Theoretical and experimental study on the placement of Xbloc

Final report

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Acknowledgements

The results of my graduation project, 'Theoretical and experimental study on the placement of Xbloc, are presented in this report. This study is carried out at Delft University of Technology, Faculty of Civil Engineering and Geosciences, Section Coastal Engineering, in cooperation with Delta Marine Consultants.
Recently Delta Marine Consultants has developed the Xbloc armour unit. The main objectives for this armour unit were, proper balance between hydraulic stability and structural integrity and easy to place on the slope. The past years Xbloc is tested extensively on hydraulic stability and structural integrity. The results of these tests are very promising. The last objective easy to place on the slope is the subject of this thesis. With this study the development of Xbloc is completed.

During this thesis I received great support from a number of people who I want to thank. First of all I would like to thank the members of my thesis committee for the contribution to my thesis, Professor M.J.F. Stive (TU Delft), Ir. H.J. Verhagen (TU Delft), Dr. Ir. H.L. Fontijn (TU Delft), Ir. J.S. Reedijk (Delta Marine Consultant).

Next I want to thank the Coastal team of Delta Marine Consultants for the positive feedback and extensive knowledge on breakwater design and especially single layer armouring. The employees at the laboratory of Delft University for the fabrication of the Xbloc test units.

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Erik ten Oever,

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Abstract

Single layer armouring is a state-of-the-art protection for rubble mound breakwaters. The quality of placement affects *interlocking* of the armour units, which is essential for the hydraulic stability of the entire armour layer.

The main objective of this study is to make a detailed design of an Xbloc placement, this includes grid design, placement accuracy and quality control. The study is based on a theoretical placement analysis that is verified by large scale model tests.

Single layer armour units are placed on a predefined staggered grid in order to achieve good interlocking, which creates a stable armour layer. The distance between armour units is essential for proper functioning of the armour layer. Therefore, single layer armour units shall be placed if possible with a constant horizontal and upslope placement distance, which results in a diamond-shaped placement pattern. However, the placement pattern will be distorted if the seabed level varies or if a section of breakwater is curved (bended trunk sections or roundhead).

The relation between horizontal and upslope placement distances and the resulting *packing density* are determined in model tests. It is found that the packing density is constant for whole range of placement distances (even for a significantly distorted ratio between horizontal and upslope placement distances). This distortion is in horizontal an upslope distances has never been tested on hydraulic stability. Therefore packing density is not enough to determine the quality of placement. In addition another indicator for the quality of armour layer is presented, the Potential Interlocking Coefficient (PIC). The PIC is calculated for each individual unit and is based on distances to the neighbouring units. This parameter will show a distortion in placement pattern even with a standard packing density.

To validate the theoretical placement grid and to determine the placement accuracy, placement tests are performed in the laboratory at Delft University. Placement tests were performed with large scale model Xbloc units of 5 kg, which corresponds to approximately 1:10 scale (on dimensions) for a typical breakwater application. This large scale is required to simulate the behaviour of the units during placement in prototype (i.e. sling techniques and interaction between units). The placement tests were performed on a straight section of breakwater with core and underlayer in a basin of 2.5x2.5m^2 with a dept of 2.0m. Units are placed above and under water by a “crane” with an accurate positioning system in the horizontal plane. After placement all units position were measured. This was done by a laser pointing downwards from the crane platform.

Various types of sling techniques are tested. An important result is that the sling technique affects the unit position on the breakwater slope. Therefore, placement grid and placement technique both influence the quality of placement. It was found that the most favourable orientation to place an Xbloc with is one leg pointing downwards. To obtain this orientation a sling length of three times the unit height is preferred.

Using the favourable orientation the designed placement pattern can be placed without any cumulative placement errors. On average the units are placed on their designed positions. The individual deviation on position both upslope as horizontally are approximately 0.15 D. This accuracy is promising for placement in prototype.

The placement tests were performed without the influence of waves. To predict the influence of waves during placement, the unit response on waves was measured in a wave flume. It is found that for long wave periods, comparable with swell, the unit response was significant. This makes it more difficult to achieve the required placement accuracy.

