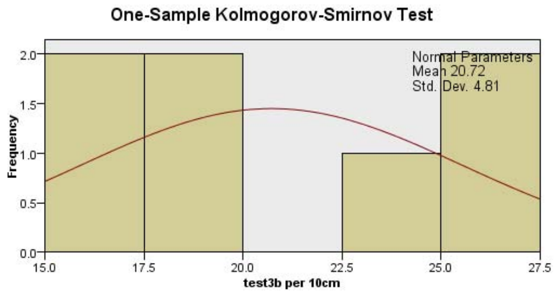


Total N		7
Most Extreme Differences	Absolute	.163
	Positive	.163
	Negative	-.158
Test Statistic		.431
Asymptotic Sig. (2-sided test)		.992

figure C-2 Structure 1, test 3a, smooth fit, measurements per 5cm/10cm

Test 3b



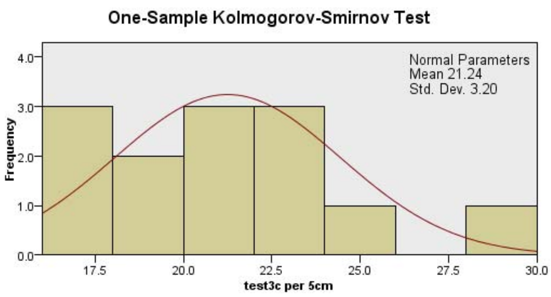


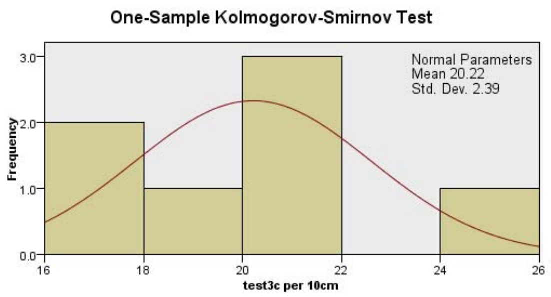
Total N		13
Most Extreme Differences	Absolute	.161
	Positive	.161
	Negative	-.139
Test Statistic		.581
Asymptotic Sig. (2-sided test)		.889

Total N		7
Most Extreme Differences	Absolute	.219
	Positive	.155
	Negative	-.219
Test Statistic		.578
Asymptotic Sig. (2-sided test)		.892

figure C-3 Structure 1, test 3b, smooth fit, measurements per 5cm/10cm

Test 3c



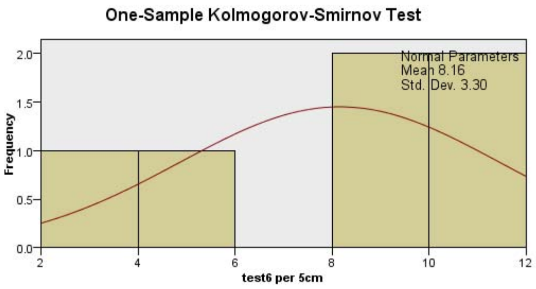


Total N		13
Most Extreme Differences	Absolute	.123
	Positive	.123
	Negative	-.116
Test Statistic		.443
Asymptotic Sig. (2-sided test)		.989

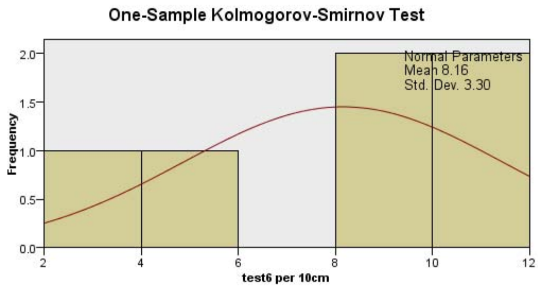
Total N		7
Most Extreme Differences	Absolute	.162
	Positive	.162
	Negative	-.134
Test Statistic		.428
Asymptotic Sig. (2-sided test)		.993

figure C-4 Structure 1, test 3c, smooth fit, measurements per 5cm/10cm

Test 6



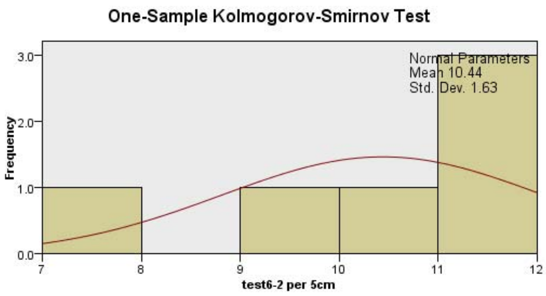
Total N		6
Most Extreme Differences	Absolute	.195
	Positive	.166
	Negative	-.195
Test Statistic		.477
Asymptotic Sig. (2-sided test)		.977



