

# The use of high density concrete in the armourlayer of breakwaters

## Flume tests on high density concrete elements

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**PREFACE**

This report is part of my master thesis at Delft University of Technology, The Netherlands. It describes flume tests performed at WL| Delft Hydraulics during October 1999. The model tests investigate the behaviour of high-density concrete armour elements under wave attack.

In the first part of this report a general study on breakwater design in the past is given.

In the second part of this report the results of the model tests on high-density concrete elements are presented. A comparison with normal density concrete elements is made and a conclusion about the validity of stability formulae is drawn.

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## ABSTRACT

### Introduction

The stability of armour units is described by several formulae like Iribarren's, Hudson's and Van der Meer's. In these formulae the required weight of the armour elements depends strongly on the density of the used material. Therefore it may be useful to change this density. According to the stability formulae, higher density will result in lighter and smaller units. Smaller units may reduce the costs.

### Literature study

In all formulae the stability of armour elements is expressed by the dimensionless stability number  $H_s/\Delta D$ . This stability number is a function of several parameters like unit shape, placing method, slope angle etc. In this function  $\Delta$  or  $\rho$  are not present but there is a linear relation between  $H_s/D$  and  $\Delta$ .

Stability formulae for breakwater armour elements are based on model experiments with elements with densities up to approximately  $3200 \text{ kg/m}^3$ . In the past several improvements on stability formulae and breakwater design were made. Several different shapes of armour units were developed and wave spectra were introduced in flume testing. By these improvements the stability formulae are refined and validated.

Now it is possible to make concrete with a density up to  $4000 \text{ kg/m}^3$ . According to the stability formulae this will result in very small and light armour units. But the stability formulae are until now not validated for densities up to  $4000 \text{ kg/m}^3$ . It is not known whether the linear relation between  $H_s/D$  and  $\Delta$  is still valid for these densities or not. In order to investigate the validity of stability formulae and the linear relation between  $H_s/D$  and  $\Delta$  for high densities, experiments are recommended.

### Flume tests

During October 1999 flume tests on concrete elements with a density up to  $4000 \text{ kg/m}^3$  were performed in the Scheldt Basin of WL| Delft Hydraulics, location "de Voorst", The Netherlands. In order to investigate whether these high-density elements behave as expected and to compare the test results also tests with normal density (approximately  $2300 \text{ kg/m}^3$ ) were performed. The elements were attacked by irregular waves.

Elements were placed by hand as well as dumped on the slope. It is concluded that the high density and normal density concrete elements do behave in a different way during placing of the elements. High-density concrete elements tend to lay more random on a slope. In order to compare test results in a correct way a new criterion, called "laying-roughness" is developed.

### Conclusions

The following main conclusions are drawn:

- The high-density concrete elements in this investigation are under equal loading conditions at least as stable as the normal density concrete elements.
- The high-density concrete elements do behave as expected based on stability formulae.
- The linear relation between  $H_s/D$  and  $\Delta$  in the stability formulae for armour elements is still valid for densities up to  $4000 \text{ kg/m}^3$ .

<b>CONTENTS</b>	<b>page</b>
<b>PREFACE</b>	
<b>ABSTRACT</b>	
<b>CONTENTS.....</b>	<b>1</b>
<b>1 INTRODUCTION .....</b>	<b>4</b>
1.1 General .....	4
1.2 Problem.....	4
<b>2 BREAKWATER DESIGN.....</b>	<b>6</b>
2.1 General .....	6
2.2 Iribarren.....	6
2.3 Hudson.....	7
2.3.1 General .....	7
2.3.2 Tests set-up .....	7
2.3.3 Wave climate.....	8
2.3.4 Volume weights.....	8
2.3.5 Determination of damage .....	8
2.3.6 Conclusions.....	8
2.4 Van der Meer .....	8
2.4.1 General .....	8
2.4.2 Test set-up .....	8
2.4.3 Wave climate.....	8
2.4.4 Volume weights.....	9
2.4.5 Determination of damage .....	9
2.4.6 Conclusions.....	9
2.5 Comparison of formulae .....	10
<b>3 DEVELOPMENT OF ARMOUREMENTS IN BREAKWATERDESIGN .....</b>	<b>11</b>
3.1 General .....	11
3.2 High density Concrete .....	11
3.2.1 Expectations on High Density Concrete .....	11
3.2.2 Experiments with High Density Concrete.....	13
<b>4 CONCLUSIONS AND FORMULATION OF PROBLEM .....</b>	<b>15</b>
4.1 General .....	15
4.2 Tests .....	15

4.3	Type of elements.....	15
4.4	Comparing the results .....	16
<b>5</b>	<b>GEOMETRY OF STRUCTURE.....</b>	<b>18</b>
5.1	Introduction .....	18
5.2	Armourlayer and elements .....	18
5.3	Filterlayers.....	19
5.4	Slope angle .....	19
5.5	Crest-height.....	19
5.6	Foreshore and waterdepth .....	19
<b>6</b>	<b>TEST EQUIPMENT AND PROCEDURE.....</b>	<b>21</b>
<b>7</b>	<b>WAVE CLIMATE .....</b>	<b>22</b>
<b>8</b>	<b>TEST PROGRAM .....</b>	<b>23</b>
<b>9</b>	<b>RESULTS OF PLACING METHODS.....</b>	<b>25</b>
9.1	Problems.....	25
9.2	Roughness.....	25
9.3	Visualising the roughness.....	25
9.4	Conclusion .....	28
<b>10</b>	<b>TEST RESULTS .....</b>	<b>29</b>
10.1	Introduction .....	29
10.2	Normal density concrete elements .....	29
10.2.1	General .....	29
10.2.2	Stability curves .....	29
10.2.3	Discussion.....	30
10.3	High density concrete elements.....	30
10.3.1	General .....	30
10.3.2	Stability curves .....	30
10.3.3	Discussion.....	31
10.4	Comparing High Density to Normal Density Concrete elements.....	32
10.4.1	Introduction .....	32
10.4.2	Comparison based on “roughness of laying” criterion.....	32
10.4.3	Discussion.....	33

10.5	Validity of stability formulae for high densities .....	33
<b>11</b>	<b>CONCLUSIONS AND RECOMMENDATIONS .....</b>	<b>36</b>
11.1	Conclusions.....	36
11.2	Recommendations .....	36

**REFERENCES**

**LIST OF SYMBOLS**

**LIST OF TABLES**

**LIST OF FIGURES**

**LIST OF FORMULAE**

**APPENDIX A: CONSIDERATIONS AND DECISIONS**

**APPENDIX B: CROSS SECTION OF TESTED STRUCTURE**

**APPENDIX C: FILTER LAYERS AND CORE MATERIAL**

**APPENDIX D: SCHELDT BASIN AND PLACES OF WAVE GAUGES**

**APPENDIX E: RELATION DEEP WATER WAVE – SHALLOW WATER WAVE**

**APPENDIX F: EXCEEDANCE CURVES AND ENERGY DENSITY SPECTRA**

**APPENDIX G: TEST SCHEDULE AND TEST RESULTS**

**APPENDIX H: PICTURES OF SLOPES BEFORE AND AFTER TESTING**

**APPENDIX I: PICTURES USED FOR DETERMINING ROUGHNESS**

## 1 INTRODUCTION

### 1.1 General

“De Weger Architects and Consulting Engineers” and “MINELCO” (a Swedish supplier of magnetite) are interested in using concrete elements with a volume weight of approximately  $4000 \text{ kg/m}^3$  in the armourlayer of breakwaters. Such high densities can be reached by using magnetite (iron ore) as concrete aggregate.

The stability of armour units is described by several formulae like Iribarren's, Hudson's and Van der Meer's. In all formulae the stability of armour elements is expressed by the dimensionless stability number  $H_s/\Delta D$ . This stability number is a function of several parameters like unit shape, placing method, slope angle etc. In this function  $\Delta$  or  $\rho$  are not present but there is a linear relation between  $H_s/D$  and  $\Delta$ . According to the stability formulae, higher density will result in smaller and lighter units. Smaller units may reduce the costs.

*Example (Van 't Zelfde, [1998]):*

*Aveco has studied the effects if, in breakwaters at the “Maasvlakte”, blocks with a higher bulk density were used. This study shows that for concrete elements with a bulk density of  $2.2 \text{ tons/m}^3$ , elements with a weight of 42.5 tons will be required. With equal loading conditions concrete elements with a volume weight of  $4.0 \text{ tons/m}^3$ , only have to weigh 5 tons. Furthermore the layer thickness of the concrete elements reduces from 5.5 to 2.4 m.*

Stability formulae are based on experiments with elements with densities up to approximately  $3200 \text{ kg/m}^3$ . Uncertain is whether these formulae are valid for densities up to  $4000 \text{ kg/m}^3$  or not. An expectation of the behaviour of high-density units based on the formulae is therefore not enough. Experiments have to be taken to investigate the validity of stability formulae and the linear relation between  $H_s/\Delta D$  for densities up to  $4000 \text{ kg/m}^3$ .

### 1.2 Problem

The problem studied in this report is: Are stability formulae for breakwater armour elements still valid when high densities are used?

The aim of the investigation is to make a comparison between the stability of armour-elements of high-density concrete and normal density concrete and to draw a conclusion about the validity of stability formulae for elements with high density (up to  $4000 \text{ kg/m}^3$ ).

## **PART ONE LITERATURE STUDY**



## 2 BREAKWATER DESIGN

### 2.1 General

Breakwater design was for many years a question of trial and error. Short before WW II *Iribarren [1938]* developed a theoretical model for the stability of stones on a slope under wave attack.

Later *Hudson [1959]* performed experiments on stones and even tetrapodes to optimise the results found by Iribarren.

Where Iribarren focussed on a theoretical approach, assisted by some experiments, Hudson concentrated on collecting a large data set from hydraulic model experiments. In both cases experiments were carried out using then standard techniques. Both subjected models to regular, monochromatic, waves. Later others, like *Van der Meer [1988]*, discussed influences of factors not studied by Iribarren and Hudson like storm duration and wave period. They subjected models to irregular waves.

Model investigations are influenced by a lot of unaccounted irregularities and unknown variables. These variables are brought together in special coefficients depending on:

- shape of the block
- thickness of the armour layer
- manner of placing units
- roughness and interlocking capacity of the units
- type of wave attack
- head or trunk section of breakwater
- angle of incidence of wave attack
- size and porosity of underlying material
- crest level
- crest type
- wave period
- shape of foreshore

In this chapter a presentation of the different stability formulae is given. It describes the methods of deriving the formulae and their advantages and disadvantages.

### 2.2 Iribarren

Iribarren observed the forces acting on a unit on slope. He found some forces responsible for stability:

- weight of the unit
- buoyancy of the unit
- wave force
- frictional resistance

These forces can be brought to equilibrium. Iribarren developed a formula based on several parameters. The required weight is a function of parameters like unit-shape, breakwater slope and specific weight of the elements (*Iribarren, [1938]*).

Iribarren developed the following stability formula:

$$\frac{H_s}{\Delta D} = N^{-\frac{1}{3}} (\mu \cos \alpha \pm \sin \alpha) \quad \dots \dots \dots \text{formula 2.1}$$

In which:

$H_s$  = wave height (m)

$\Delta$  = relative density  $(\rho_r - \rho_w)/\rho_w$ ,  $\rho_w$  = density of water,  $\rho_r$  = density of unit (kg/m<sup>3</sup>)

$D$  = nominal diameter element,  $(W/\rho)^{1/3}$

$\mu$  = coefficient of friction

$\alpha$  = angle of slope

$N$  depends on the shape of the block and must be derived from model experiments, it is a function of the damage level.  $\mu$  can be determined as the angle of internal friction.

Iribarren's formula is not sufficient accurate to be used in designing rubble mound breakwaters unless it is used on conjunction with values of  $N$ .  $N$  varies appreciable with the coefficient of friction  $\mu$ . Values of  $\mu$  are difficult to obtain because  $\mu$  varies with armour unit shape and method of placing and even from test to test.

## 2.3 Hudson

### 2.3.1 General

Hudson wanted to develop a more general stability equation. He made an analytical study on wave attack on slopes and described characteristics of the motion of water particles when short-period wind waves encounter a rubble mound breakwater.

During experiments (since 1942 at U.S. Army Engineer Waterways Experiment Station, Vicksburg) Hudson found data about stability, porosity and thickness of armour layers of quarry-stone and tetrapodes.

The required weight of the armour units is according to Hudson a function of several parameters like shape of unit, breakwater slope and specific weight of element.

### 2.3.2 Tests set-up

In Hudson's test series (*Hudson [1959]*) design-wave heights were determined for breakwater sections of sufficient height to prevent overtopping. Design wave height is defined as the maximum wave height measured at the location of a proposed breakwater before it is constructed which will not damage the cover layer. "No damage" means the removal of up to one per cent of the total number of armour units in the cover layer.

The design wave heights for the no-damage criterion ( $H_{D=0}$ ) were determined by subjecting test sections to waves made successively higher until the maximum wave height was found that would not remove more than one per cent of the armour units from the cover layer.

### 2.3.3 Wave climate

Hudson performed experiments with regular waves. He did not take into account the statistic and random character of wave attack and storm duration. Therefore these parameters are not present in his formula.

### 2.3.4 Volume weights

The densities of the used materials in Hudson's tests were between 2146 kg/m<sup>3</sup> and 3076 kg/m<sup>3</sup>.

### 2.3.5 Determination of damage

Hudson related the removal of elements in the cover layer to the number of total elements in the area from 1 \*H<sub>s</sub> below still water level to 1\*H<sub>s</sub> above still water level. The removal of up to 1 percent is called "no damage".

### 2.3.6 Conclusions

Hudson developed the following stability formula for armour units:

$$\frac{H_s}{\Delta D} = (K_D \cot \alpha)^{\frac{1}{3}} \dots \dots \dots \text{formula 2.2}$$

The coefficient K<sub>D</sub> in the formula varies primarily with the shape of the unit and is a function of the damage level.

Hudson's formula is well known because of its simplicity. It can be used for designing breakwaters in an easy way.

Hudson developed his formula based on experiments taken with slopes from 1:1,5 to 1:4. Because of this, Hudson's formula can only be used within this interval.

## 2.4 Van der Meer

### 2.4.1 General

Between 1965 and 1970 several investigations were made on breakwater design because of shortcomings of Hudson's formula. It does e.g. not include the influence of the wave period and random waves. Some investigators like Ahrends, Pilarsky and de Boer showed the importance of the wave period, but their tests were performed with regular waves (*Van der Meer [1985]*). Others like Thompson and Shuttler investigated the influence of storm duration. It became possible to generate irregular waves and Thompson and Shuttler described the behaviour of breakwater units exposed to random waves. Instead of Ahrends c.s. they found no clear dependency on wave period. Van der Meer however found a clear dependency on wave period reanalysing their data.

### 2.4.2 Test set-up

Van der Meer performed lots of experiments because of his doctoral thesis. He investigated a lot of variables. Mostly all tests were performed using stones. He only performed a few tests with cubes (*Van der Meer [1986]*). These test were performed on slopes 1:1,5. The crest was of sufficient height to prevent overtopping at the start of damage.

Van der Meer placed cubes randomly on the slope by using a bucket. In this way the armour layer was build in horizontal layers from the toe up to the crest.

### 2.4.3 Wave climate

Van der Meer used irregular waves. He found an influence of the storm duration on static stability. After N (number of waves)=0 to N=500 or 1000 the damage increase reduces. According to Van der Meer it could be expected that after N=1000 the damage development is completed.

2.4.4 Volume weights

Van der Meer's tests were performed with stones of densities between 1950 kg/m<sup>3</sup> and 3050 kg/m<sup>3</sup>. The density of the cubes was 2340 kg/m<sup>3</sup>.

2.4.5 Determination of damage

Van der Meer used a clear and measurable definition of damage. He expressed the damage (S) by dividing the erosion area in the cross section by the nominal diameter of the stones ( $D_n = (W/\rho)^{1/3}$ ).

For tests with concrete cubes he used an other definition of damage. Damage was defined as the total number of cubes eroded within a width of one nominal diameter divided by the number of nominal diameters in a width of one meter, resulting in damage number  $N_{od}$ . Cubes displaced out of their coloured band were counted only (Van de Meer [1986]).  $N_{od} = 2$  is called failure.

2.4.6 Conclusions

Van der Meer developed several formulae for quarry stones, cubes, tetrapodes, doloses and accropodes.

The formula derived for concrete cubes attacked by irregular, plunging waves reads as follows:

$$\frac{H_s}{\Delta D} = \left( 6.7 \frac{N_{od}^{0.4}}{N^{0.3}} + 1.0 \right) s_{om}^{-0.1} \dots \dots \dots \text{formula 2.3}$$

In which:

$H_s$  =  $H_{1/3}$  or  $4\sqrt{m_0}$ , where  $m_0$  is the zeroth of the energy density spectrum. For deep-water conditions both definitions give almost the same values.

$s_{om}$  = the ratio between the wave-height at the toe of the construction and the wavelength, calculated for deep water ( $2\pi H_s/gT_m^2$ ). It is therefore a fictitious steepness.

$N_{od}$  = damage number (see Section 2.4.5)

D = nominal diameter concrete cube,  $(W/\rho)^{1/3}$

Van der Meer performed lots of experiments varying a large number of parameters. He found minimum stability for the transition from breaking (plunging) waves to non-breaking (surging) waves.