On the bases of the theoretical knowledge and the test results a mathematical model is developed. The model optimises the placement grid for single layer armouring (applicable for straight and curved trunk sections and for roundheads). This model assumes certain unit behaviour during placement, which is described in model parameters. These parameters are calibrated by the physical tests to ensure a realistic placement grid.

The proposed placement model proved to predict stable unit positions even for breakwater heads. The model has been recently applied for the design of a breakwater, which is currently under construction in Ireland.

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List of parameters

V	Volume of armour unit	[m^3]
W_{Xbloc}	Weight of the Xbloc	[kg]
W_n	The rock weight that is exceeded by n% of the rocks in the underlayer	[kg]
D_{n50}	Nominal diameter of rock	[m]
ρ_{rock}	Density of the rock	[kg/m^3]
H_s	Significant wave height	[m]
D	Characteristic Dimension of Xbloc	[m]
PD	Packing density	[1/m^2]
N_x	Horizontal number of units	[-]
N_y	Number of horizontal rows	[-]
L_x	Horizontal length of section	[m]
L_y	Length upslope along the slope	[m]
D_x	Recommended horizontal placement distance	[D]
D_y	Recommended upslope placement distance	[D]
PIC	Potential interlocking coefficient	[-]
Δx	Distance off centre	[D]
α	Unit adjust angle	[Degree]
d1	Distance to base unit 1	[D]
d2	Distance to base unit 2	[D]
d3	Distance to the unit to the left	[D]
$\hat{u}$	Maximal horizontal velocity	[m/s]
h	Water depth	[m]
L	Wave length	[m]
H	Wave height	[m]
ω	Angle speed	[1/s]
f	Force acting on unit	[N]
C_m	Inertia coefficient	[-]
C_d	Drag coefficient	[-]
ρ	Density of water	[kg/m^3]
g	Gravitation	[m/s^2]
l	Pendulum length	[m]
θ	Angle of pendulum	[rad]

List of definitions

- *Base units* are two units one row below on which the unit is placed.
- *Horizontal distance* is the centre-to-centre distance between two units along the breakwater profile.
- *Individual packing density* is one over the area an individual unit covers.
- *Interlocking* is a phenomenon that armour units hook into each other, improving the hydraulic stability.
- *Off centre distance* is the distance the unit is shifted along the unit adjust line to find the ideal position.
- *Off centre placement* is the placement of a unit a-symmetric to the two base units.
- *Packing density* is number of units per square meter.
- *Potential interlocking coefficient [PIC]* is a mark between 0 and 10 for the potential interlocking of an individual, in which a 0 is for no interlocking and a 10 stands for a perfect diamond-shaped pattern.
- *Sling* is a cable which is slung around a unit to attach it to a crane.
- *Sling path* is the route the sling follows around the unit.
- *Unit adjust angle* is the angle between the horizontal and the line which is used to shift a unit along to find the optimal unit position.
- *Upslope distance* is the distance between two succeeding rows upslope the breakwater profile.

1 Introduction

Most commonly applied breakwaters are rubble mound breakwaters. A rubble mound breakwater is constructed by core of small natural rock which is protected by an outer layer of large units. The outer layer is called the armour layer, this armour layer can be constructed out of natural rock or concrete armour units. When concrete armour units are used, the placement pattern is of great importance for the hydraulic stability of the armour layer.
In this study the placement pattern of single layer armour layers will be systematically analysed, with these results an optimised placement grid for Xbloc can be designed.

1.1 History armour unit design

Port facilities have always responded to the ship development, the last century showed a steady increase in ship size. Old ports were designed for ships with relative small draughts, as a result ports were often built in shallow water. With the increasing ship size the draught also increased, resulting in a demand for larger water depth in the ports, which often led to an extension of port in seaward direction.
The shift of the ports activities into deeper water results in higher wave loads at the breakwaters of a port. This increase in wave load on the rubble mount breakwater requires the usage of larger rock which is often limited by the available size and quality, a good alternative is the usage of concrete armour units.