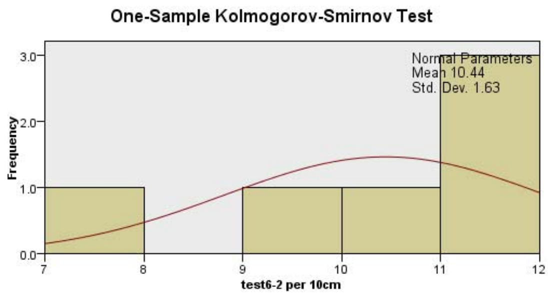
Total N		6
Most Extreme Differences	Absolute	.195
	Positive	.166
	Negative	-.195
Test Statistic		.477
Asymptotic Sig. (2-sided test)		.977

figure C-5 Structure 1, test 6, smooth fit

Test 6-2



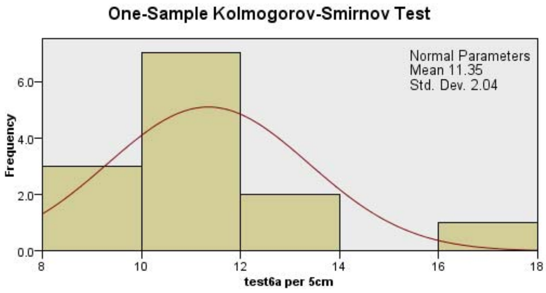
Total N		6
Most Extreme Differences	Absolute	.242
	Positive	.218
	Negative	-.242
Test Statistic		.593
Asymptotic Sig. (2-sided test)		.873

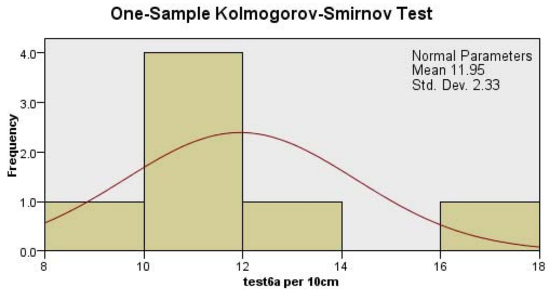


Total N		6
Most Extreme Differences	Absolute	.242
	Positive	.218
	Negative	-.242
Test Statistic		.593
Asymptotic Sig. (2-sided test)		.873

figure C-6 Structure 1, test 6-2, smooth fit, measurements per 5cm/10cm

Test 6a



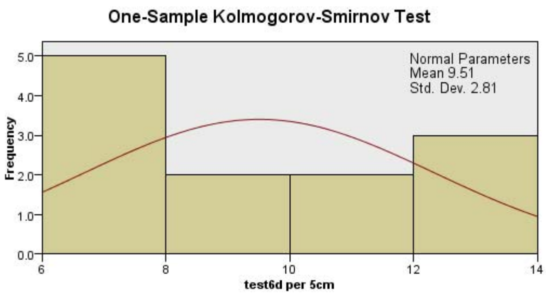


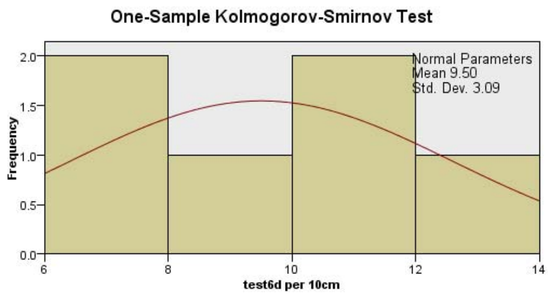
Total N		13
Most Extreme Differences	**Absolute**	.197
	Positive	.197
	Negative	-.104
Test Statistic		.711
Asymptotic Sig. (2-sided test)		.693

Total N		7
Most Extreme Differences	**Absolute**	.287
	Positive	.287
	Negative	-.204
Test Statistic		.761
Asymptotic Sig. (2-sided test)		.610

figure C-7 Structure 1, test 6a, smooth fit, measurements per 5cm/10cm

Test 6d



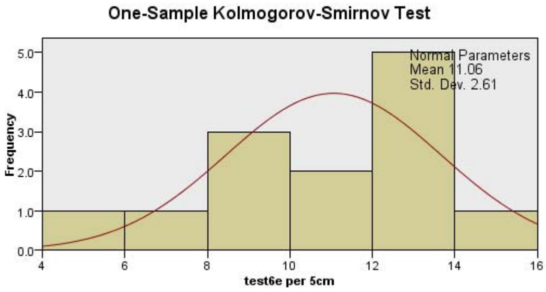


Total N		12
Most Extreme Differences	**Absolute**	.177
	Positive	.177
	Negative	-.134
Test Statistic		.612
Asymptotic Sig. (2-sided test)		.848