It is possible to put his formula in a figure by showing the damage number  $N_{od}$  to the dimensional stability number  $H_s/\Delta D$ . Figures of stability formulae with test results given by Van der Meer show a lot of scatter for the stability curves which include both the scatter to be expected in nature and the scatter due to the curve fitting. This scatter can be taken into account by the stability formula resulting in confidence bands.

The 90% confidence bands are drawn in Figure 2.1.

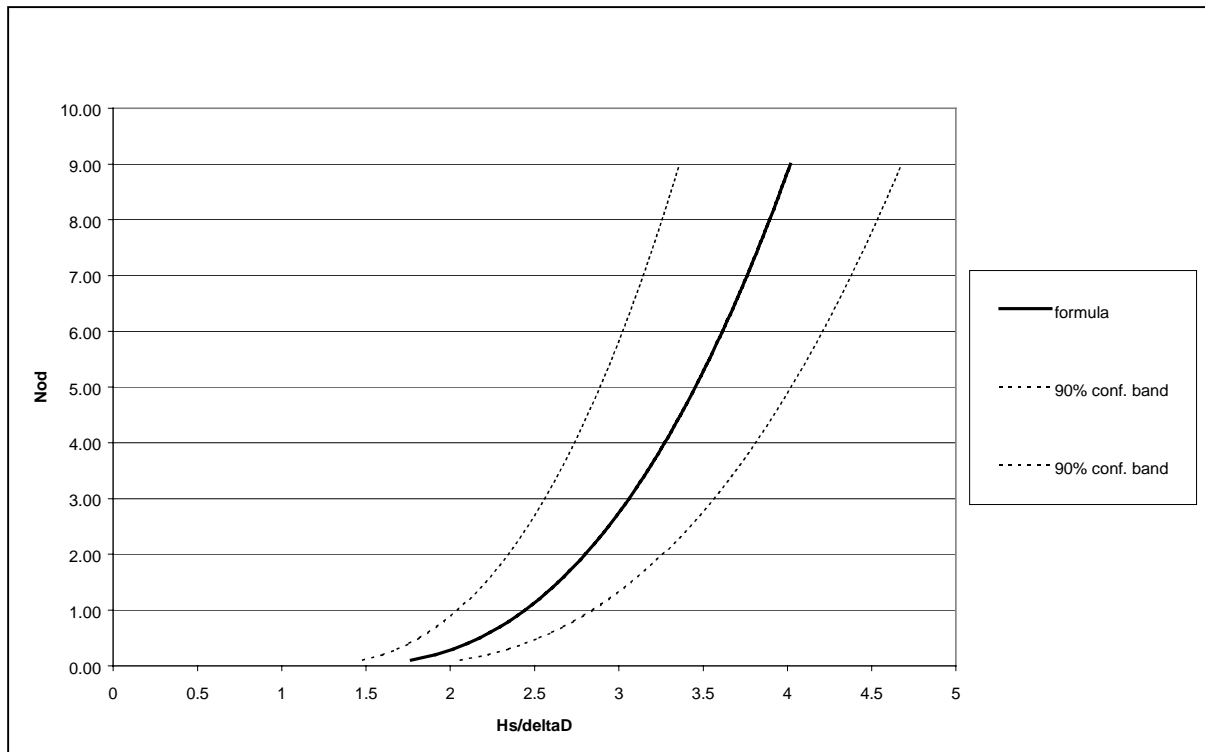


Figure 2.1: Van der Meer-formula for cubes with 90% confidence bands

## 2.5 Comparison of formulae

Comparing the stability formulae of the previous sections it is concluded that the stability of armour units in all formulae is expressed by the dimensionless stability number  $H_s/\Delta D$ . In all formulae the influence of wave height, element density and relative density is equal. In the formulae the stability number is a function of several parameters and depends on unit shape, placing method, slope angle et cetera, but not on  $\Delta$  or  $\rho$ . Although the function differs from formula to formula, in all formulae there is a linear relation between  $H_s/D$  and  $\Delta$ . Therefore a general stability formula reads as follows:

$$\frac{H_s}{D} = K_1 \cdot K_2 \cdots K_n \cdot \Delta^x \quad \dots \dots \dots \text{formula 2.4}$$

In which:

- $H_s$  = characteristic wave height
- $D$  = nominal diameter element
- $K_{1,2,n}$  = functions signifying the influence of slope angel, damage level, number of waves, wave period, etc.
- $\Delta$  = relative density  $(\rho_r - \rho_w)/\rho_w$ ,  $\rho_w$  = density of water,  $\rho_r$ = density of unit (kg/m<sup>3</sup>)
- $x$  = 1

### 3 DEVELOPMENT OF ARMOURELEMENTS IN BREAKWATERDESIGN

#### 3.1 General

It is recommended to continue the model work started by Iribarren, Hudson and Van der Meer in order to improve and refine the design formulae. It is also recommended to investigate the influence of parameters not investigated earlier on the stability of armour elements.

In order to improve stability of armour units several options can be investigated e.g.:

- increasing  $K_D$  in Hudson's formula by using special shaped units
- decreasing slope
- increasing density of used material

In the past, several different unit shapes are developed in order to increase  $K_D$ . Shapes developed are:

- tetrapode
- akmon
- dolos
- accropode
- quadripode
- tribar
- hexapod

The advantage of these elements is the high  $K_D$ -number for these elements in Hudson's formula. The higher the  $K_D$  number the less weight per unit will be required.

The effect of decreasing the slope can be calculated by the formula and is investigated by several experiments in the past.

The effect of changing the density of the used material is investigated by only a very few experiments in the past. In order to get more information about the influence of changing the density, more experiments are recommended.

#### 3.2 High density Concrete

##### 3.2.1 Expectations on High Density Concrete

Observing formula 2.4 it is seen that increasing the density of units with equal loading conditions will reduce the required size (and therefore the required weight) of the armour units.

The effect of the density on the resistance against wave action can be calculated and visualised by e.g. Hudson's formula.

In Figure 3.1 (Ito [1994]) the effect of the  $\rho_r/\rho_w$  (the density of the used material divided by the density of the water) on  $H/H_c$  (the design wave height by given  $\rho_r$  divided by the design wave height by standard  $\rho=2254 \text{ kg/m}^3$ ) is shown. In this figure the armour unit-size,  $K_D$  and the slope angel are constant. It is seen that the design wave height for armour units with  $\rho_r \approx 4000 \text{ kg/m}^3$  ( $\rho_r/\rho_w= 3$ ) is about 1,5 times the design wave height for armour units with normal concrete ( $\rho_r=2254 \text{ kg/m}^3$ ) of the same size.

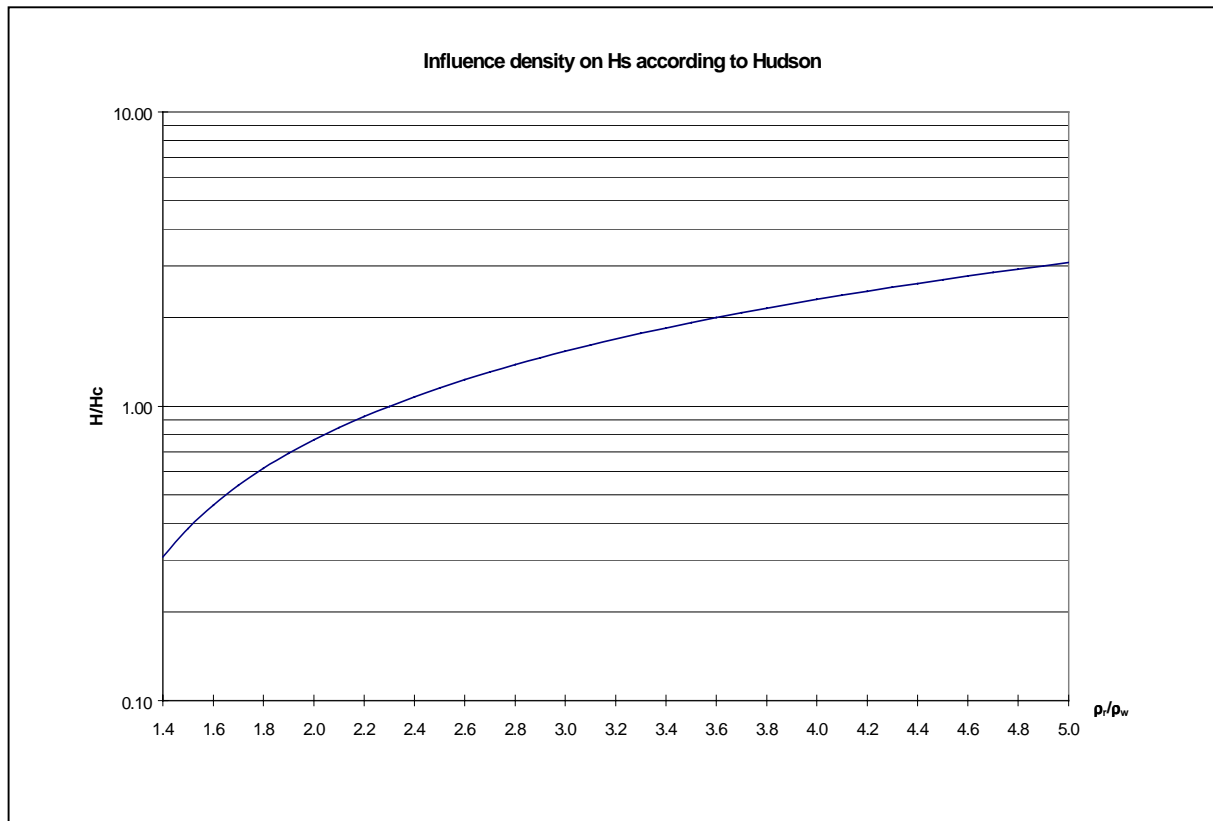


Figure 3.1: the effect of the density on the damage causing wave-height

It is possible to calculate the influence of using high-density material on the required sizes and weight of the elements.

The formulae mentioned in Chapter 2 express the stability in the dimensionless stability number  $H_s/\Delta D$ . Using this stability number it is possible to calculate the influence of changing the density of the used material on the sizes of the elements (for otherwise identical conditions):

$$\frac{H_s}{\Delta_1 D_1} = \frac{H_s}{\Delta_2 D_2}$$

That means a relation between  $D_1$  and  $D_2$ :

$$\frac{D_1}{D_2} = \frac{\Delta_2}{\Delta_1}$$

Using a density of  $4000 \text{ kg/m}^3$  in stead of  $2200 \text{ kg/m}^3$  results in the following  $\Delta_1$  and  $\Delta_2$ :

$$\Delta_1 = \frac{2200 - 1025}{1025} = 1,15$$

$$\Delta_2 = \frac{4000 - 1025}{1025} = 2,90$$

The nominal diameter of the units will then reduce by a factor:

$$\frac{D_1}{D_2} = \frac{2,90}{1,15} = 2,5$$

The weight will reduce by a factor:

$$\frac{W_1}{W_2} = \frac{D_1^2 \cdot \rho_1}{D_2^3 \cdot \rho_2} = \frac{2,5^3 \cdot 2200}{1^3 \cdot 4000} = 8,6$$

In Table 3.1 a comparison between armour units made of normal-density concrete and high-density concrete is given.

	$\rho = 2200\text{kg/m}^3$	$\rho = 4000\text{kg/m}^3$
W (weight)	100%	12%
V (volume)	100%	6%
$D_n$ (nominal diameter)	100%	40%
Layer thickness (2 elements)	100%	40%
Units/ $\text{m}^3$ (porosity 35%)	100%	1560%

Table 3.1: comparison between normal density and high density concrete elements

### 3.2.2 Experiments with High Density Concrete

As stated in Section 1.1 and 2.3 stability formulae are derived using concrete with standard densities. Therefore it is not known whether the formulae are valid for high densities or not. Reviewing the formulae it is not to be expected that high-density concrete will behave in a different way, but that is not sure. It is also possible that the relation between wave-height and size of unit become relevant by reducing the sizes of the armour units. Based on several formulae and theory of breakwaters nothing about the behaviour of high density concrete under wave attack, can be stated for sure. Therefore experiments must prove whether stability formulae are valid for high densities or not.

Until now only a few experiments with high-density concrete elements ( $\rho > \pm 3200 \text{ kg/m}^3$ ) are taken. Ito [1994] did some experiments with high-density tetrapodes. Densities in these tests were between  $17,8 \text{ kN/m}^3$  and  $42,8 \text{ kN/m}^3$ . The design wave height of these armour units was nearly similar. The damage of the tetrapodes of each different specific gravity should therefore be similar to each other. However, damage curves differed due to specific gravity. The damage-curves showed more damage for higher densities. Ito also showed the relationship between Hudson's stability coefficient  $K_D$ , and the specific gravity. In Hudson's formula the stability number should be constant because it should depend mainly on the shape of the armour unit and other parameters, but not on  $\Delta$ . Therefore the stability coefficient must be independent of the change of specific gravity. But  $K_D$  values showed by Ito scatter wildly for the different specific gravities. That means that, according to Ito's test results, the power of  $\Delta$  in the expression  $H_s/\Delta D$  is  $\neq 1$ .

Ito concluded that there is a relationship between  $K_D$  and the specific gravity.  $K_D$  decreases with increasing specific gravity. He also concluded that the stability of high specific gravity armour blocks in his investigation, was significantly affected by scale effects due to very small units.



In order to obtain more information about the behaviour of high-density concrete elements, more flume tests are recommended.

## 4 CONCLUSIONS AND FORMULATION OF PROBLEM

### 4.1 General

In the past several stability formulae have been derived and refined. All formulae were only validated for densities of max.  $3200 \text{ kg/m}^3$ . Now it is possible to make concrete with a density up to  $4000 \text{ kg/m}^3$  by using magnetite as aggregate. According to stability formulae it may be economic to use high-density concrete in the armourlayer of breakwaters.

In order to investigate the behaviour of high-density concrete elements, the validity of stability formulae and the linear relation between  $H_s/D$  and  $\Delta$  for high densities, flume test are recommended.

### 4.2 Tests

Tests with high-density concrete elements are to be compared with test with normal density concrete elements. Therefore test with high-density concrete elements must be similar to test with normal density concrete elements. In these tests only the difference in density is important. All other parameters should be constant.

### 4.3 Type of elements

Because of the fact no tests with high-density concrete elements have been carried out until now (except by *Ito[1994]*), high-density model elements are not available and are to be made. Cubes are the easiest to make; therefore cubes are the most likely elements to use in high-density concrete flume tests.

Iribarren and Hudson started testing on quarry run. Later cubes were introduced and after cubes elements characterised by great interlocking capacity. Stability of elements with great interlocking capacity is dictated by their weight and their interlocking capacity. The stability of cubes is dictated only by their weight and not by the capacity of interlocking.

Stability of elements can be expressed in contributions of weight, interlocking capacity and increase of density. The contribution of weight on the stability of normal density concrete elements is set at 100%. Using high density concrete the elements have to weigh only 12% of the weight of normal density concrete elements (see Table 3.1). This difference in weight is caused by the increase of density. The elements do have the same stability under identical conditions. It can be stated in that way that 12% of the stability of high density concrete elements comes from the contribution of weight and the other 88% from the contribution of the increase of density.

Using interlocking armour elements reduces the required weight as well. Part of the stability is then contributed by the weight and part by the interlocking capacity. It is possible to show the contribution of the interlocking capacity in the same way of showing the contribution of weight. In Figure 4.1 the contributions on stability of weight, interlocking capacity and increase of density is given for cubes ( $K_D = 6.8$ ), tetrapodes ( $K_D = 8.3$ ) and dolosses ( $K_D = 22$ ).