The first concrete armour units were cubes, which are easy to produce and have a high structural strength. However, cube shaped armour units have a high concrete consumption. The hydraulic stability of the cube is primarily generated by its own weight, this is the same principle as with rock. In 1950 the Laboratory Dauphinios d'Hydraulique (predecessor of Sogreah) introduced the Tetrapod, the first *interlocking* armour unit. The main advantages of the Tetrapod over the cube were improved interlocking and a larger porosity of the armour layer, resulting in a lower concrete consumption.
From 1950 – 1980 a large variety of concrete armour units has been developed. The armour units were typically either randomly or uniformly placed in double layers.

The expression random placement is often misunderstood: a randomly placed armour unit has a predefined location, only the orientation of the units has some randomness. For some units, like the Accropode and Core-loc, the orientation is not random at all because the orientation of the units is dependent on the position and orientation of the other units.
The reason a placement is called random is because the pattern of the finished placement looks like it has been randomly placed.

The failure of the Sines breakwater (Portugal, 1978) and the introduction of the first single layer armour unit the Accropode by Sogreah in 1980 set an end to the rapid development of randomly placed concrete armour units. A single layer armour unit is applied in a layer thickness of one unit, all other concrete armour units until then had been applied in two layers.
Since 1980 single layer randomly placed armour units have been applied as an alternative to the traditional double layer armour layers, of these single layer armour units the Accropode became the leading armour unit worldwide for the next 20 years. Typical features of these single layer armour units are high interlocking, random placement and economical advantages. The economical benefits of a single layer armour unit in comparison to the traditional multilayer armour layers are low concrete consumption and shorter construction time.
In recent years coastal engineers of Delta Marine Consultants [DMC] have developed a new single layer randomly placed armour unit, the Xbloc. The main improvements of the Xbloc in

comparison with the Accropode are the improved constructability and slightly less concrete consumption.

1.2 Background of this study

The motivation for DMC to develop a new armour unit came from experience gained during a breakwater rehabilitation project on Frégate Island, the Seychelles, in which DMC had made the detailed design and provided site assistance during the execution of the works. The armour layer applied consisted of Accropode units. Experiences on this project lead to the idea to develop an improved armouring system based on a single layer system.
The main objectives for the development of the Xbloc were to create an armour unit that:

- is applied in a single layer,
- has proper balance between hydraulic stability and structural strength,
- is easy to produce and to handle,
- is easy to place on the slope.

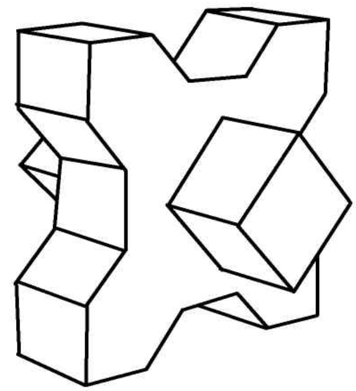

Fig. 1.1 Xbloc

These four objectives lead to the creation of the single layer armour unit, the Xbloc, as shown in Fig. 1.1.
The hydraulic stability of the Xbloc was tested at Delft Hydraulics and other reputable hydraulic laboratories, like the Danish Hydraulic. Results from these tests demonstrate that the Xbloc has similar hydraulic stability as Core-Loc and slightly higher than Accropode.
The structural strength of the Xbloc was evaluated using prototype drop tests and Finite Element calculations. These studies indicate that the Xbloc has similar structural strength as Accropode and is significantly stronger than Core-Loc.
Due too the simple shape of the Xbloc production and handling is easier than that of Accropode and Core-Loc.
The important advantage in comparison to other units like Accropode and Core-loc is the ease of placement. Therefore Xbloc is chosen as main unit for the study of placement of single layer armour units.

1.3 Problem analysis

In the literature little attention is paid to the placement of concrete armour units. This is strange because a poor placement has a major effect on the quality of the armour layer.
The guidelines for placement of single layer armour unit are only briefly given by the developers of the armour units themselves. Placement guidelines are only given for a straight section of breakwater in which is a diamond-shaped pattern. However, for a curved section of breakwater a diamond shape does not satisfy anymore.
The problem with a curved section of a breakwater is the difference in radius lengths of the upslope rows, resulting in improper placement distances between the units higher upslope.
Using the current placement guidelines a detailed design of a placement grid for a breakwater is not possible at the moment. As a result the execution of an armour layer is some kind of a puzzle on which each unit has to be fitted on the already placed units.
To ensure a good armour layer, a proper placement grid has to be designed which includes the problems encountered at curved sections.