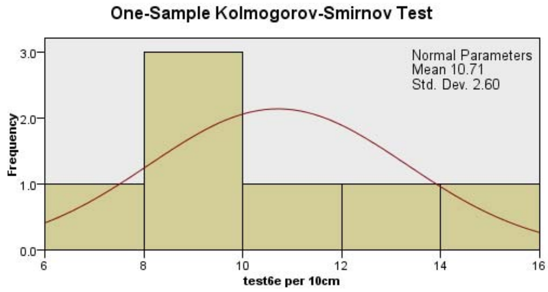
Total N		6
Most Extreme Differences	**Absolute**	.173
	Positive	.173
	Negative	-.135
Test Statistic		.424
Asymptotic Sig. (2-sided test)		.994

figure C-8 Structure 1, test 6d, smooth fit, measurements per 5cm/10cm

Test 6e



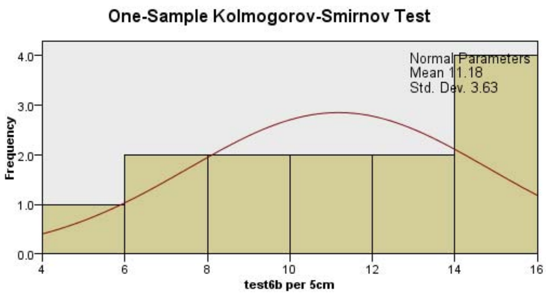
Total N		13
Most Extreme Differences	Absolute	.166
	Positive	.134
	Negative	-.166
Test Statistic		.600
Asymptotic Sig. (2-sided test)		.864



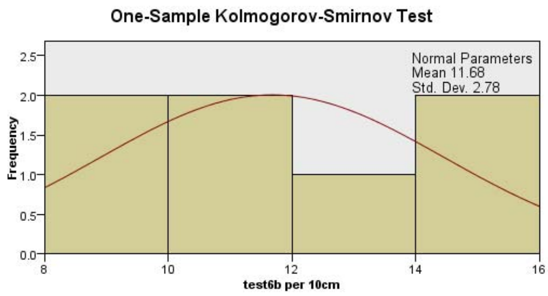
Total N		7
Most Extreme Differences	Absolute	.314
	Positive	.314
	Negative	-.179
Test Statistic		.831
Asymptotic Sig. (2-sided test)		.494

figure C-9 Structure 1, test 6e, smooth fit, measurements per 5cm/10cm

Test 6b



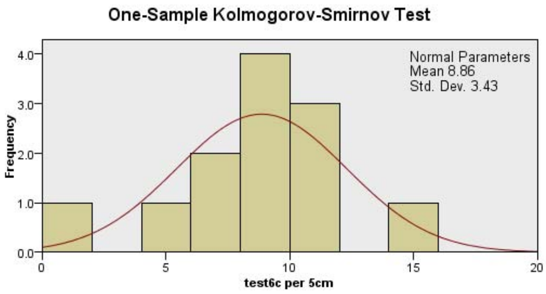
Total N		13
Most Extreme Differences	Absolute	.155
	Positive	.099
	Negative	-.155
Test Statistic		.560
Asymptotic Sig. (2-sided test)		.912



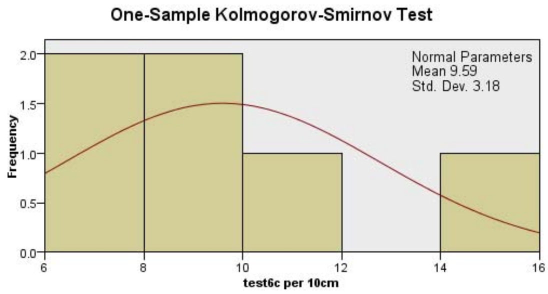
Total N		7
Most Extreme Differences	Absolute	.195
	Positive	.195
	Negative	-.163
Test Statistic		.517
Asymptotic Sig. (2-sided test)		.952

figure C-10 Structure 1, test 6b, smooth fit, measurements per 5cm/10cm

Test 6c



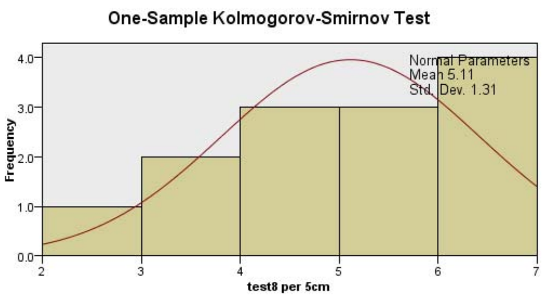
Total N		12
Most Extreme Differences	Absolute	.122
	Positive	.122
	Negative	-.108
Test Statistic		.423
Asymptotic Sig. (2-sided test)		.994