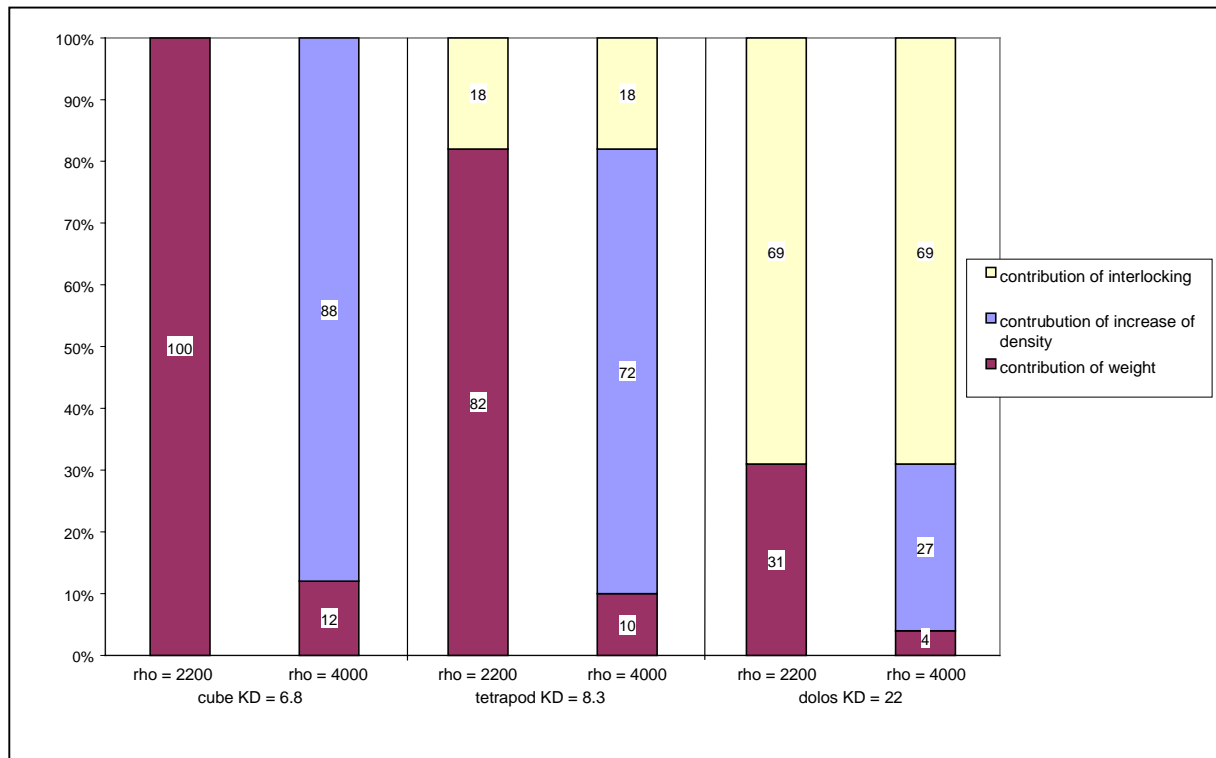


Figure 4.1: contributions on stability

It is seen from Figure 4.1 that the contribution of the increase of density on the stability decreases with increasing interlocking capacity. Therefore the effect of changing the density on the stability will be showed the best by elements without interlocking capacity. Tests with elements with interlocking capacity will show the effect of changing the density in a less absolute way. Therefore testresults on the effect of changing the density will be more sensitive for irregularities and model effects when elements with interlocking capacity will be used.

The sizes of high-density concrete model elements will be very small because of reduction of weight. Furthermore, the weight and sizes of elements will also reduce by using elements with interlocking capacity. Smaller elements will result in a smaller test scale. Using cubes (without interlocking capacity) results in the largest test-scale, minimising scale effects.

Summarising it is concluded that cubes are the most likely elements to use in model tests on the behaviour of high-density concrete elements.

#### 4.4 Comparing the results

In order to investigate whether high-density concrete elements perform in a minor or superior way normal density concrete elements do, the results of the tests must be compared.

Also results can be compared to expectations based on Hudson and Van der Meer. A conclusion about the validity of stability formulae for high densities can be made by investigating the relation between  $H_s/D$  and  $\Delta$ .

## **PART TWO FLUME TESTS**

## 5 GEOMETRY OF STRUCTURE

### 5.1 Introduction

In order to investigate the validity of stability formulae for high-density concrete, several tests were performed. The tests for this investigation were “theoretical” tests. That means no prototype was scaled. Elements were placed on a simple slope and attacked by waves of different height, in order to obtain a relation between wave-height and damage. In order to link up with current investigations the elements were attacked by irregular waves.

All tests were performed in the Scheldt Basin of WL| Delft Hydraulics, location the Voorst (see also Chapter 6).

One cross-section was used for the tests. This cross-section was subsequently used for tests with normal density elements as well as for tests with high-density elements. Because of the “theoretical” aspect of the study no breakwater-section was build but an “infinite” slope was used, preventing overtopping. In the following sections the dimensions and used materials are described. In Appendix A several decisions taken in the next sections are motivated. A drawing of the cross-section is given in Appendix B.

### 5.2 Armourlayer and elements

In order to investigate the effect of the density on the stability, models of two different densities were used. Model weights were obtained for each density using a constant Hudson design wave height. In that way the design wave height of the model elements becomes nearly equal, despite difference in density.

The used elements are cubes. A design wave height of 14 cm was used (dictated by the capacity of the flume), resulting in the elements of Table 5.1 (according to Hudson’s formula,  $K_D=6.8$ ,  $\cot\alpha=1.5$ ,  $\rho_w=1000 \text{ kg/m}^3$ ).

Element	$\gamma \text{ (kg/m}^3\text{)}$ (mean value)	W (kg) (mean value)	Dn (m)
1 (Normal Density Concrete)	2328 (var = 3.7%)	0.203 (var= 4.4%)	0.0443
2 (High Density Concrete)	3907 (var = 2.4%)	0.042 (var= 3.1%)	0.0221

Table 5.1: sizes and weights of used elements

All tests with normal density concrete elements were performed with elements number 1, all tests with high-density concrete elements were performed with elements number 2. In Figure 5.1 a picture of the elements is given.

The elements did have a different surface. Elements number 1 were made of



Figure 5.1: picture of model elements

epoxy and elements number 2 of cement with magnetite. Elements number 1

were painted. Elements number 2 were painted except the grey coloured one's (=1/6 of all elements). The painted elements number 2 were painted on five sides, one side was not painted. The painted and non-painted sides do have a slight difference in coefficient of friction. This is shown by a little experiment. Cubes of normal density and cubes of high density (painted as well as non-painted) were placed on a horizontal wooden board. While lifting one side of the board the slope angle at the start of movement was measured. The angles are listed in Table 5.2.

Nr.	NDC	HDC	
	painted	painted side	non-painted side
1	248	298	338
2	298	298	318
3	248	288	288
4	298	248	318
5	208	238	278
Average	26,88	26,18	32,48

Table 5.2: cubes on wooden board, angle at start of movement

### 5.3 Filterlayers

In total 3 different filter materials have been used (see also Table 5.3):

1. A filter layer between the required filter layer for tests with normal density concrete and the required filter layer for tests with high density concrete, used for tests with normal and high density concrete (filter1 see Appendix C).
2. A filter layer used only for test with high-density concrete (filter 2, see Appendix C).
3. A filter layer used only for test with normal density concrete (filter 3, see Appendix C)

	$D_{n50}$ (m)
Filter 1	0,012
Filter 2	0,008
Filter 3	0,019

Table 5.3: used filterlayers

The design process of the filter layers is described in Appendix A.

The core consisted of a huge amount of quarry run. This was granular material without specifications. This material was covered with a layer of about 15 cm of core-material with specifications of Appendix C.

### 5.4 Slope angle

Almost all slope angles applied by Hudson and Van der Meer were 1:1,5. This slope angle was also used in this investigation.

### 5.5 Crest-height

To prevent overtopping a high crest was used. The distance from the crown above still water level was equal to 1,5 times the maximum wave height and set at 0.30 m.

### 5.6 Foreshore and waterdepth

Waves were generated on deep water with a depth of 0,70 m. The waves reached the structure on a sloping foreshore. A straight slope of 1:110 was used as foreshore. This is a very flat slope in order to maintain deep-water conditions.

The waterdepth at the toe of the structure was 0,57 m, considered to be deep-water conditions.

## 6 TEST EQUIPMENT AND PROCEDURE

All tests have been performed in the “Scheldt Basin” at WL| Delft Hydraulics, location “de Voorst”. The size of the basin is 26,4 \* 14 meter. The structure was build on a distance of 21,90 meter from the wave-board in a 1 meter wide flume consisting of two walls 1,2 meter high (see Appendix D).

On deep water and at the structure, wave-heights were measured. Therefore three wave gauges were placed on deep water (5,00m; 5,46m and 5,78m from the waveboard) and three wave gauges at the toe of the construction (21,17m; 21,61m and 20,90m from the waveboard)(see Appendix D).

After all tests some tests without structure were taken in order to measure the wave-height at the place of the structure without reflection. Waves were measured on deep and shallow water. The relation between those two values is given in Appendix E. With this relation the wave height at the construction during testing was determined.

The armourlayer consisted of two layers of cubes. In order to compare the results of tests with different elements, the porosity of all tests was taken constant. For the tests with normal density cubes approximately 950 cubes ( $D_{n50} = 0,0443$  m) were placed on approximately  $0,127$  m<sup>3</sup>, resulting in a porosity of 35%  $[(1 - (950 * 0,0443^3) / 0,127) * 100\%]$ . For the tests with high density cubes approximately 3840 cubes ( $D_{n50} = 0,0221$  m) were placed on approximately  $0,063$  m<sup>3</sup>, resulting in a porosity of 34%  $[(1 - (3840 * 0,0221^3) / 0,063) * 100\%]$ . Van der Meer used for his tests with cubes a porosity of 33% (van der Meer [1986]).

Cubes were placed in coloured bands, two cubes wide. Two different placing methods were used:

1. *Placing*: cubes were placed by hand in horizontal layers from the toe up to the crest.
2. *Dumping*: the amount of cubes required for one coloured band was placed in a bucket. This bucket was emptied on the slope. The cubes were slightly rearranged by hand. In this way the armourlayer was also built in horizontal layers from the toe up to the crest.

In total 8 different test series were performed. Each test series consisted of 5 or 6 runs with increasing wave-heights but with the same wave-steepness, resulting in different wave-periods.

After each test, pictures were taken and damage was determined by counting cubes eroded within a width of one nominal diameter.

After runs of the same test series the armourlayer was not rebuilt. After each complete test series the armourlayer was removed and rebuilt.

In order to get reliable results, tests were repeated several times.



## 7 WAVE CLIMATE

In total 8 different test series were performed.

All tests were performed with irregular waves using standard JONSWAP-spectrum. An example of the exceedance curves and energy density spectra of wave gauge 2 is given in Appendix F.

Each test series consisted of 5 or 6 runs with different wave-heights but with similar wave-steepness, resulting in different wave-periods. In total 43 runs were performed.

The following waves were used:

1. 60% of design wave height
2. 80% of design wave height
3. 100% of design wave height
4. 120% of design wave height
5. 140% of design wave height
6. 160% of design wave height

The design wave for the normal density cubes and the high-density cubes as given in Section 4.2.1 are respectively 0,129 m and 0,140 m. The 100%-wave for the tests was set at 0,14 m.

All runs were performed with 1000 waves. According to Van der Meer the damage-development is completed then (see Section 2.4.3).

Van der Meer used the following stability-formula for cubes (see also Section 2.4):

$$\frac{H_s}{\Delta D} = \left( 6.7 \frac{N_{od}^{0.4}}{N^{0.3}} + 1.0 \right) s_{om}^{-0.1} \dots \dots \dots \text{formula 2.3}$$

The wave-steepness was taken constant for all runs. The wave-steepness on deep water ( $2\pi H_s/gT_p^2$ ) was set at 0,050% resulting in a fictitious steepness  $s_{om}$  at the construction ( $2\pi H_s/gT_m^2$ ) of approximately 0,059% (using measured values).

Van der Meer [1988] found minimum stability for the transition from breaking (plunging) waves to non-breaking (surging) waves. The breakertype is defined by the breaker parameter  $\xi = \tan \alpha/\sqrt{s}$ . Transition from plunging to surging waves is found for  $\xi = 2,5$  to 3,5. This region was derived for quarry run and is also to a less extent applicable for cubes. The breaker parameter  $\xi$  for the tests in this investigation is 3,0 and in the region of minimum stability.

## 8 TEST PROGRAM

Six different types of profiles were attacked by waves in 8 different test series:

1. Slope covered with dumped normal density cubes, filter 1 (series T1000)
2. Slope covered with dumped high density cubes, filter 1 (series T2000)
3. Slope covered with dumped high density cubes, filter 2 (series T3000 and T5000)
4. Slope covered with placed high density cubes, filter 2 (series T4000 and T6000)
5. Slope covered with placed normal density cubes, filter 3 (series T7000)
6. Slope covered with dumped normal density cubes, filter 3 (series T8000)

The tests are performed according the test-schedule of Table 8.1:

Test number	Placing method	Gamma (kg/m <sup>3</sup> )	Dn	$\Delta$	Wave %	Duration(min)
<b>filter 1</b>						
T1002	Dumped	2328	0.0443	1.328	80	18
T1003	Dumped	2328	0.0443	1.328	100	19
T1004	Dumped	2328	0.0443	1.328	120	21
T1005	Dumped	2328	0.0443	1.328	140	22
T2001	Dumped	3910	0.0221	2.91	60	14
T2002	Dumped	3910	0.0221	2.91	80	17
T2003	Dumped	3910	0.0221	2.91	100	19
T2004	Dumped	3910	0.0221	2.91	120	21
T2005	Dumped	3910	0.0221	2.91	140	22
<b>filter 2</b>						
T3001	Dumped	3910	0.0221	2.91	60	14
T3002	Dumped	3910	0.0221	2.91	80	17
T3003	Dumped	3910	0.0221	2.91	100	19
T3004	Dumped	3910	0.0221	2.91	120	21
T3005	Dumped	3910	0.0221	2.91	140	22
T4001	Placed	3910	0.0221	2.91	60	14
T4002	Placed	3910	0.0221	2.91	80	17
T4003	Placed	3910	0.0221	2.91	100	19
T4004	Placed	3910	0.0221	2.91	120	21
T4005	Placed	3910	0.0221	2.91	140	22
T4006	Placed	3910	0.0221	2.91	160	24
T5001	Dumped	3910	0.0221	2.91	60	14
T5002	Dumped	3910	0.0221	2.91	80	17
T5003	Dumped	3910	0.0221	2.91	100	19
T5004	Dumped	3910	0.0221	2.91	120	21
T5005	Dumped	3910	0.0221	2.91	140	22
T6001	Placed	3910	0.0221	2.91	60	14
T6002	Placed	3910	0.0221	2.91	80	17
T6003	Placed	3910	0.0221	2.91	100	19
T6004	Placed	3910	0.0221	2.91	120	21
T6005	Placed	3910	0.0221	2.91	140	22
T6006	Placed	3910	0.0221	2.91	160	24
<b>filter 3</b>						
	Placed					

T7001	Placed	2328	0.0443	1.328	60	14
T7002	Placed	2328	0.0443	1.328	80	17
T7003	Placed	2328	0.0443	1.328	100	19
T7004	Placed	2328	0.0443	1.328	120	21
T7005	Placed	2328	0.0443	1.328	140	22
T7006	Placed	2328	0.0443	1.328	160	24
T8001	Dumped	2328	0.0443	1.328	60	14
T8002	Dumped	2328	0.0443	1.328	80	17
T8003	Dumped	2328	0.0443	1.328	100	19
T8004	Dumped	2328	0.0443	1.328	120	21
T8005	Dumped	2328	0.0443	1.328	140	22

*Table 8.1: test program*

In Appendix G the test-schedule is given with the results of wave measuring, measured periods, number of displaced cubes and the damage numbers.

In Appendix H several pictures of slopes before and after testing are given.

## 9 RESULTS OF PLACING METHODS

### 9.1 Problems

Cubes of both densities were placed as well as dumped. During placing the high-density concrete elements and the normal density concrete elements behaved in a different way. The normal density cubes settled after placing by hand, resulting in a very constant placing pattern. Placing high-density cubes by hand did not show this. High-density cubes did remain in exactly the same position as they were placed. Therefore after placing, these elements did lay more random. High-density cubes did not tend to settle after placing. This was also observed when cubes where dumped. High-density concrete elements dumped on the slope did lay much more random than normal density concrete elements. This problem is possibly caused by the different coefficient of friction of the used materials (see also Section 5.2.1).

### 9.2 Roughness

The method of placing is not important for the stability of the elements. Cubes “do not know” in what way there were placed. The way cubes are laying on the slope is however very important for the stability. The roughness of laying does influence the mobility and therefore the stability of the cubes. By translating the way cubes are laying on a slope in the “roughness of laying”, it is possible to compare cubes which do lay in the same way on the slope to each other.

### 9.3 Visualising the roughness

In Figures 9.1 and 9.3 a method of visualising the roughness of a slope covered with cubes is shown. Pictures of slopes covered with normal and high-density elements by hand and by bucket were compared. The pictures of high-density concrete elements were enlarged until these elements were as big as the normal density elements. A sheet was placed on the pictures. Lines were drawn between the coloured bands. This resulted in Figure 9.1A - 9.1D.