The placement of Xbloc is relatively easy because the placement is only depending on the position and not on orientation. With this independency of orientation the only one variable to construct a proper armour layer is the position of each unit. This dependency on position only makes the Xbloc an ideal unit for a systematic design of a placement grid.

Another problem encountered with the design of an armour layer is the hydraulic stability of the designed placement grid. There is no relation found in literature between placement grid and hydraulic stability. The only distinction made in hydraulic stability is between a straight section and a head of a breakwater. This is a crude schematization because there are more locations on a breakwater on which the placement pattern has irregularities.

Problem definition:
How to design a proper placement grid for the Xbloc while maintaining sufficient hydraulic stability and ease of placement.

Objective:
To make a detailed design of an Xbloc placement, this includes grid design, placement accuracy and quality control.

1.4 Approach

This study consists of three parts, theoretical analysis of a placement grid, placement experiments and description of systematic design procedure.
In the first part of this study all the aspects of a placement grid will be looked at, with this information an analysis for the best theoretical placement will be made. In the second part the theoretical placement is checked on constructability and accuracy by placement test with 18.2 cm Xbloc units. The last part of this study presents a systematic procedure to automatically design a placement grid. This will be based on the theory and experiments described in part one and two.

2 Design and construction of single layer armouring

2.1 Introduction

The armour layer is designed in close relation with the total breakwater design. The objective of this chapter is to give an introduction on the subjects and activities which play a role in the preparation and execution of the placement of a concrete armour unit. With this knowledge it is easier to understand the difficulties in the placement of single layer armour units.
In the design part the geometry of a breakwater and placement pattern will be shortly explained. In the construction part the attention in focused on the production and handling of Xbloc armour units.

2.2 Design issues

The layout of a harbour and the orientation of the marine structures such as breakwaters are mainly based on the dominant wave direction and tidal current. After the layout of the marine structures has been determined the detail design of the breakwaters can be made.
The most important design parameter of a breakwater is the wave height as this determines the type and size of armouring used. For relative small waves the armour layer is generally constructed with natural stone but when the waves are larger than 3 to 4 meters [H_s] it can be more economical to use concrete armour units or other type of breakwaters.
The design presented here will be a rubble mount breakwater with concrete armour units.

2.2.1 Waves

To predict the highest significant wave height during the lifespan of a breakwater, say 50 years, is rather difficult. The significant wave height is defined as the average wave height of the highest one third. This wave height is approximately the same as the visually observed wave height.

The most commonly technique used is extrapolation of existing wave data. The wave data available differs significant around the world. Historically wave data is collected by officers on board ships who are experienced and well trained in observing waves. Since the 1970 modern methods of wave measurement have been applied, the most commonly used techniques are electric wave gauges, floating wave buoys and satellites.

Because the wave data has to be extrapolated for life time of the structure it is important that the length of the dataset is long enough to ensure a statistical reliable design wave height.
Most wave data is collected at offshore locations whereas the near shore wave height is often required. The near shore wave height can be calculated on basis of offshore wave height by shoaling and refraction.
After this offshore/near shore calculation is made one last check has to be made. This is the comparison between the near shore wave height and the depth limited wave height. This is approximately at 60% of the water depth.

2.2.2 Crest level

The most important function of a breakwater is to provide shelter and to prevent wave penetration into the harbour. This wave penetration occurs in three different ways, via the entrance of the port, through the breakwater and via overtopping. The wave penetration by overtopping is mainly determined by the crest height.

Besides wave penetration a few other subjects can influence the crest level such as construction method or functions located at the breakwater.
A breakwater built with land-based equipment must be at least above high water level. The same holds for functions located at the breakwater. For example, if a quay is designed onto a breakwater the breakwater must be at least be at quay level. These secondary design values can be evenly important for determining the crest height as overtopping.