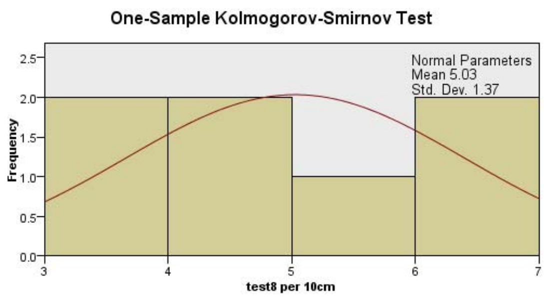
Total N		6
Most Extreme Differences	Absolute	.209
	Positive	.209
	Negative	-.152
Test Statistic		.511
Asymptotic Sig. (2-sided test)		.956

figure C-11 Structure 1, test 6c, smooth fit, measurements per 5cm/10cm

Test 8



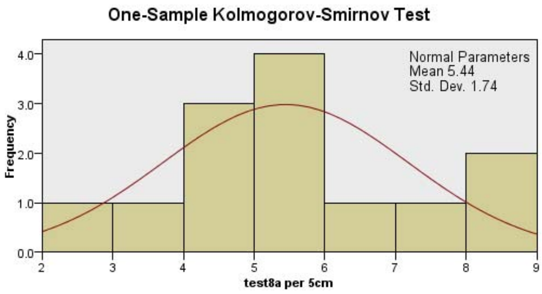
Total N		13
Most Extreme Differences	Absolute	.113
	Positive	.086
	Negative	-.113
Test Statistic		.409
Asymptotic Sig. (2-sided test)		.996



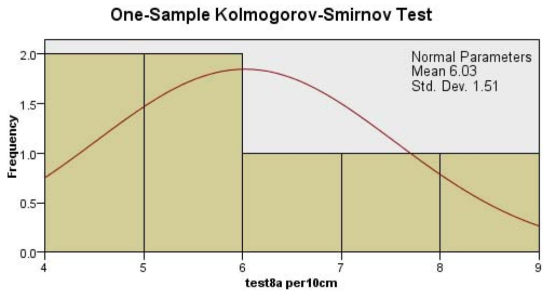
Total N		7
Most Extreme Differences	Absolute	.222
	Positive	.222
	Negative	-.184
Test Statistic		.588
Asymptotic Sig. (2-sided test)		.880

figure C-12 Structure 2, test 8, smooth fit, measurements per 5cm/10cm

Test 8a



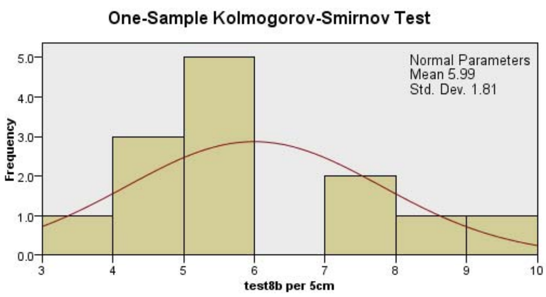
Total N		13
Most Extreme Differences	Absolute	.121
	Positive	.121
	Negative	-.098
Test Statistic		.436
Asymptotic Sig. (2-sided test)		.991



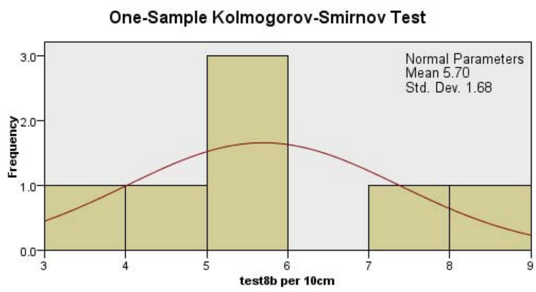
Total N		7
Most Extreme Differences	Absolute	.142
	Positive	.142
	Negative	-.120
Test Statistic		.375
Asymptotic Sig. (2-sided test)		.999

figure C-13 Structure 2, test 8a, smooth fit, measurements per 5cm/10cm

Test 8b



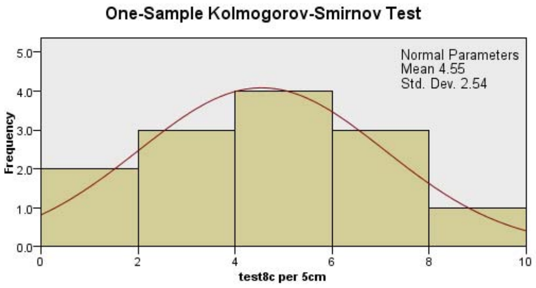
Total N		13
Most Extreme Differences	Absolute	.246
	Positive	.246
	Negative	-.090
Test Statistic		.886
Asymptotic Sig. (2-sided test)		.412