(for figures see appendix I)

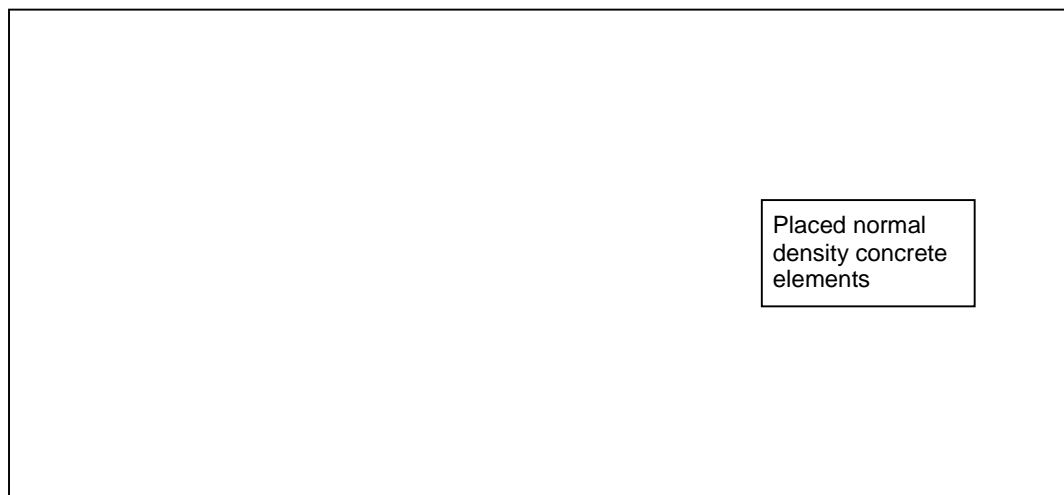
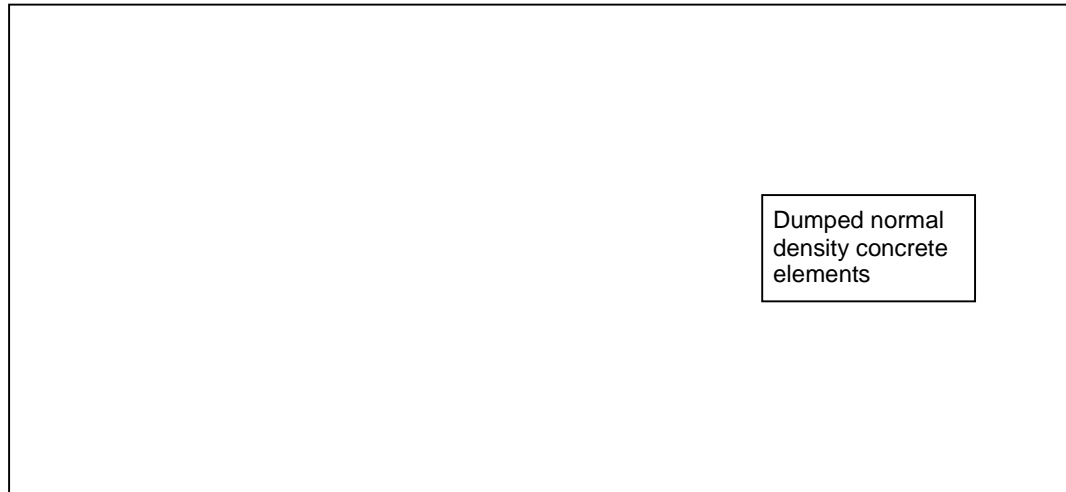
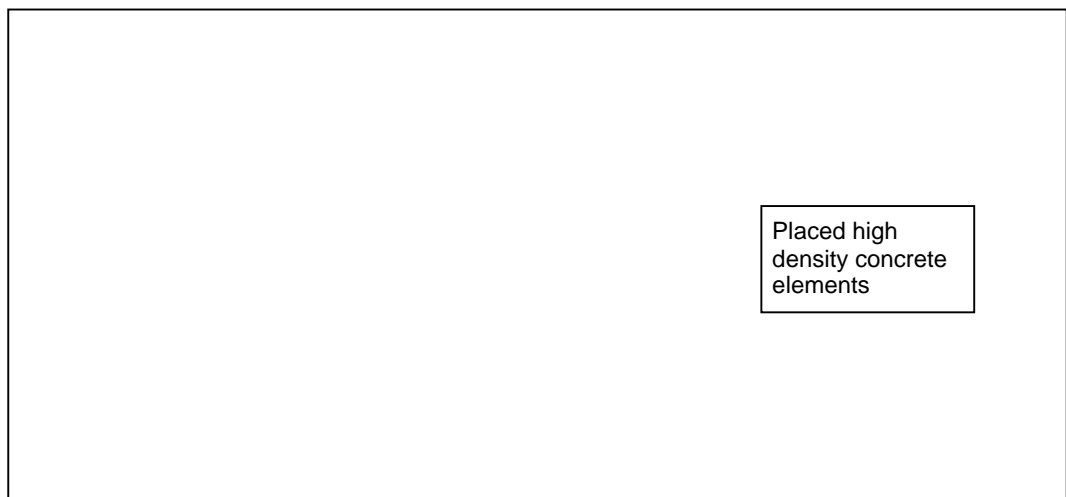


Figure 9.1A: roughness of cubes laying on the slope, lines between coulored bands



*Figure 9.1B: roughness of cubes laying on the slope, lines between colored bands*



*Figure 9.1C: roughness of cubes laying on the slope, lines between colored bands*



*Figure 9.1D: roughness of cubes laying on the slope, lines between colored bands*

Another sheet was placed on the pictures and all elements were copied on the sheet. Elements positioned in the way of Figure 9.2A (flat) were kept white, elements positioned in the ways of Figure 9.2B (rough) were painted black. For figures see appendix I

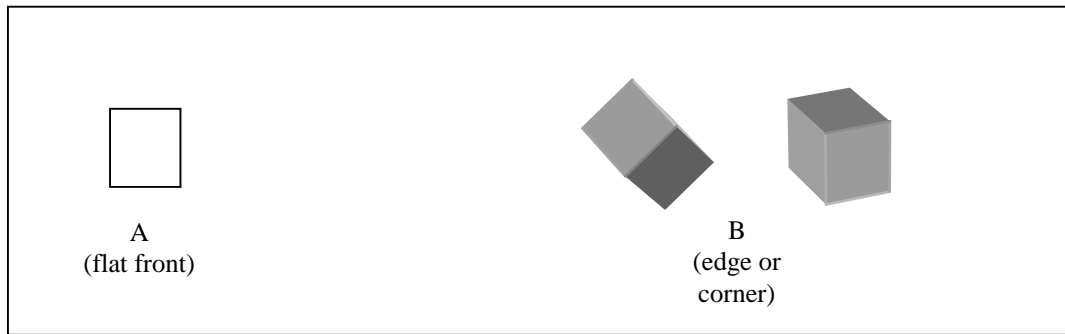


Figure 9.2: positions of cubes on the slope

This results in Figure 9.3A – 9.3D.

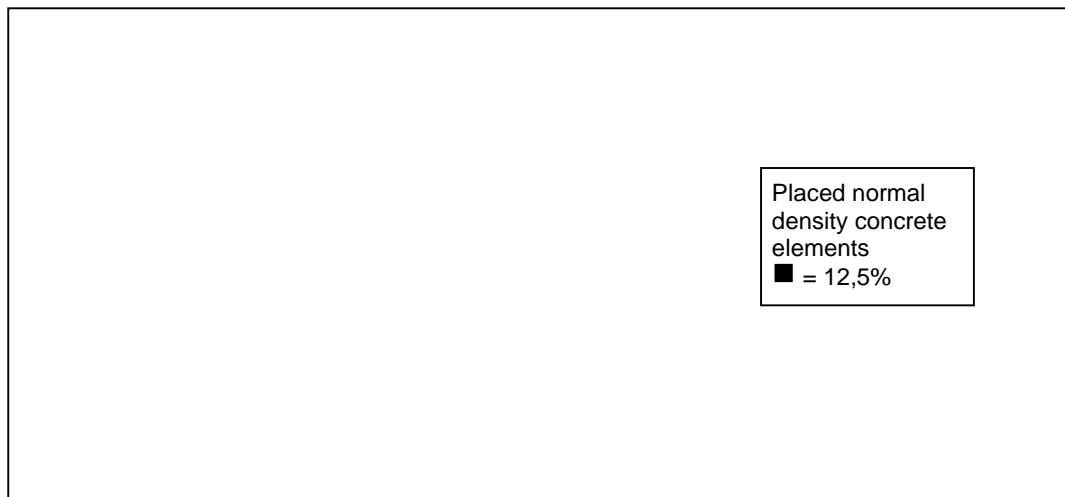


Figure 9.3A: roughness of cubes laying on the slope, percentage of rough laying cubes

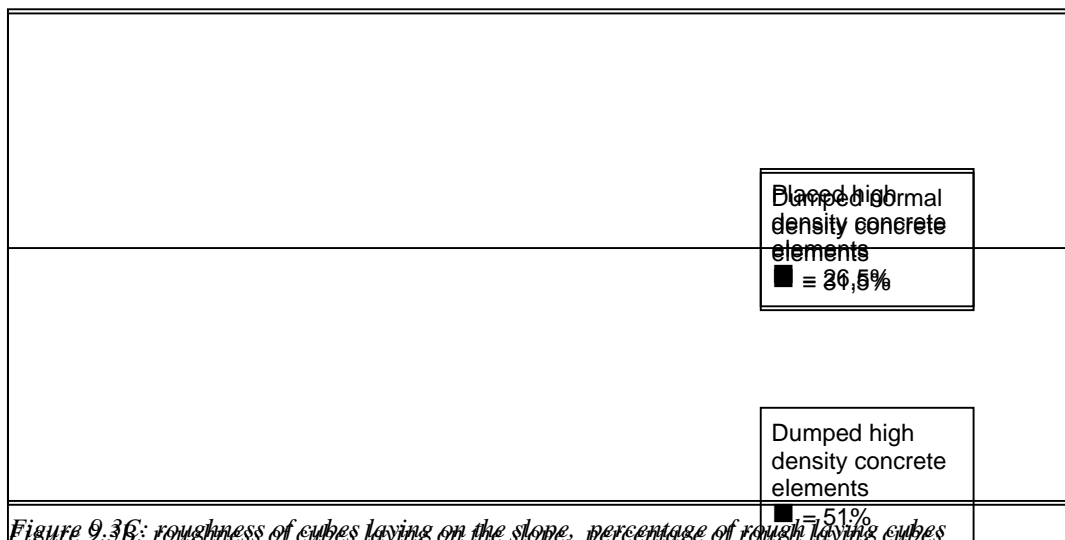


Figure 9.3B: roughness of cubes laying on the slope, percentage of rough laying cubes

Figure 9.3D: roughness of cubes laying on the slope, percentage of rough laying cubes

In this way a new parameter is introduced called “laying-roughness” which can be shown by above-mentioned methods. It must be mentioned that the way of determining the roughness in this section is a comparative way of determining. Although it is not an absolute way, the shown trend is consistent. By repeating the described method (also by different people) the same trend was shown.

#### **9.4 Conclusion**

It is seen from Figures 9.1 and 9.3 that the same method of placing did not result in the same laying-roughness for both element-types. Dumped high-density cubes did lay more random than normal density cubes placed in the same way. High-density cubes placed by hand did also lay more random than normal density cubes placed by hand. High-density cubes placed by hand did lay almost as random as normal density cubes placed by bucket.

The pictures and copied areas of the pictures used for the visualisation of Figures 9.1 and 9.3 are presented in Appendix I.

## 10 TEST RESULTS

### 10.1 Introduction

In this chapter the test results are presented. Aim of the project is to compare the test results of normal and high density concrete elements to each other and to investigate whether the linear relation between  $H_s/D$  and  $\Delta$  is still valid for high densities or not.

In Sections 10.2 and 10.3 stability curves for normal density concrete respectively high density concrete elements are presented. In these sections the results are also compared to Van der Meer's and Hudson's expectations .

In Section 10.4 the comparable stability curves for normal and high density concrete elements are presented. These stability curves are in Section 10.5 used to investigate the linear relation between  $H_s/D$  and  $\Delta$ .

### 10.2 Normal density concrete elements

#### 10.2.1 General

In total 3 test series with normal density concrete elements were performed (T1000, T7000, T8000). Series T1000 and T8000 did have the same placing method but different filter. Series T7000 and T8000 did have the same filter layer but different placing method.

#### 10.2.2 Stability curves

By showing  $N_{od}$  (see Section 2.4.5) to the dimensionless stability number  $H_s/\Delta D_n$  it is possible to visualise the test results. In Figure 10.1 the results and the expectations according to Van der Meer's formula are given. In this investigation  $H_s = 4\sqrt{m_0}$  is used.

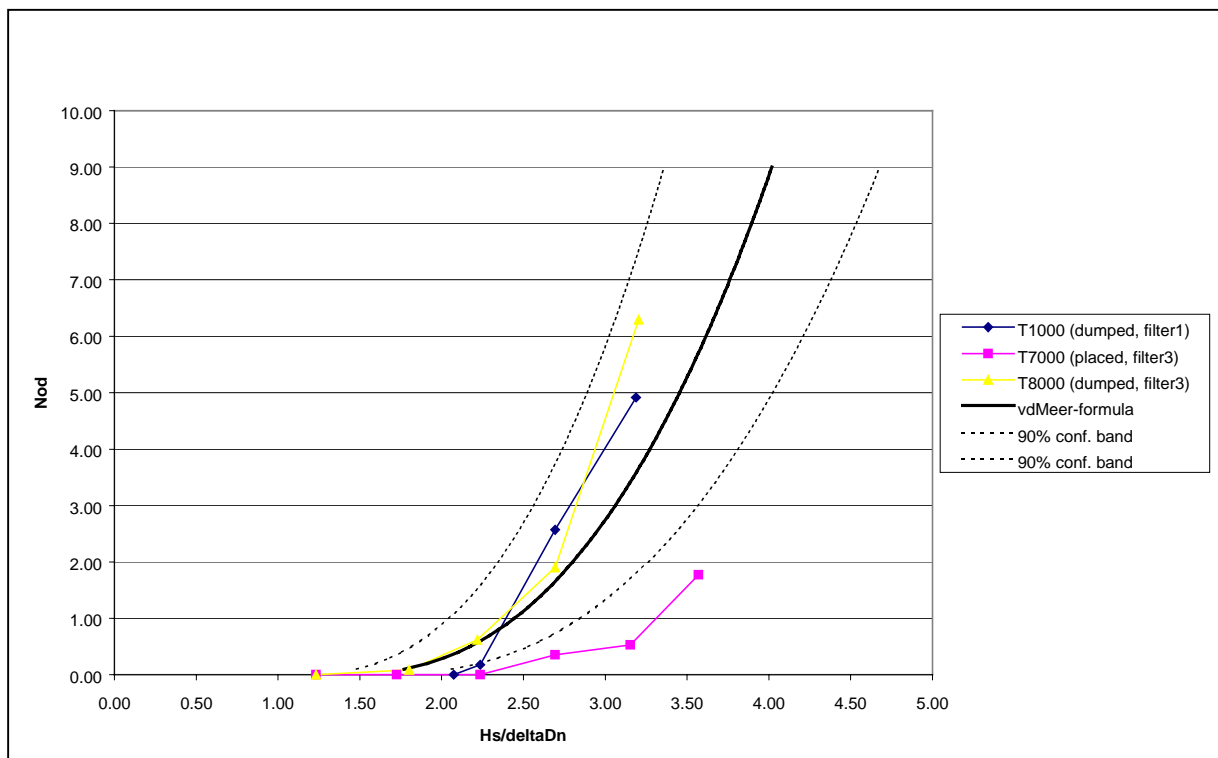


Figure 10.1: stability curves Normal Density Concrete elements



The weight and sizes of the used cubes as given in Section 4.2.1 have been calculated with Hudson's formula. The used  $K_D$  value was 6.8 corresponding with the removal of 0-5% of all elements in the cover layer. Hudson used a cover layer from  $1 \cdot H_s$  below still water level to  $1 \cdot H_s$  above still water level.

In this investigation cubes were laying on the slope from  $2 \cdot H_s$  below still water level to  $1,5 \cdot H_s$  above still water level. It was seen after the tests that almost all displaced cubes were cubes laying in the area of  $1 \cdot H_s$  below still water level to  $1 \cdot H_s$  above still water level. The design wave of the normal density cubes according to Hudson is 0,129 m, resulting in a stability number of 2,2. Test series T1000, T7000 and T8000 showed for that stability number a removal of 1.1%, 0% and 3.6% of all cubes in the area from  $1 \cdot H_s$  below still water level to  $1 \cdot H_s$  above still water level.

### 10.2.3 Discussion

It is seen from Figure 10.1 that placing cubes by hand resulted in less damage than expected based on Van der Meer's investigations. This is explained by the fact Van der Meer placed his cubes not by hand but with a bucket. By placing cubes by hand they lay less random and therefore more stable. Test-results for cubes dumped on the slope are according to the expectations and within the 90% confidence bands.

There is a slight difference between results with filter 1 and filter 3. By "failure" ( $N_{od} = 2$ ) cubes on filter 3 are a little bit more stable. This is explained by the fact that filter 3 is more suited for the cubes (see Section 5.3) and  $D_{n50}$  of filter 1 is too small. A filter with a larger  $D_{n50}$  may result in a better embedding of the armourlayer.

All tests show a removal of 0% - 5% of all elements in the area of  $1 \cdot H_s$  below still water level to  $1 \cdot H_s$  above still water level, according to Hudson's expectations.

## 10.3 High density concrete elements

### 10.3.1 General

In total 5 test series with high-density concrete elements were performed (T2000 – T6000). Series T2000, T3000 and T5000 did have the same placing method but T2000 a different filter. Series T4000 and T6000 did have the same filter layer but different placing method.

### 10.3.2 Stability curves

By showing  $N_{od}$  (see Section 2.4.5) to the dimensionless stability number  $H_s/\Delta D_n$  it is possible to visualise the test results. In Figure 10.2 the results and the expectations according to Van der Meer's formula are given. In this investigation  $H_s = 4\sqrt{m_0}$  is used.