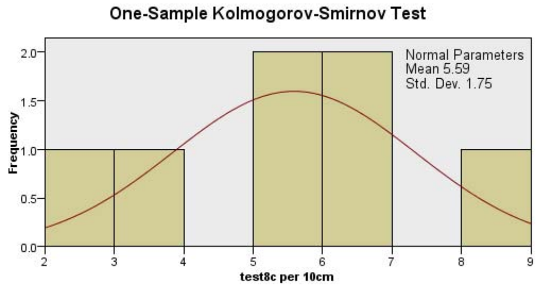
Total N		7
Most Extreme Differences	Absolute	.239
	Positive	.239
	Negative	-.133
Test Statistic		.633
Asymptotic Sig. (2-sided test)		.817

figure C-14 Structure 2, test 8b, smooth fit, measurements per 5cm/10cm

Test 8c



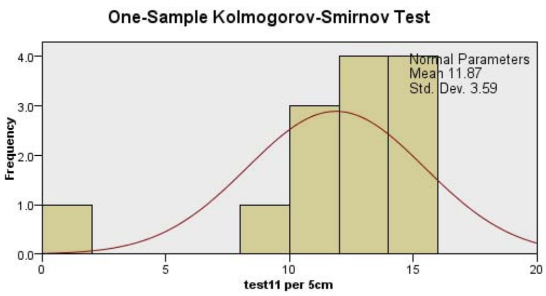
Total N		13
Most Extreme Differences	Absolute	.199
	Positive	.117
	Negative	-.199
Test Statistic		.716
Asymptotic Sig. (2-sided test)		.685



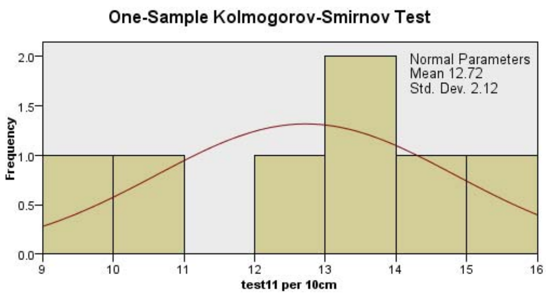
Total N		7
Most Extreme Differences	Absolute	.217
	Positive	.140
	Negative	-.217
Test Statistic		.575
Asymptotic Sig. (2-sided test)		.896

figure C-15 Structure 2, test 8c, smooth fit, measurements per 5cm/10cm

Test 11



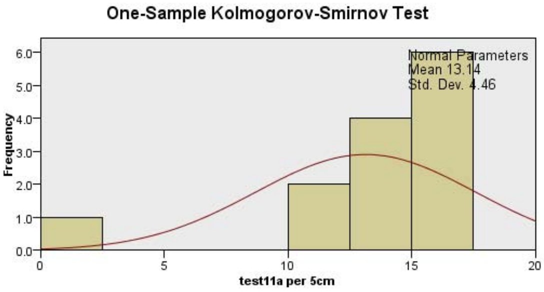
Total N		13
Most Extreme Differences	Absolute	.203
	Positive	.189
	Negative	-.203
Test Statistic		.732
Asymptotic Sig. (2-sided test)		.658



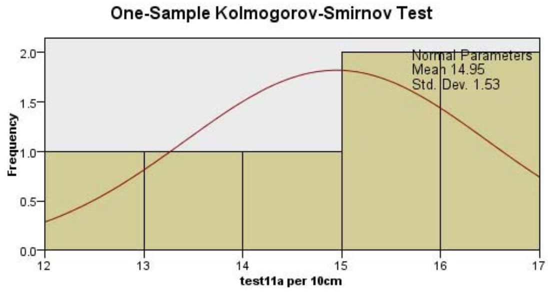
Total N		7
Most Extreme Differences	Absolute	.210
	Positive	.184
	Negative	-.210
Test Statistic		.556
Asymptotic Sig. (2-sided test)		.916

figure C-16 Structure 2, test 11, smooth fit, measurements per 5cm/10cm

Test 11a



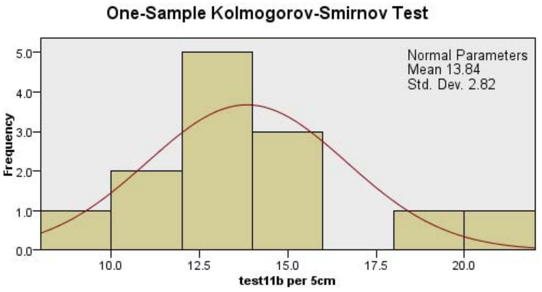
Total N		13
Most Extreme Differences	Absolute	.231
	Positive	.225
	Negative	-.231
Test Statistic		.833
Asymptotic Sig. (2-sided test)		.492



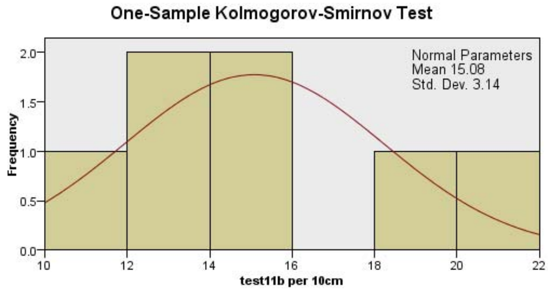
Total N		7
Most Extreme Differences	Absolute	.222
	Positive	.170
	Negative	-.222
Test Statistic		.587
Asymptotic Sig. (2-sided test)		.881

figure C-17 Structure 2, test 11a, smooth fit, measurements per 5cm/10cm

Test 11b



Total N		13
Most Extreme Differences	Absolute	.205
	Positive	.205
	Negative	-.108
Test Statistic		.738
Asymptotic Sig. (2-sided test)		.647

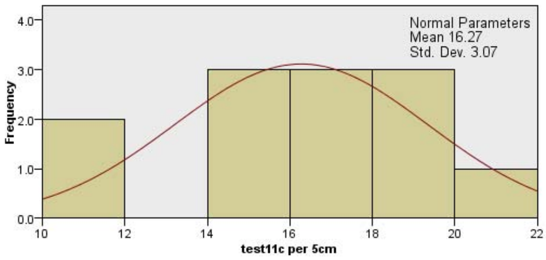


Total N		7
Most Extreme Differences	Absolute	.242
	Positive	.242
	Negative	-.161
Test Statistic		.641
Asymptotic Sig. (2-sided test)		.806

figure C-18 Structure 2, test 11b, smooth fit, measurements per 5cm/10cm

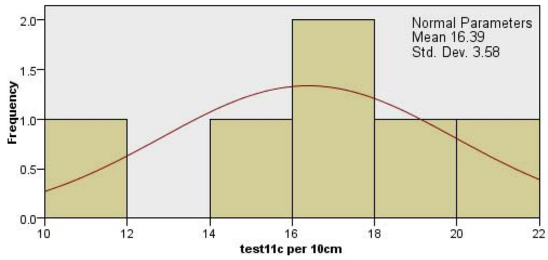
Test 11c

One-Sample Kolmogorov-Smirnov Test



Total N		12
Most Extreme Differences	Absolute	.120
	Positive	.105
	Negative	-.120
Test Statistic		.417
Asymptotic Sig. (2-sided test)		.995

One-Sample Kolmogorov-Smirnov Test

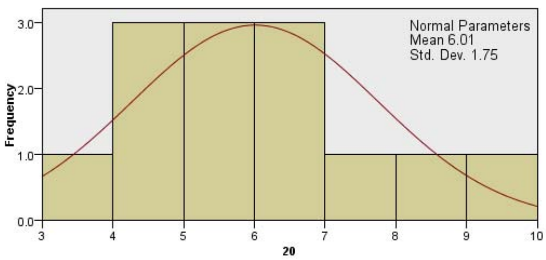


Total N		6
Most Extreme Differences	Absolute	.160
	Positive	.112
	Negative	-.160
Test Statistic		.392
Asymptotic Sig. (2-sided test)		.998

figure C-19 Structure 2, test 11c, smooth fit, measurements per 5cm/10cm

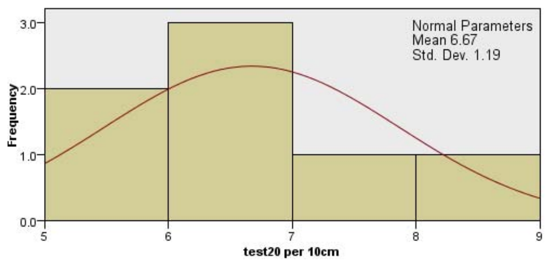
Test 20

One-Sample Kolmogorov-Smirnov Test



Total N		13
Most Extreme Differences	Absolute	.118
	Positive	.118
	Negative	-.094
Test Statistic		.424
Asymptotic Sig. (2-sided test)		.994

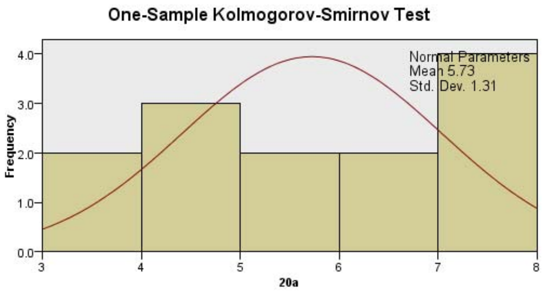
One-Sample Kolmogorov-Smirnov Test



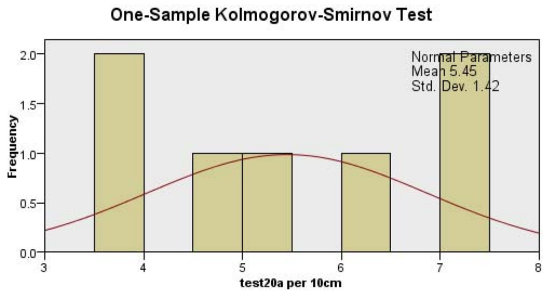
Total N		7
Most Extreme Differences	Absolute	.162
	Positive	.162
	Negative	-.139
Test Statistic		.428
Asymptotic Sig. (2-sided test)		.993

figure C-20 Structure 3, test 20, smooth fit, measurements per 5cm/10cm

Test 20a



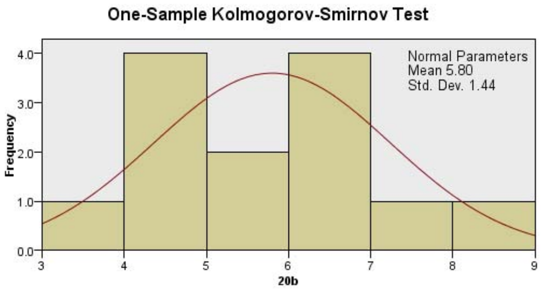
Total N		13
Most Extreme Differences	Absolute	.160
	Positive	.148
	Negative	-.160
Test Statistic		.577
Asymptotic Sig. (2-sided test)		.893