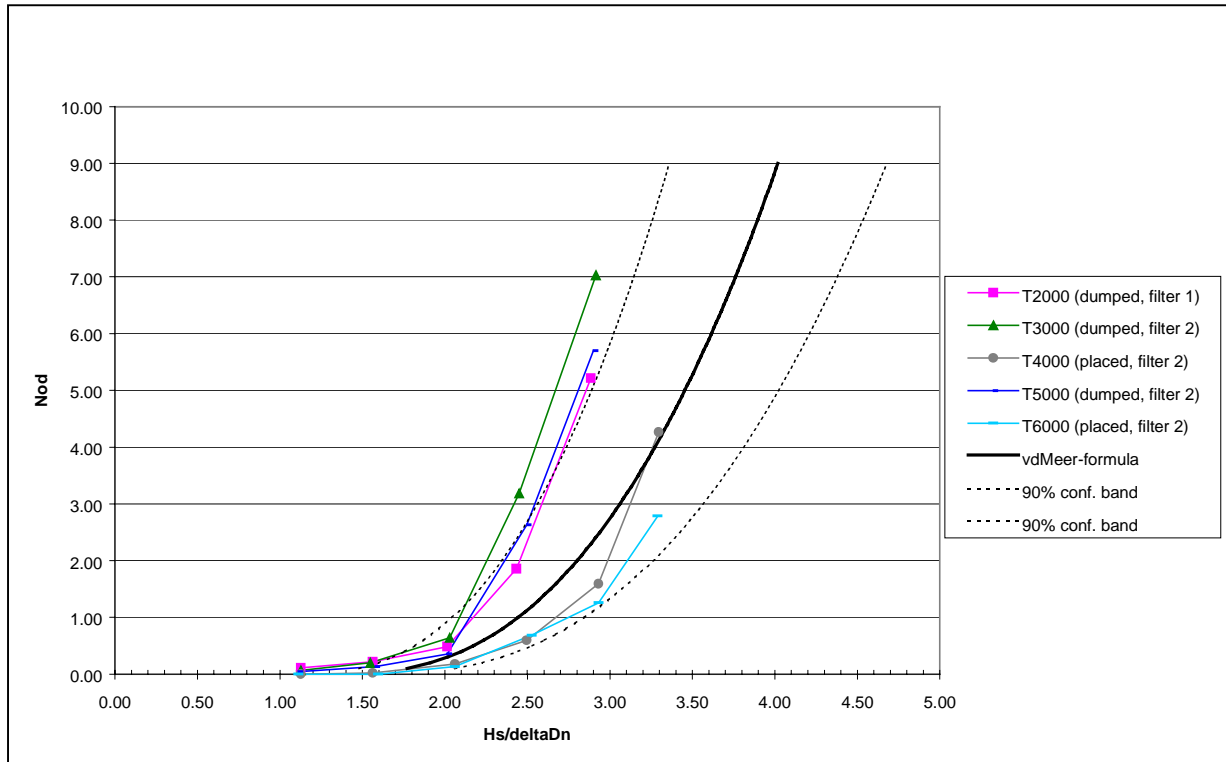


Figure 10.2: stability curves High Density Concrete elements

The weight and sizes of the used cubes as given in Section 4.2.1 have been calculated with Hudson's formula. The used  $K_D$  value was 6.8 corresponding with the removal of 0-5% of all elements in the cover layer. Hudson used a cover layer from  $1 \cdot H_s$  below still water level to  $1 \cdot H_s$  above still water level.

In this investigation cubes were laying on the slope from  $2 \cdot H_s$  below still water level to  $1,5 \cdot H_s$  above still water level. It was seen after the tests that almost all displaced cubes were cubes laying in the area of  $1 \cdot H_s$  below still water level to  $1 \cdot H_s$  above still water level. The design wave of the high-density cubes according to Hudson is 0,140 m, resulting in a stability number of 2,2. Test series T6000, T4000, T2000 and T5000 showed for that stability number a removal 1.1%, 1.1%, 3.5% and 3.8% of all cubes in the area from  $1 \cdot H_s$  below still water level to  $1 \cdot H_s$  above still water level.

Test series T3000 did have for that stability number a removal of 5.1% in the area from  $1 \cdot H_s$  below still water level to  $1 \cdot H_s$  above still water level.

### 10.3.3 Discussion

Cubes placed by hand are a lot more stable than cubes dumped on the slope (this was also seen on normal density cubes). Cubes dumped on the slope are less stable than expected. By  $N_{od} = 2$ , two of the 3 curves are between the 90% confidence bands, one is out of the band.

Test series T2000, T4000, T5000 and T6000 show a removal of 0% - 5% of all elements in the area of  $1 \cdot H_s$  below still water level to  $1 \cdot H_s$  above still water level, according to Hudson's expectations. Test series T3000 show a removal of >5% in the area of  $1 \cdot H_s$  below still water level to  $1 \cdot H_s$  above still water level. It is seen from Figure 10.2 that the effect of changing the filter layer on the stability is almost negligible. Cubes on filter 1 looks like a little more stable however filter 2 is more suited. This is possibly caused by the fact that  $D_{n50}$  of filter 1 is a little too large resulting in a better embedding of the armourlayer.

Because the influence of the filter layer is almost negligible in comparison with the effect of placement, test series T2000, T3000 and T5000 as well as T4000 and T 6000 can be considered as repetition-test.

The results of the tests with high-density concrete elements are very reliable because of two reasons. In the first place the results of repetition-tests do not differ a lot. In the second place the test were performed with a very large number of elements (almost 4 times the number of normal density elements) reducing the influence of unaccounted irregularities.

## 10.4 Comparing High Density to Normal Density Concrete elements

### 10.4.1 Introduction

In order to say in what way high-density concrete elements behave compared to equivalent normal density elements, a comparison between the test results must be made.

Comparing the results as given in Sections 10.1 and 10.2 at first sight it seems right to say that high-density concrete elements perform in a minor way than normal density concrete elements do. Placing the cubes in the same way gives stability curves for high-density concrete, which are on the left side of the curves of normal density concrete. Comparing the results of high-density concrete elements with Van der Meer using the same placing method Van der Meer used, gives stability curves which are on the edges of the 90% confidence bands. However, almost all tests (except one) give damage as expected based on Hudson's formula.

Comparing the results there are problems. It looks right to compare results of tests with the same placing method to each other. The placing method is however not the most important criterion, the result of placing method is more important (see Chapter 9).

### 10.4.2 Comparison based on "roughness of laying" criterion

In Chapter 9 it is stated that *placing* high-density cubes by hand will result in the same roughness as *dumping* normal density cubes on the slope. Considering the remarks made in Chapter 9 it now can be concluded that normal density concrete elements dumped on the slope are to be compared with high-density concrete elements placed by hand.

It is not known in what way the elements did lay on the slope in Van der Meer's tests. Van der Meer used the same normal density concrete elements as used in this investigation (*Van der Meer [1986]*). He dumped the elements on the slope by using a bucket. Therefore it seems right to say that the elements used by Van der Meer did lay as rough as the normal density concrete elements dumped on the slope in this investigation. Because of this and of remarks made in Chapter 9, it can be stated that Van der Meer's curve is applicable for high-density concrete elements placed by hand and not for high-density concrete elements dumped by bucket.

In Figure 10.3 the stability curves of test with NDC elements placed by bucket and HDC elements placed by hand are given.

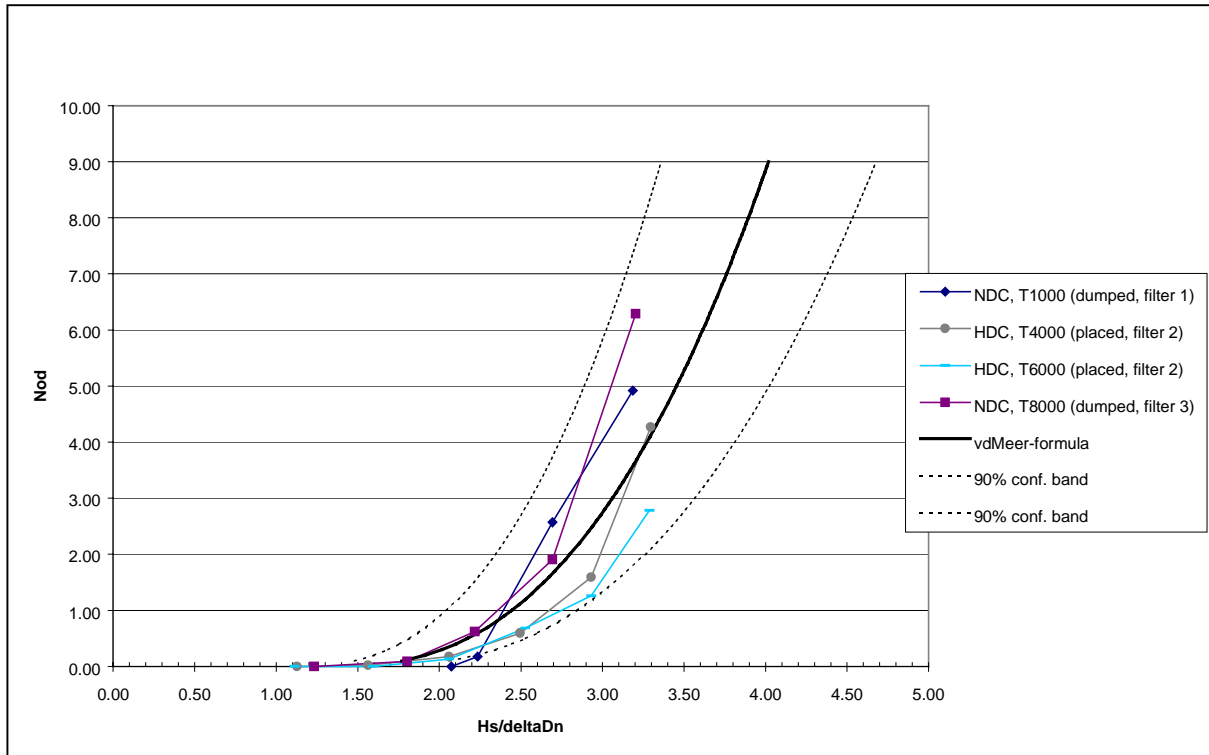


Figure 10.3: stability curves comparable Normal and High Density Concrete elements

#### 10.4.3 Discussion

Reviewing the test results of Section 10.1 and 10.2 using the “roughness of laying” criterion, it can be concluded that the high-density concrete elements are at least as stable as the normal density concrete elements (see Figure 10.3). It also can be concluded that the high-density concrete elements do behave at least as expected based on the formulae.

#### 10.5 Validity of stability formulae for high densities

As mentioned in Section 2.5 a general stability formula for armour elements reads:

$$\frac{H_s}{D} = K_1 \cdot K_2 \cdots K_n \cdot \Delta^x \quad \dots \dots \dots \text{formula 2.4}$$

In all formulae there is a linear relation between  $H_s/D$  and  $\Delta$ . That means  $x$  in formula 2.4 is 1. This linear relation is until now not validated for high densities up to  $4000 \text{ kg/m}^3$ . With the test results as presented in Figure 10.3 now it is possible to investigate the power of  $\Delta$  in formula 2.4 for high densities.

In Figure 10.4 the relation between  $H_s/D$  and  $\Delta$  for different  $N_{od}$  is given, using the test results of Section 10.4. For each  $N_{od}$  the average value of tests with the same density was used.

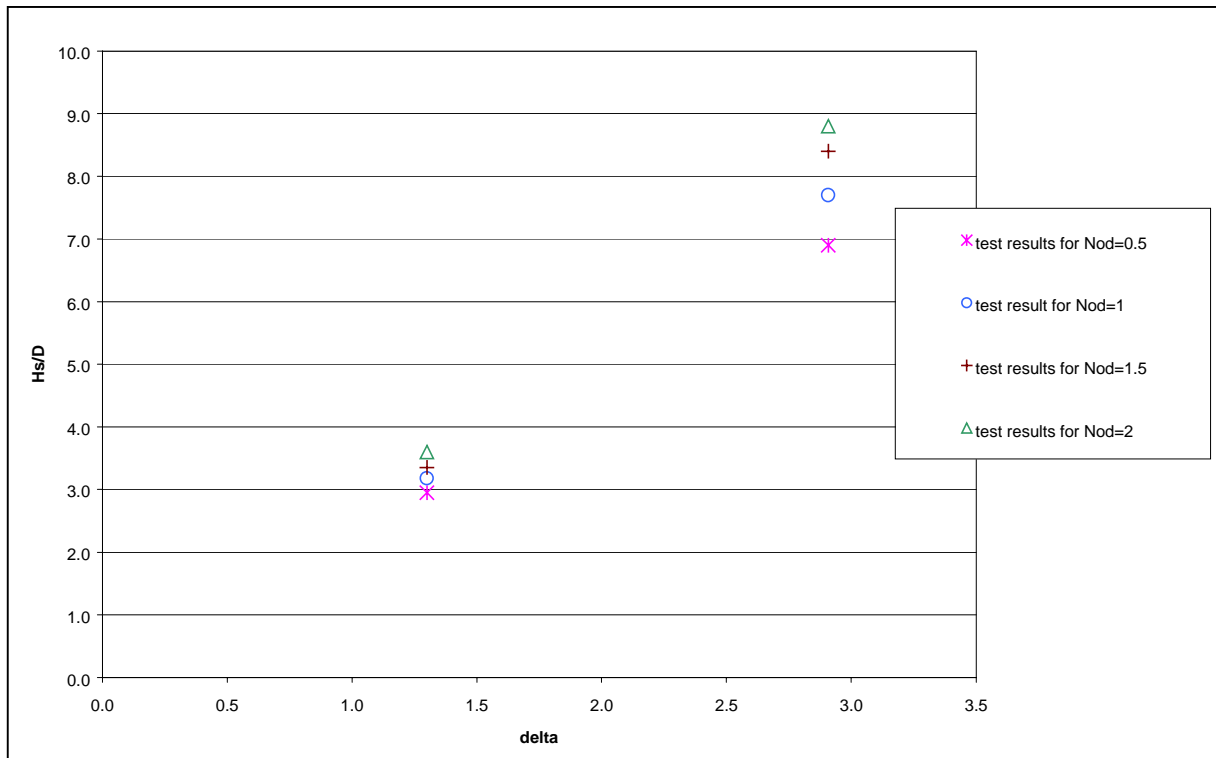


Figure 10.4: relation between  $H_s/D$  and  $\Delta$  obtained from test results

If there is a linear relation between  $H_s/D$  and  $\Delta$  it is possible to draw a straight line between points of the same  $N_{od}$ . According to formula 2.4 all lines should go through the origin (0,0) of Figure 10.4 ( $H_s/D=0$  for  $\Delta=0$ ).

Drawing lines between the points and the origin of Figure 10.4, resulted in Figure 10.5

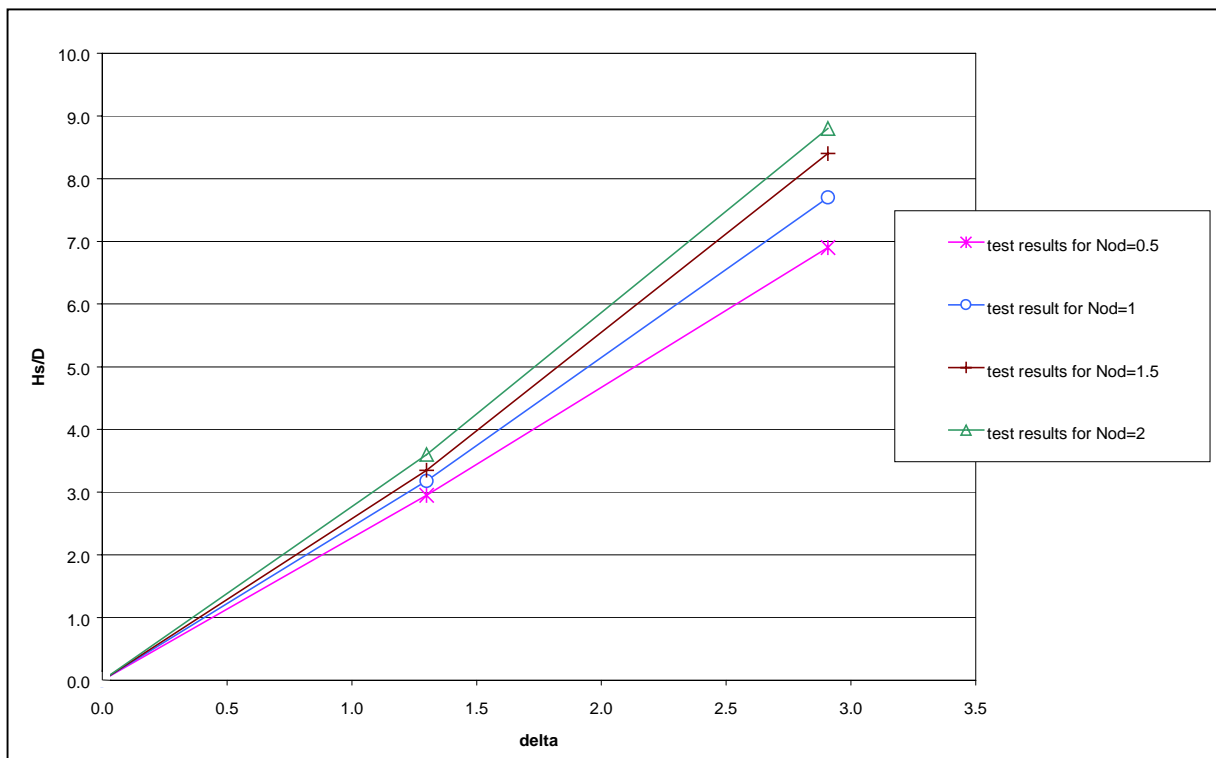


Figure 10.5: lines between test results and origin

It is seen from Figure 10.5 that it is not possible to draw exactly a straight line between the origin and the test results.