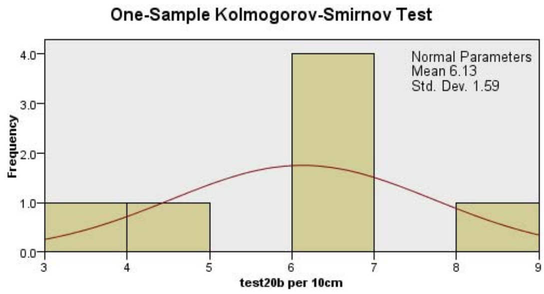
Total N		7
Most Extreme Differences	Absolute	.172
	Positive	.172
	Negative	-.164
Test Statistic		.455
Asymptotic Sig. (2-sided test)		.986

figure C-21 Structure 3, test 20a, smooth fit, measurements per 5cm/10cm

Test 20b



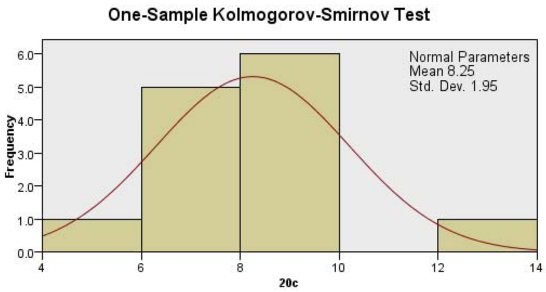
Total N		13
Most Extreme Differences	Absolute	.143
	Positive	.123
	Negative	-.143
Test Statistic		.517
Asymptotic Sig. (2-sided test)		.952



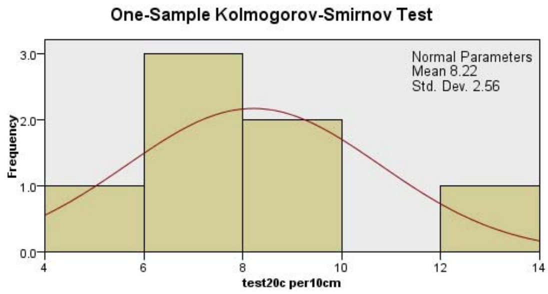
Total N		7
Most Extreme Differences	Absolute	.302
	Positive	.194
	Negative	-.302
Test Statistic		.799
Asymptotic Sig. (2-sided test)		.546

figure C-22 Structure 3, test 20b, smooth fit, measurements per 5cm/10cm

Test 20c



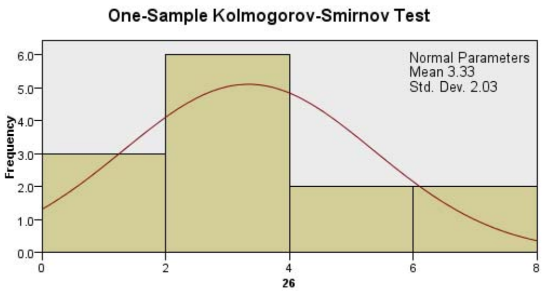
Total N		13
Most Extreme Differences	Absolute	.255
	Positive	.255
	Negative	-.157
Test Statistic		.920
Asymptotic Sig. (2-sided test)		.365



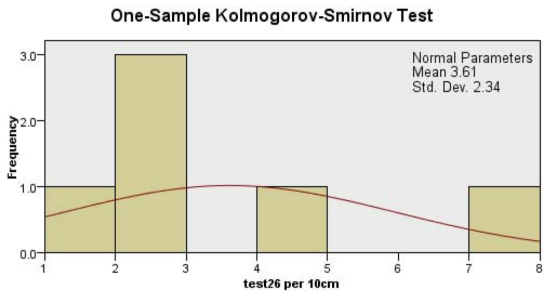
Total N		7
Most Extreme Differences	Absolute	.280
	Positive	.280
	Negative	-.137
Test Statistic		.740
Asymptotic Sig. (2-sided test)		.644

figure C-23 Structure 3, test 20c, smooth fit, measurements per 5cm/10cm

Test 26



Total N		13
Most Extreme Differences	Absolute	.146
	Positive	.146
	Negative	-.136
Test Statistic		.525
Asymptotic Sig. (2-sided test)		.946