In Table 10.1 the gradient ( $\Delta[H_s/D]/\Delta[\Delta]$ ) of the different parts of the lines of Figure 10.5 are given.

	<b>gradient part 1</b>	<b>gradient part 2</b>
$N_{od} = 0,5$	2,3	2,4
$N_{od} = 1,0$	2,4	2,8
$N_{od} = 1,5$	2,6	3,1
$N_{od} = 2,0$	2,8	3,2

Table 10.1: gradient of lines of Figure 10.5

It is seen from Table 10.1 that there is a slight difference in gradient for the first and second part of the lines of Figure 10.5.

Although there is a slight difference in gradients it is seen that there is a tendency that the relation between  $H_s/D$  and  $\Delta$  is linear.

The gradients of part 2 of all lines are a little above the gradients of part 1. That means that in this investigation there is at least a linear relation between  $H_s/D$  and  $\Delta$  for high density concrete elements. According to this, the high density concrete elements in this investigation tend to be a little more stable under equal loading conditions than normal density concrete elements. This was also seen in Section 10.4.3.

Because there is only a very slight difference in gradients of Table 10.1 and a very slight deviation from a straight line of the lines in Figure 10.5, it is concluded that the linear relation between  $H_s/D$  and  $\Delta$  is still valid for densities up to 4000 kg/m<sup>3</sup>. In other words: the power of  $\Delta$  in formula 2.4 is still 1 ( $x=1$ ).

## 11 CONCLUSIONS AND RECOMMENDATIONS

### 11.1 Conclusions

- Stability of elements on slope is largely influenced by the “laying-roughness” of the elements.
- The “laying-roughness” of the elements is changing from placing method to placing method as well as from density to density.
- It is not correct to compare results of tests with the same placing method to each other.
- It is correct to compare results of tests with the same “laying-roughness” to each other.
- Using the laying-roughness-criterion it is very well possible to compare elements of different densities in a correct way.
  
- The high-density concrete elements used in this investigation are, under equal loading conditions at least as stable as the normal density concrete elements.
- The high-density concrete elements do behave like expected based on stability formulae.
  
- The linear relation between  $H_g/D$  and  $\Delta$  in stability formulae for breakwater armour elements is still valid for densities up to  $4000\text{kg/m}^3$ .
- It seems to be that the well-known stability formulae for breakwater armour elements are valid for densities up to  $4000\text{ kg/m}^3$ .

### 11.2 Recommendations

- In this investigation, cubes with a slight difference in coefficient of friction were used. It is not known in what way the stability of elements is influenced by this difference in coefficient of friction.  
Reviewing Iribarren’s formula (formula 2.1, Section 2.1) it can be expected that cubes with a higher coefficient of friction will be more stable. In Hudson’s and Van der Meer’s formula the coefficient of friction is not present. Only 1/6 of the high-density cubes had a higher coefficient of friction. Therefore the results may be influenced a little by this difference. In order to eliminate the influence of this coefficient, tests with elements with the same coefficient of friction are recommended.
- The Reynolds-number of the used high-density cubes was  $2,6 \cdot 10^4$ . According to *Dai and Kamel [1969]* scale-effects can be expected for Reynolds-numbers below  $3 \cdot 10^4$ . Therefore, the results obtained in this investigation are to be verified in large-scale test.
- In this investigation the influences of only a very few parameters are investigated. More tests with a large number of different parameters will result in a more general statement about the validity of stability formulae for high densities.

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## LIST OF SYMBOLS

$\alpha$	slope angel of construction
$D_n$	nominal diameter, $(W/\rho_r)^{1/3}$
$G$	acceleration of gravity
$H_s$	significant wave height
$K_D$	stability coefficient in Hudson formula
$M_{50}$	average mass of stone class
$m_0$	zeroth moment of spectrum
$N$	number of waves
$N_{od}$	damage number in Van der Meer formula
$Re$	Reynolds number
$\rho_r$	density element
$\rho_w$	density water
$T_p$	peak period
$T_m$	mean period
$s_{0m}$	wave steepness
$V$	volume of element
$W$	weight of element
$\xi$	surf similarity parameter

## LIST OF TABLES

Table 3.1	comparison between normal density and high-density concrete elements
Table 5.1	sizes and weights of used elements
Table 5.2	cubes on wooden board, angle at start of movement
Table 5.3	used filterlayers
Table 8.1	test program
Table 10.1	gradients of lines of Figure 10.5

## LIST OF FIGURES

- Figure 2.1 Van der Meer formula for cubes with 90% confidence bands  
Figure 3.1 the effect of the density on the damage causing wave height  
Figure 4.1 contributions on stability  
Figure 5.1 picture of model elements  
Figure 9.1A-D roughness of cubes laying on the slope, lines between coloured bands  
Figure 9.2 position of cubes on the slope  
Figure 9.3A-D roughness of cubes laying in the slope, percentage of rough laying cubes  
Figure 10.1 stability curves Normal Density Concrete elements  
Figure 10.2 stability curves High-Density Concrete elements  
Figure 10.3 stability curves comparable Normal and High Density Concrete elements  
Figure 10.4 relation between  $H_s/D$  and  $\Delta$  obtained from test results  
Figure 10.5 lines between test results and origin

## LIST OF FORMULAE

Formula 2.1	Iribarren formula
Formula 2.2	Hudson formula
Formula 2.3	Van der Meer formula for cubes
Formula 2.4	general stability formula

**APPENDIX A  
CONSIDERATIONS AND DECISIONS**

### 11.3 Considerations and scale-effects

Dynamic similarity would be obtained for rubble mound stability models if the models are constructed geometrically similar to their prototypes and if both the Froude- ( $U/\sqrt{gd}$ ) and Reynolds- ( $Ud/\nu$ ) numbers are equal, model to prototype, or model to model by comparing two. It is not possible to take Froude and Reynolds both equal. In breakwater-models in which gravity plays a role, scaling according to Froude's law is required. It can be calculated that in that case the scale of the dynamic viscosity  $\nu$  in the Reynolds-number is equal to (linear-scale)<sup>3/2</sup>. It is seen that the use of a practical linear scale will result in a non-existing required viscosity for the model fluid. The most practical model fluid is water, and water is used in all rubble mound stability models. Thus perfect dynamic similarity can not be obtained and some dissimilarity between model and prototype action will occur. This dissimilarity is called scale effects (*Hudson [1975]*).

Reviewing the Hudson formula it can be calculated that  $K_D$  is affected by the Reynolds-number.  $K_D$  is proportional of the 2nd power of the Reynolds number (*Ito [1994]*):

$$K_D = \frac{R_e^2}{\xi^4 (S_r - 1)^3} C_R \quad \dots\dots\dots \text{formula A.1}$$

It is seen from formula A.1 that decreasing the Reynolds-number decreases the  $K_D$  value. When the Reynolds number is small,  $K_D$  become very small, resulting in higher required unit weights according to Hudson's formula. *Ito [1994]* concluded that after approximately Reynolds-number =  $1 \cdot 10^5$ ,  $K_D$  gradually reaches a constant. In other words if the Reynolds-number is high enough, scale-effects caused by not scaling the viscosity of the liquid are negligible. These conclusions are also drawn by *Hudson [1975, 1979]* and *Dai and Kamel [1969]*.

Van der Meer investigated in his doctoral thesis several authors on scale effects (*Dai and Kamel, Thompson, Broderick and Ahrens, Jensen and Klinting, Sørensen and Jensen, Burcharth and Frigaard*) and concluded that the results are not throughout consistent. Lowest values for which no scale effects will be present can be set at  $Re=1 \cdot 10^4 - 4 \cdot 10^4$  (*Van der Meer [1988]*). Others (*Owen [1985]*) discussed  $Re=3 \cdot 10^4$  as too conservatives and give values of  $Re = 8 \cdot 10^3$  or even  $3 \cdot 10^3$  (referring to *Mol, Jensen and Klinting, Shuttler*).

In table A.1 minimum Reynolds numbers given by several authors are listed.

	Minimum Reynolds number
Dai and Kamel [1969]	$3 \cdot 10^4$
Oumeraci [1984]	$3 \cdot 10^4$
Stive [1984]	$3 \cdot 10^4$
Liu [1984]	$1 \cdot 10^4$
Van der Meer [1988]	$1 \cdot 10^4 - 4 \cdot 10^4$
Owen [1985]	$3 \cdot 10^3 - 8 \cdot 10^3$

Table A.1: minimum Reynolds numbers

It must be mentioned that the minimum values listed in table A.1 are estimations. No absolute minimum values are given by the authors. Furthermore the values given by Dai and Kamel were derived for the start of damage, no scale effects were present for higher damage levels.

Experiments with high density tetrapodes described by *Ito [1994]* (see also paragraph 2.6.3) give more damage using high density elements than using normal density elements under same wave-attack. Densities in these tests were between  $17,8 \text{ kN/m}^3$  and  $42,8 \text{ kN/m}^3$ . Reynolds-numbers differ from  $2,2 \cdot 10^4$  to  $4,6 \cdot 10^4$  and higher. The damage-curves of these tests show more damage for higher densities. These results are, according to Ito, caused by above mentioned scale effects due to very small units. Considerations about these results and conclusions must be given because the

damage of the high density-elements looks like progressive damage. Therefore the damage is likely caused by other aspects, like e.g. placing method.

The Reynolds-numbers of the cubes for the present investigation are listed in table A.2 ( $Re = \sqrt{g \cdot H} \cdot D_n / \nu$ , using design wave height for H).

	Reynolds number
Elements 1 (NDC)	$5,2 * 10^4$
Elements 2 (HDC)	$2,6 * 10^4$

Table A.2: Reynolds numbers used elements

According to values given by some authors of table A.1 scale effects are to be expected for elements number 2.

In order to obtain experiments not influenced by scale-effect several options have been investigated (see also table A.3):

1. The most proper way is to make Reynolds for both elements  $> 3 * 10^4$ .  
But the 140% wave-height for Reynolds  $> 3 * 10^4$  can not be generated in the flume.
2. Another option is to investigate the influence of using the same element-size for normal and high density concrete, instead of using the same wave-height. The Reynolds-number of the normal concrete elements then reach a value of approximately  $1,8 * 10^4$ , also  $< 3 * 10^4$ . Therefore this is not a proper option.
3. Using the same Reynolds-number for both densities will eliminate the scale-effects by comparing the results (both experiments are influenced by the same scale effects). This is however not a usual way, because the model-scale for these test are not equal and scaling to a prototype will be difficult.

option	Element	$D_n$	Reynolds	140% waveheight
1	1 (NDC)	0,025 m	$3 * 10^4$	0,26 m
2	1 (NDC)	0,022 m	$2,6 * 10^4$	0,20 m
	2 (HDC)	0,022 m	$1,8 * 10^4$	0,065 m
3	1 (NDC)	0,022 m	$2,6 * 10^4$	0,20 m
	2 (HDC)	0,028 m	$2,6 * 10^4$	0,068 m

Table A.3: options to eliminate scale effects

These considerations lead to the following conclusions:

1. Using the same wave-height (dictated by the maximum wave in the flume) for experiments with both densities, will result in minimum Reynolds-numbers of approximately  $2,6 * 10^4$ .
2. Using Reynolds-numbers  $> 3 * 10^4$  is not possible because of the maximum wave in the flume.
3. Using the same elements-size will result in even lower values of Re.
4. Using the same Reynolds-numbers is not usual.

Using the same wave height for experiments with both densities is the best option, although Reynolds  $< 3 * 10^4$ .

Based on above mentioned references of *Van der Meer* and *Owen* and following discussions with several experts of TUDelft De Weger and WL| Delft Hydraulics, no scale-effects are to be expected with experiments with Reynolds-numbers of  $2,5 * 10^4$ . Furthermore (see earlier mentioned remarks) the values of minimum Reynolds numbers are not as absolute as given in table A.1. Therefore it was decided to perform experiments with the elements as mentioned in paragraph 5.2.1 with the same wave-height for normal density and high-density elements.

#### 11.4 Ratio armourlayer/filterlayer



The ratio between the armour layer and filter layers is normally dictated by weight. More important than the ratio in weight is the geometry. Calculation of the filter layer based on the ratio in weight will only satisfy if the density of the armour layer- and filter layer-material is the same.

The formula for the ratio between armour- and filter material is:

$$M_{50,filter} = \frac{1}{10} a \frac{1}{25} * M_{50,armour} \dots\dots\dots formula A.2$$

For tests with armour-elements of normal density the following filter material is required:

$$M_{50,filter} = 1/10 \text{ à } 1/25 * 0,203 = 0.020 \text{ à } 0,008 \text{ kg}$$

By using filter material with  $\rho \approx 2600 \text{ kg/m}^3$ ,  $D_{n50} =$

$$\sqrt[3]{\frac{W}{\rho}} = 0.020m - 0.015m$$

$D_{n50, armour}$  (by using normal density elements) = 0.045 m, that means a ratio between  $D_{n50, armour}$  and  $D_{n50, filter}$  of 2,3 to 3,1. Using the same ratio between  $D_{n50, armour}$  and  $D_{n50, filter}$  for the high-density elements results in  $D_{n50, filter} = 0,007$  to  $0,010$  m, see table A.4

	$D_{n50, armour}$	$D_{n50, filter} \text{ (m)}$
NDC-elements	0,044	0,015 – 0,020
HDC-elements	0,022	0,007 – 0,010

Table A.4: required filterlayers

In total 3 different filter materials have been used (see also table A.5):

1. A filter layer between the required filter layer for tests with normal density concrete and the required filter layer for tests with high density concrete, used for tests with normal and high density concrete (filter1 see Appendix C).
2. A filter layer calculated with above-mentioned relations, used for test with high-density concrete (filter 2, see Appendix C).
3. A filter layer calculated with above-mentioned relations, used for test with normal density concrete (filter 3, see Appendix C)

	$D_{n50} \text{ (m)}$
Filter 1	0,012
Filter 2	0,008
Filter 3	0,019

Table A.5: used filterlayers

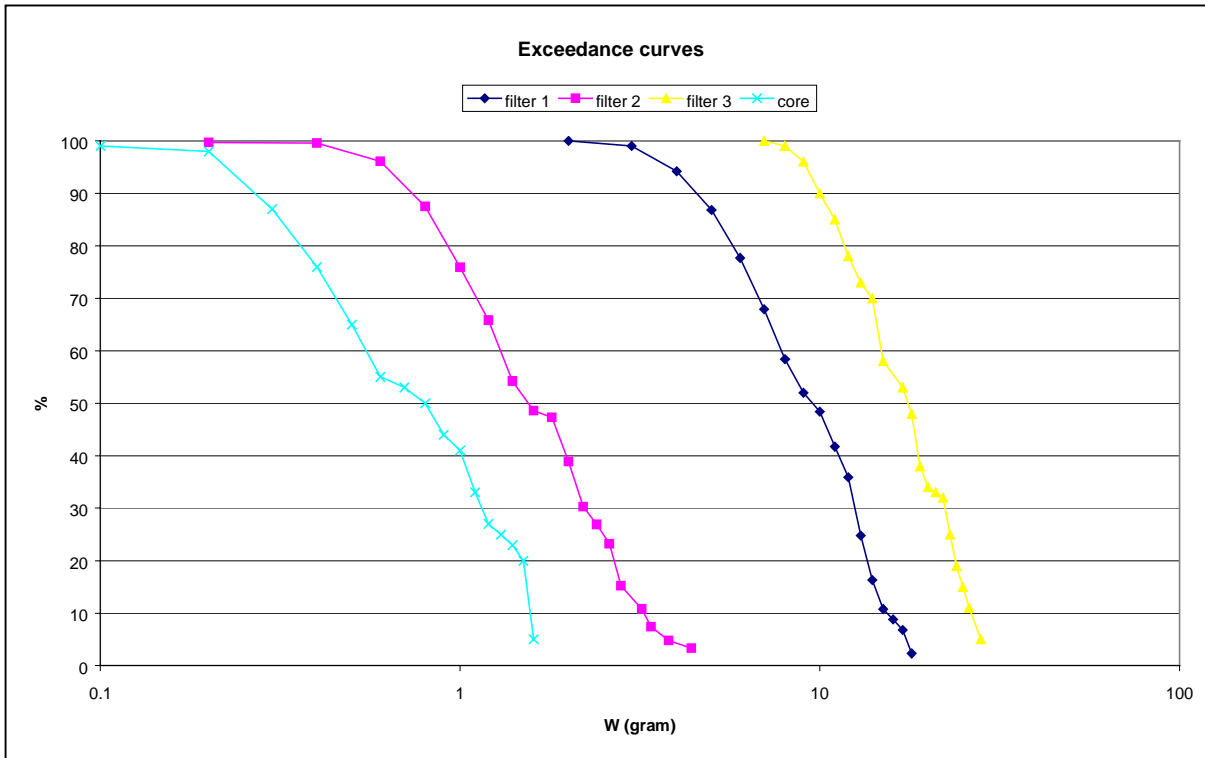
The core consisted of a huge amount of quarry run. This was granular material without specifications. This material was covered with a layer of about 15 cm of core-material with specifications of Appendix B.