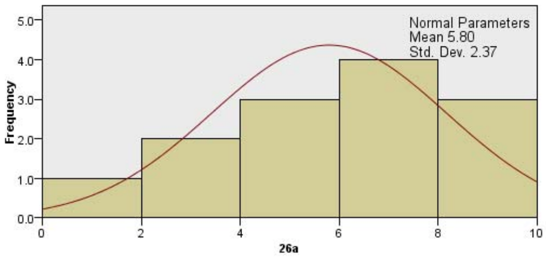


Total N		6
Most Extreme Differences	Absolute	.325
	Positive	.325
	Negative	-.209
Test Statistic		.795
Asymptotic Sig. (2-sided test)		.552

figure C-24 Structure 3, test 26, smooth fit, measurements per 5cm/10cm

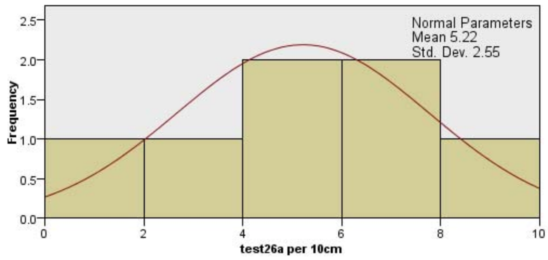
Test 26a

One-Sample Kolmogorov-Smirnov Test



Total N		13
Most Extreme Differences	Absolute	.156
	Positive	.122
	Negative	-.156
Test Statistic		.563
Asymptotic Sig. (2-sided test)		.909

One-Sample Kolmogorov-Smirnov Test

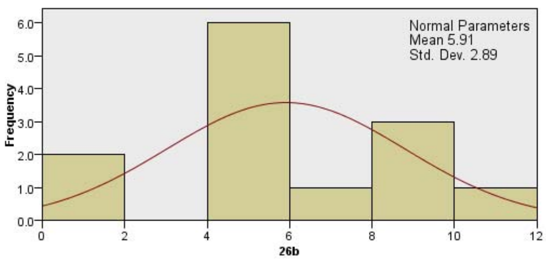


Total N		7
Most Extreme Differences	Absolute	.175
	Positive	.124
	Negative	-.175
Test Statistic		.464
Asymptotic Sig. (2-sided test)		.983

figure C-25 Structure 3, test 26a, smooth fit, measurements per 5cm/10cm

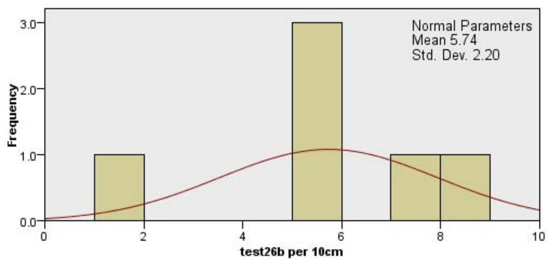
Test 26b

One-Sample Kolmogorov-Smirnov Test



Total N		13
Most Extreme Differences	Absolute	.176
	Positive	.106
	Negative	-.176
Test Statistic		.634
Asymptotic Sig. (2-sided test)		.816

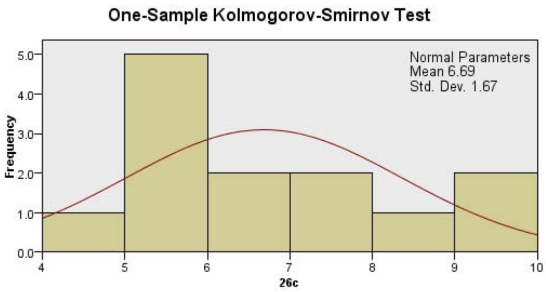
One-Sample Kolmogorov-Smirnov Test



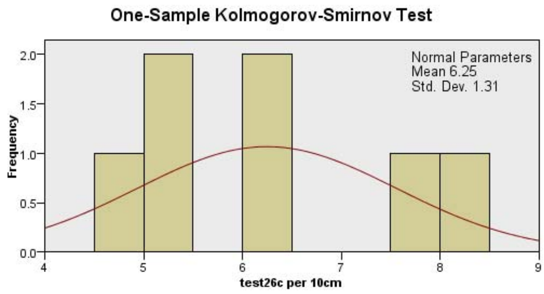
Total N		6
Most Extreme Differences	Absolute	.352
	Positive	.152
	Negative	-.352
Test Statistic		.863
Asymptotic Sig. (2-sided test)		.446

figure C-26 Structure 3, test 26b, smooth fit, measurements per 5cm/10cm

Test 26c



Total N		13
Most Extreme Differences	Absolute	.190
	Positive	.190
	Negative	-.124
Test Statistic		.685
Asymptotic Sig. (2-sided test)		.735



Total N		7
Most Extreme Differences	Absolute	.181
	Positive	.177
	Negative	-.181
Test Statistic		.480
Asymptotic Sig. (2-sided test)		.976

figure C-27 Structure 3, test 26c, smooth fit, measurements per 5cm/10cm

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