**APPENDIX B**  
**CROSS SECTION OF TESTED STRUCTURE**



**APPENDIX C**  
**FILTER LAYERS AND CORE MATERIAL**

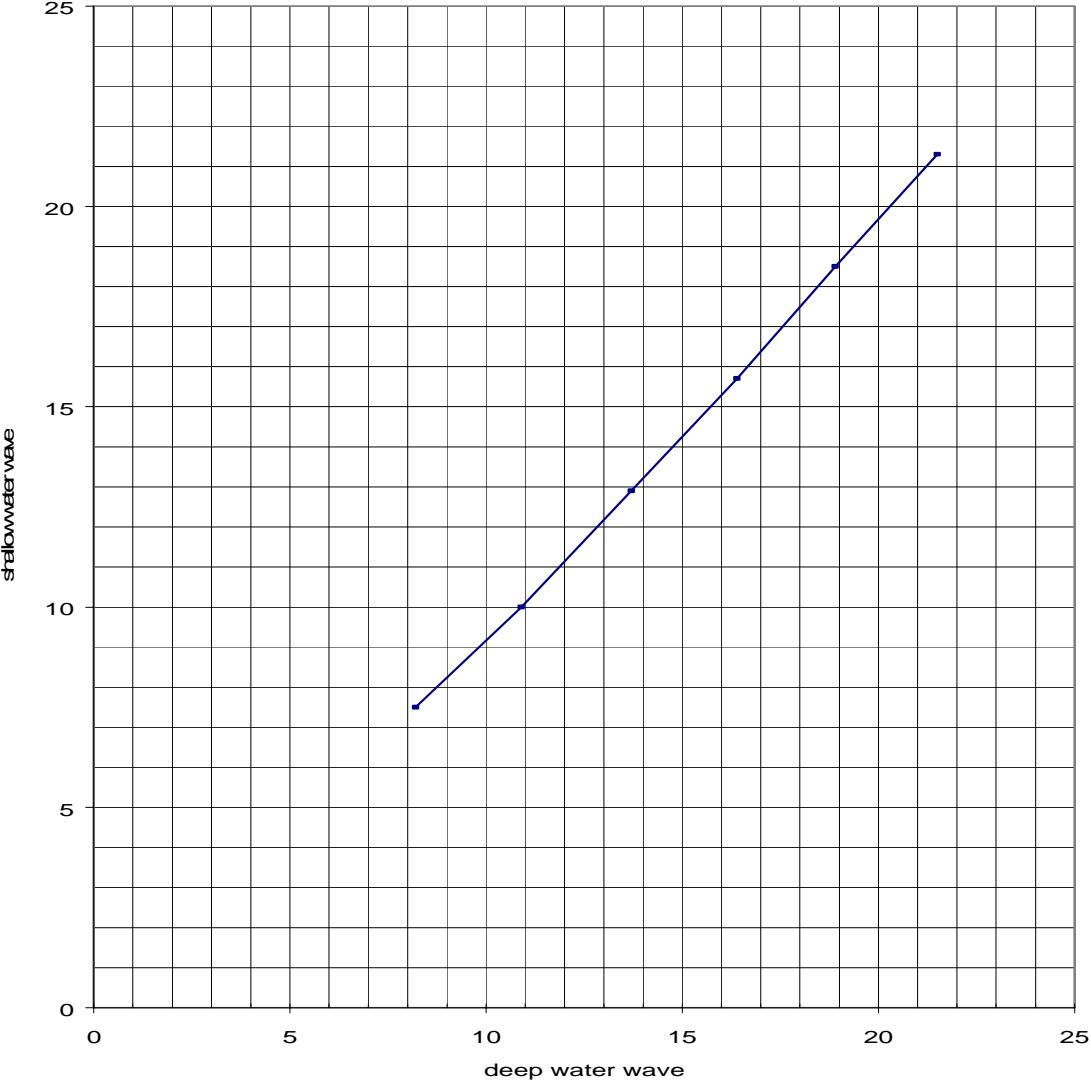
	$M_{50}$ (gram)	$D_{n50}$ (cm)
Filter 1	9.0	1.2
Filter 2	1.5	0.8
Filter 3	17.5	1.9
core	0.8	0.6



**APPENDIX D**  
**SCHELDT BASIN AND PLACES OF WAVE GAUGES**

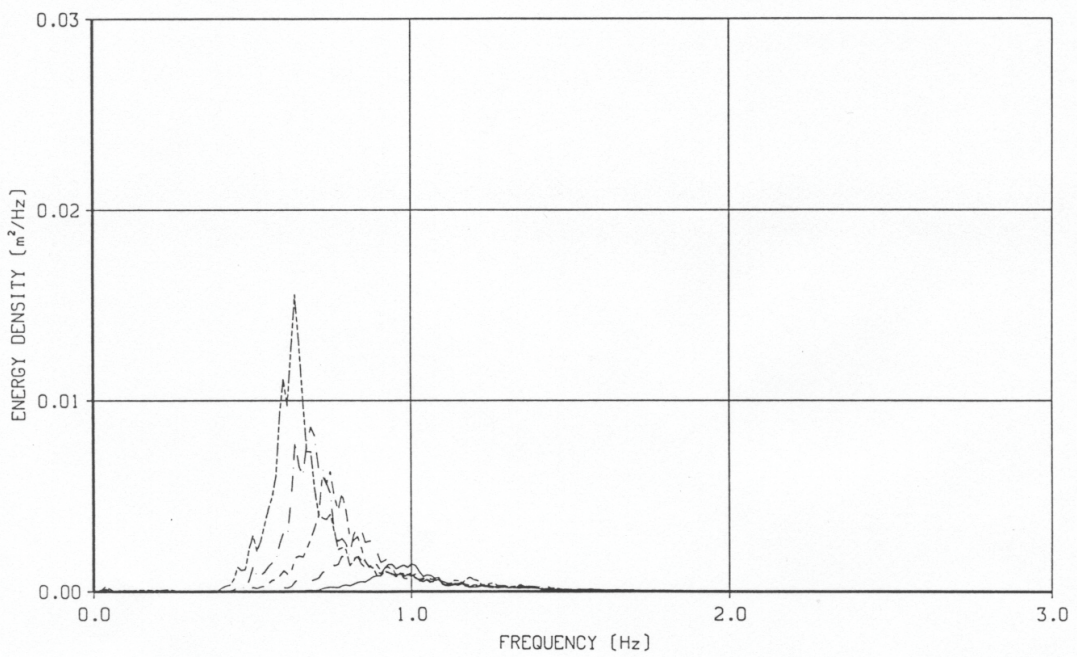
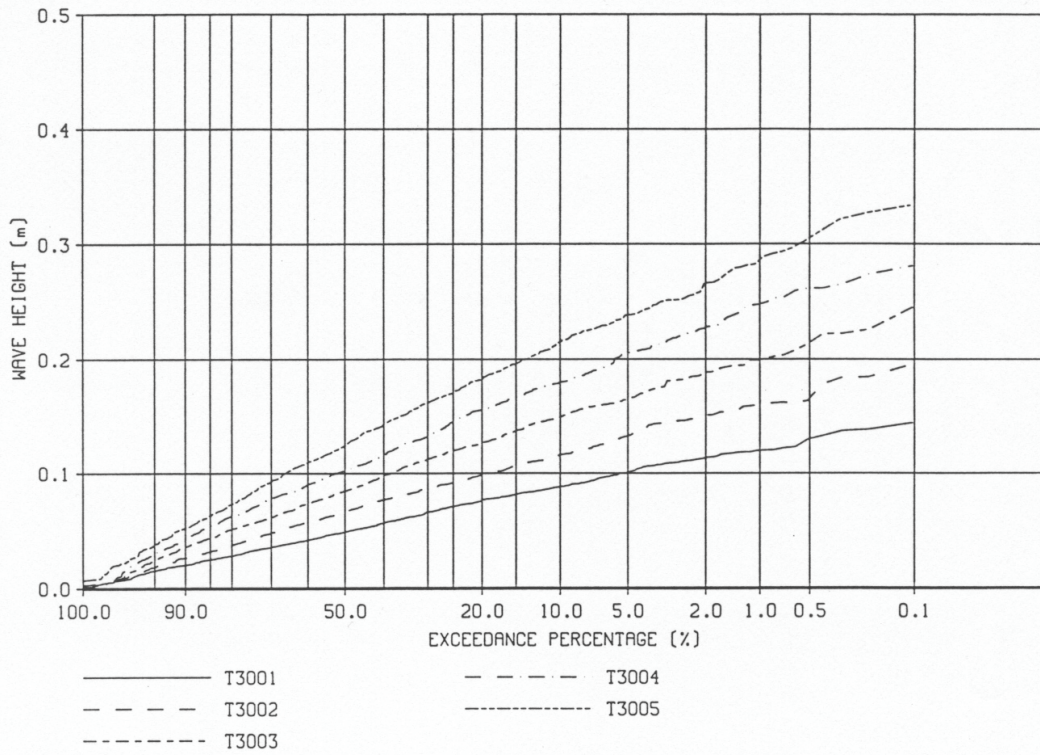
**APPENDIX E**  
**RELATION DEEP WATER WAVE – SHALLOW WATER WAVE**

Relation deep water wave - shallow water wave





**APPENDIX F**  
**EXCEEDANCE CURVES AND ENERGY DENSITY SPECTRA**



EXCEEDANCE CURVES AND  
ENERGY DENSITY SPECTRA OF WHM 2

#T3000

WL | DELFT HYDRAULICS

H3594

FIG.

**NDIX G**  
**TEST SCHEDULE AND TEST RESULTS**

Test number	Gamma (kg/m <sup>3</sup> )	Dn	delta	Wave %	Height (m)	Tp0(s)	Tm0(s)	Duration(min)	Hs/deltaDn	number of displaced cubes	Nod
<b>filter 1</b>											
T1002 (dumped)	2328	0.0443	1.328	80	0.122	1.25	1.04	18	2.07	0	0.00
T1003	2328	0.0443	1.328	100	0.132	1.30	1.08	19	2.24	4	0.18
T1004	2328	0.0443	1.328	120	0.159	1.42	1.18	21	2.69	58	2.57
T1005	2328	0.0443	1.328	140	0.188	1.55	1.29	22	3.19	111	4.92
<b>filter 2</b>											
T2001 (dumped)	3910	0.0221	2.91	60	0.073	0.96	0.80	14	1.13	5	0.11
T2002	3910	0.0221	2.91	80	0.101	1.13	0.94	17	1.56	10	0.22
T2003	3910	0.0221	2.91	100	0.130	1.29	1.07	19	2.01	22	0.49
T2004	3910	0.0221	2.91	120	0.157	1.42	1.18	21	2.43	84	1.86
T2005	3910	0.0221	2.91	140	0.186	1.54	1.28	22	2.88	236	5.22
<b>filter 2</b>											
T3001 (dumped)	3910	0.0221	2.91	60	0.073	0.96	0.80	14	1.13	3	0.07
T3002	3910	0.0221	2.91	80	0.100	1.13	0.94	17	1.55	9	0.20
T3003	3910	0.0221	2.91	100	0.131	1.29	1.07	19	2.03	29	0.64
T3004	3910	0.0221	2.91	120	0.158	1.42	1.18	21	2.45	144	3.18
T3005	3910	0.0221	2.91	140	0.188	1.55	1.29	22	2.92	318	7.03
<b>filter 2</b>											
T4001 (placed)	3910	0.0221	2.91	60	0.073	0.96	0.80	14	1.13	0	0.00
T4002	3910	0.0221	2.91	80	0.101	1.13	0.94	17	1.56	1	0.02
T4003	3910	0.0221	2.91	100	0.133	1.30	1.08	19	2.06	8	0.18
T4004	3910	0.0221	2.91	120	0.161	1.43	1.19	21	2.50	27	0.60
T4005	3910	0.0221	2.91	140	0.189	1.55	1.29	22	2.93	72	1.59
T4006	3910	0.0221	2.91	160	0.212	1.65	1.37	24	3.30	193	4.27
<b>filter 2</b>											
T5001 (dumped)	3910	0.0221	2.91	60	0.072	0.96	0.79	14	1.11	2	0.04
T5002	3910	0.0221	2.91	80	0.102	1.14	0.95	17	1.58	6	0.13
T5003	3910	0.0221	2.91	100	0.130	1.29	1.07	19	2.01	16	0.35
T5004	3910	0.0221	2.91	120	0.161	1.43	1.19	21	2.50	119	2.63
T5005	3910	0.0221	2.91	140	0.187	1.55	1.28	22	2.90	258	5.70
<b>filter 2</b>											
T6001 (placed)	3910	0.0221	2.91	60	0.072	0.96	0.79	14	1.11	0	0.00
T6002	3910	0.0221	2.91	80	0.103	1.15	0.95	17	1.59	0	0.00
T6003	3910	0.0221	2.91	100	0.133	1.30	1.08	19	2.06	6	0.13
T6004	3910	0.0221	2.91	120	0.163	1.44	1.20	21	2.53	31	0.69
T6005	3910	0.0221	2.91	140	0.189	1.55	1.29	22	2.93	57	1.26
T6006	3910	0.0221	2.91	160	0.212	1.65	1.37	24	3.29	126	2.78
<b>filter 3</b>											
T7001 (placed)	2328	0.0443	1.328	60	0.073	0.96	0.80	14	1.23	0	0.00
T7002	2328	0.0443	1.328	80	0.102	1.14	0.95	17	1.73	0	0.00
T7003	2328	0.0443	1.328	100	0.132	1.30	1.08	19	2.24	0	0.00
T7004	2328	0.0443	1.328	120	0.159	1.42	1.18	21	2.69	8	0.35
T7005	2328	0.0443	1.328	140	0.186	1.54	1.28	22	3.15	12	0.53
T7006	2328	0.0443	1.328	160	0.210	1.64	1.36	24	3.57	40	1.77
<b>filter 3</b>											
T8001 (dumped)	2328	0.0443	1.328	60	0.073	0.96	0.80	14	1.23	0	0.00
T8002	2328	0.0443	1.328	80	0.106	1.17	0.97	17	1.80	2	0.09
T8003	2328	0.0443	1.328	100	0.131	1.29	1.07	19	2.22	14	0.62
T8004	2328	0.0443	1.328	120	0.159	1.42	1.18	21	2.69	43	1.90
T8005	2328	0.0443	1.328	140	0.189	1.55	1.29	22	3.20	142	6.29

**APPENDIX H**  
**PICTURES OF SLOPES BEFORE AND AFTER TESTING**



Picture 2: after T1002 and before T1003



Picture 1: before T1002



Picture 3: after T1003 and before T1004



Picture 4: after T1004 and before T1005



Picture 3: after T1003 and before T1004



Picture 4: after T1004 and before T1005





Picture 3: after T1005



Picture 7: after T2005



Picture 6: before T2001



Picture 9: after T3005



Picture 8: before T3001



Picture 10: before T4001



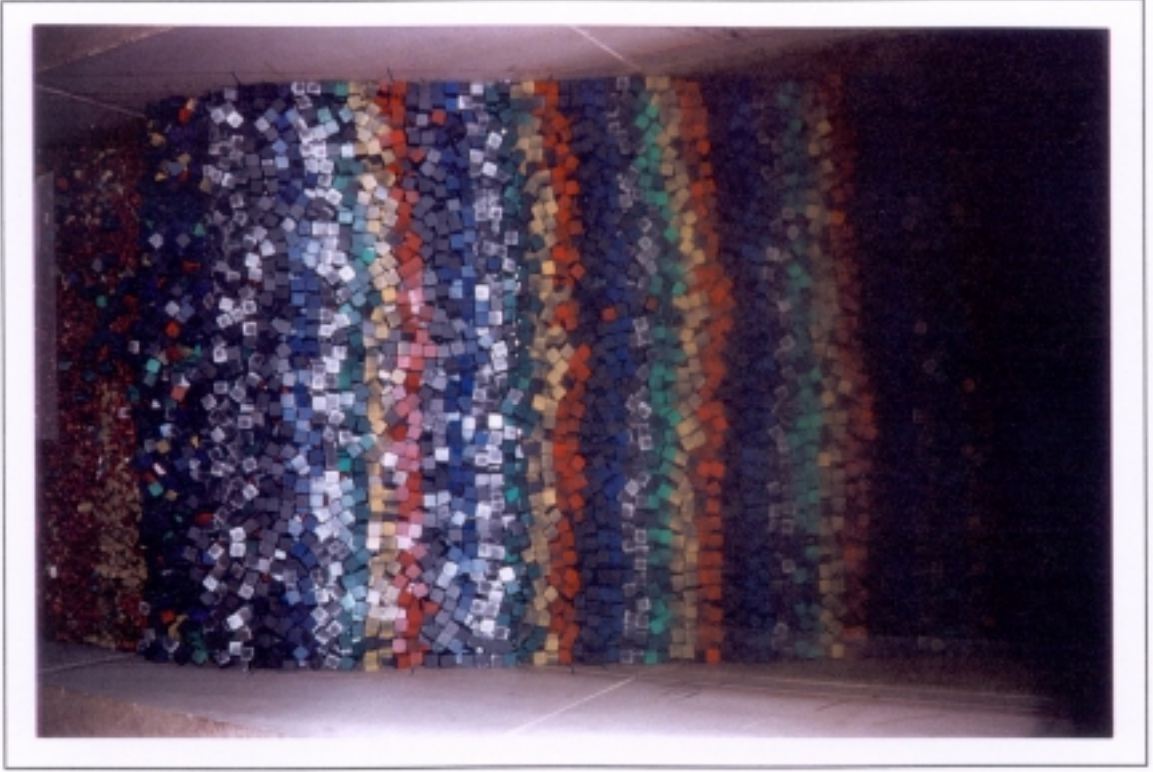
Picture 11: after T4001 and before T4002



*Picture 13: after T4003 and before T4004*



*Picture 12: after T4002 and before T4003*



Picture 15: after T4005 and before T4006



Picture 14: after T4004 and before T4005



Picture 16: after T4006



*Picture 18: after T5005*



*Picture 17: before T5001*

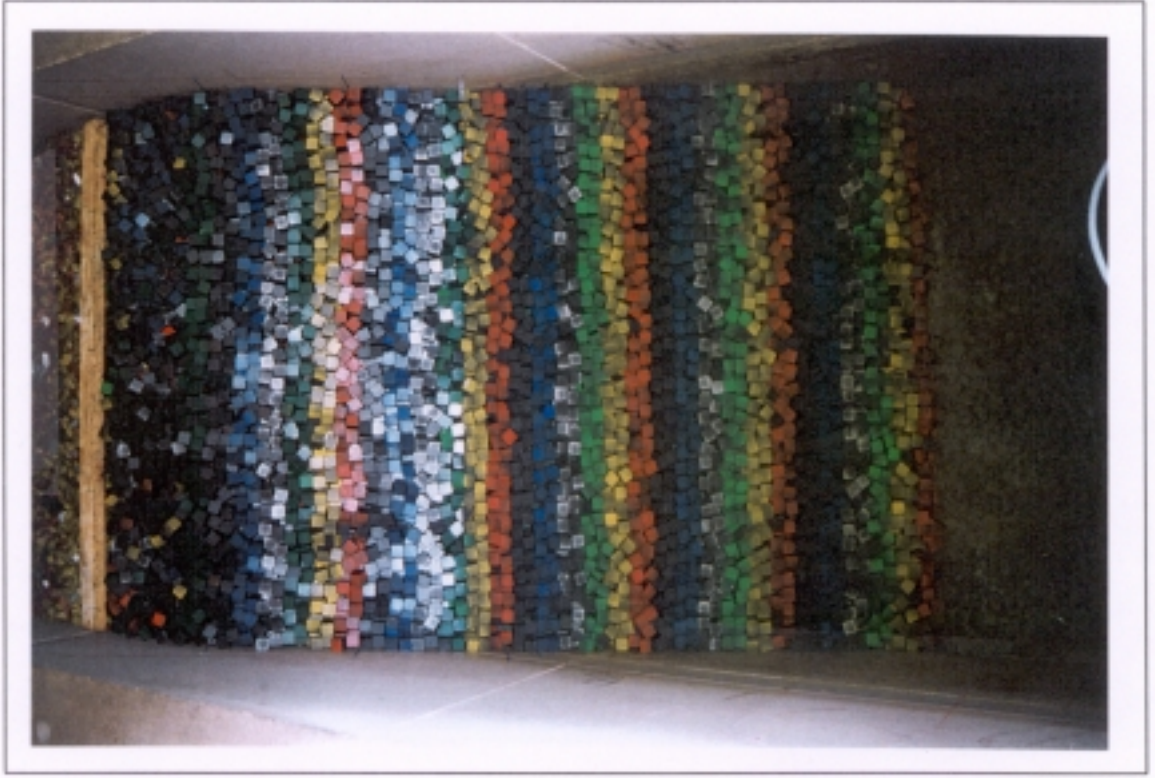




Picture 19: before T6001



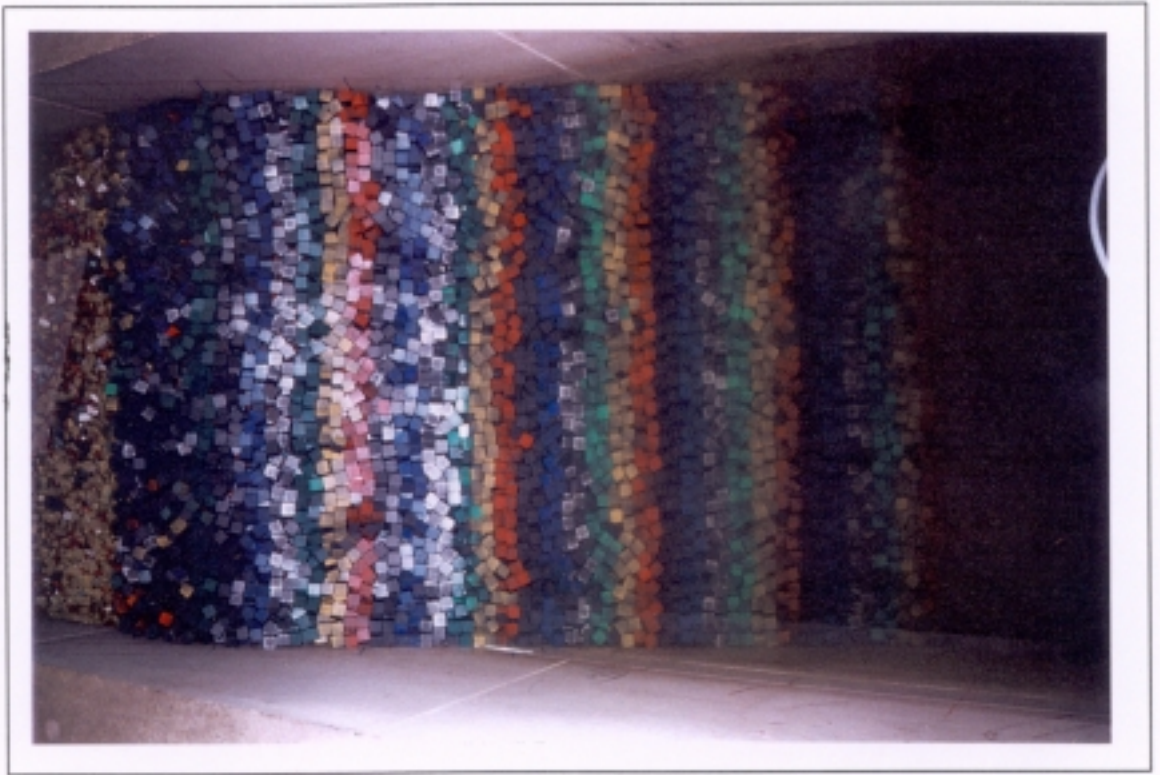
Picture 20: after T6001 and before T6002



Picture 21: after T6002 and before T6003



Picture 22: after T6003 and before T6004



Picture 24: after T6005 and before T6006



Picture 23: after T6004 and before T6005



Picture 25: after T6006



Picture 27: after T7006



Picture 26: before T7001



Picture 29: after T8001 and before T8002



Picture 28: before T8001



Picture 31: after T8003 and before T8004



Picture 30: after T8002 and before T8003



Picture 33: after T8005



Picture 32: after T8004 and before T8005



**APPENDIX I**  
**PICTURES USED FOR DETERMINING ROUGHNESS**





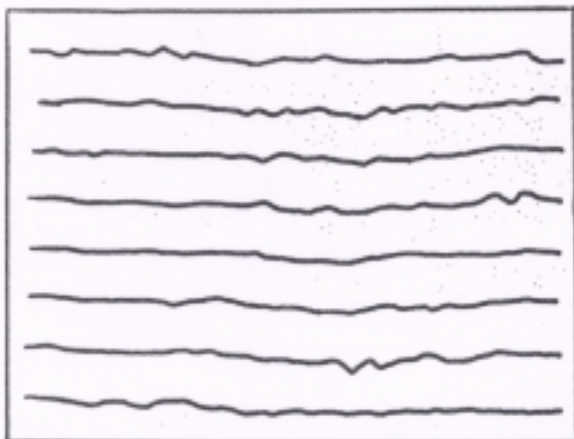
Picture 4: HDC clumped



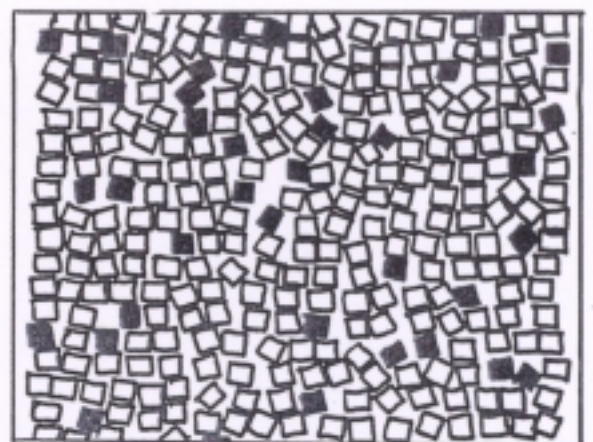
Picture 3: HDC placed



*NDC – placed, area of picture 1 used for determining roughness*



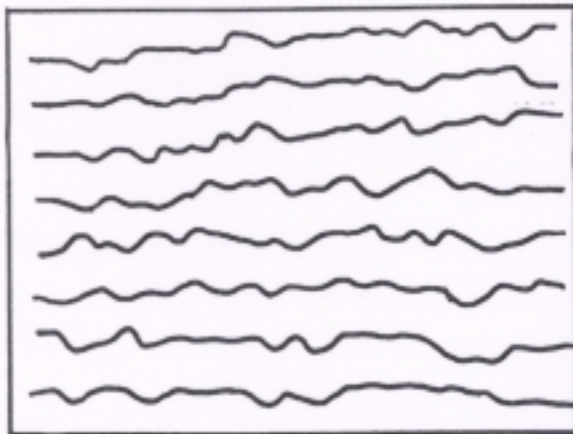
*Lines between coloured bands*



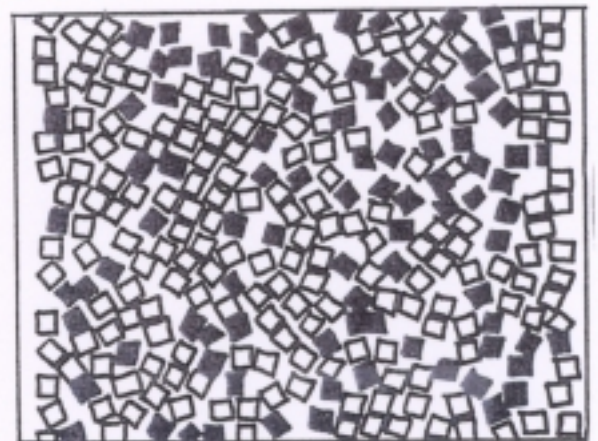
*Percentage of rough laying cubes*



*NDC - dumped, area of picture 2 used for determining roughness*



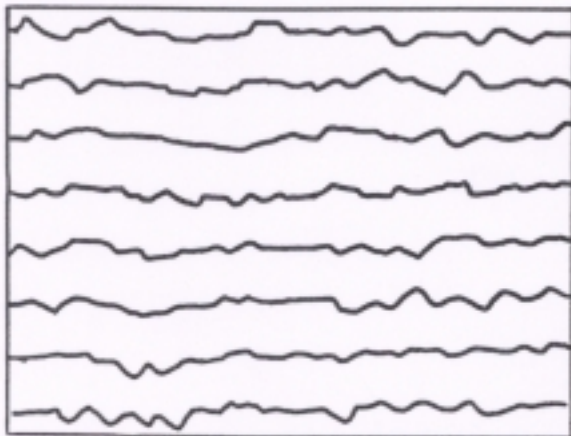
*Lines between coloured bands*



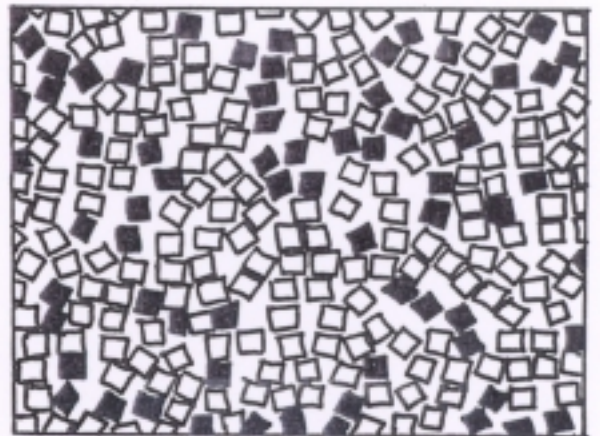
*Percentage of rough laying cubes*



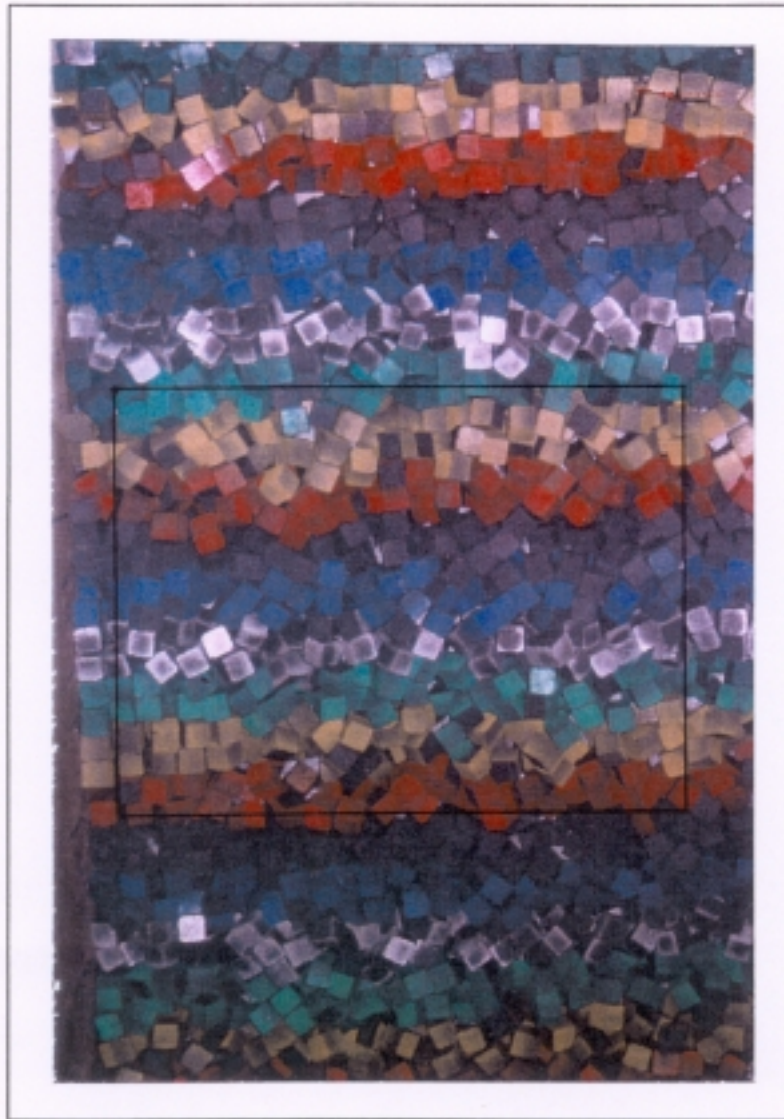
*HDC – placed, area of picture 3(enlarged) used for determining roughness*



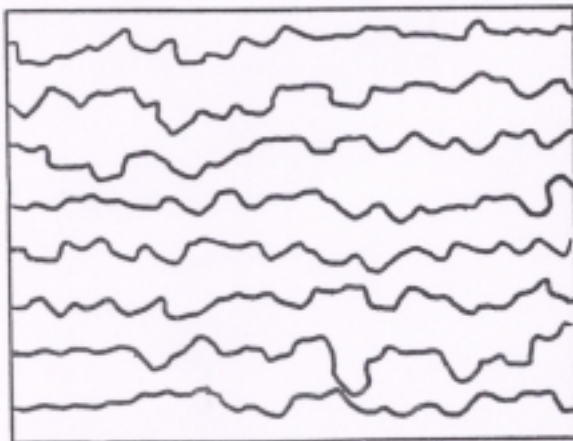
*Lines between coloured bands*



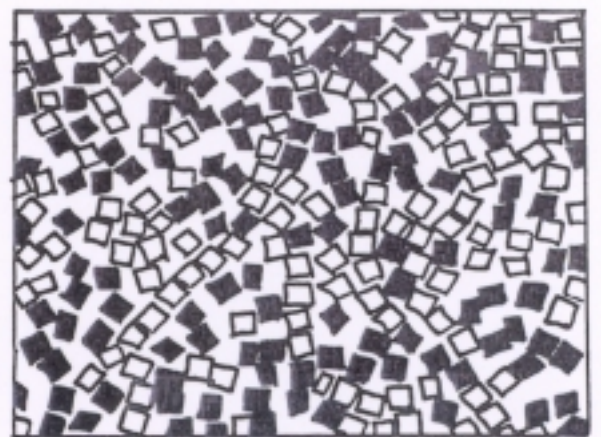
*Percentage of rough laying cubes*



*HDC – dumped, area of picture 4(enlarged) used for determining roughness*



*Lines between coloured bands*



*Percentage of rough laying cubes*