2.2.3 Underlayer

Introduction

Before armour layers can be placed a proper foundation is required, this is called an underlayer. The underlayer has two main functions. Firstly a filter function between the small core material and the large armour units. Secondly provide a smooth surface for the placement of the armour layer. The first function, prevention of scour holes in the core is obvious. If a scour hole develops below the armour layer, the armour layer becomes instable which can result in the failure of the armour layer.
The second function, smoothness of the underlayer, has a great influence on the quality of the armour layer. The hydraulic stability of the armour layer is largely originated by *interlocking*, irregularity in the underlayer makes it more difficult to obtain proper interlocking, if reached at all. Lack of interlocking will result in loss of hydraulic stability of the armour layer. To ensure a proper armour layer, design specifications for the armour layer have been drawn up for the Xbloc.

Weight of the underlayer

The weight of the underlayer is based on the hydraulic stability. The required weight of the underlayer is chosen based on the size of the armour unit.

For the underlayer of an Xbloc breakwater, it is recommended to use standard rock grading as specified in CUR/CIRIA and listed in the Xbloc design table. If the use of this standard grading is not desired, the following requirements are given by DMC:
- The W_{85} of the underlayer grading shall be smaller or equal to $W_{Xbloc}/7$,
- The W_{50} of the underlayer grading shall be between $W_{Xbloc}/9$ and $W_{Xbloc}/11$,
- The W_{15} of the underlayer grading shall be larger or equal to $W_{Xbloc}/15$,

In Which:
W_{Xbloc} = the weight of the Xbloc,
W_{85} = the rock weight that is exceeded by 15% of the rocks in the underlayer
W_{50} = the rock weight that is exceeded by 50% of the rocks in the underlayer
W_{15} = the rock weight that is exceeded by 85% of the rocks in the underlayer

Layer thickness

The normal design thickness of the underlayer is two times the D_{n50} (D_{n50} is the nominal diameter of the rock in the underlayer). The D_{n50} is directly connected with weight of the rock by $\left(\frac{W_{50}}{\rho_{rock}}\right)^{1/3}$. The value of two times D_{n50} is derived from the hydraulic stability and the constructability in prototype.

Smoothness of the underlayer

The allowable deviation in the underlayer is currently expressed in the stone size of the underlayer itself. With this approach the allowable deviation of layer thickness is only dependent on the underlayer itself and not directly linked to the armour units which will be placed onto the underlayer.
The new function of the underlayer, smooth surface for the placement of concrete armour units, means that the allowable deviation is also dependent on the armour unit size, this aspect has been overlooked in the specifications for the Xbloc.
The standard grading for the underlayer is constant for a number of Xbloc sizes, this means that the allowable deviation for the underlayer is also constant for a number of Xbloc sizes. This is not correct from the point of required smoothness for the placement of the armour units. For proper interlocking it would be better to express the allowable deviation of the underlayer in D (characteristic dimension of Xbloc) instead of D_{50} of the underlayer, the interlocking must be realised with the Xbloc and therefore it makes more sense to use the characteristic size of the Xbloc.
To formulate a proper allowable deviation of the underlayer it is important that both functions are included in the determination of the allowable deviation.

2.2.4 Toe

Because the armour layer is relatively expensive part of the breakwater it is tried to minimize the area on which the armour layer has to be applied. For the stability of the breakwater it is not always necessary to extend the armour layer to full water depth. The shore protection manual gives a rule-of-thumb, indication that the armour layer should extend down to about 1 wave height below the still water level. Below this water level the armour layer should be supported by rock with 1/10 of the armour weight, this is approximately the same size as the underlayer.
The standard toe consists of natural rock but when the armour layer is extended down to the seabed it is also possible to use the armour units itself to construct a toe. This is necessary to prevent the other units to slide down the slope.

A general formula to calculate the required stone size at various water depths is given by Van der Meer, d'Angremond and Gerding [1995].

2.2.5 Unit size

For the design of a placement grid it is crucial to know the unit size. This is not only for the characteristic diameter of the unit but also the dimensionless placing distances between the units are dependent on the unit size, see section 3.3.6.
The unit size depends on the maximum significant wave height [H_s] at the location of the breakwater during the lifetime of the structure.
For the concept design the unit size is calculated by an easy to apply and widely accepted stability equation, see below.

$$V = \left[\frac{H_s}{2.8\Delta}\right]^3$$

V = Volume of Xbloc [m^3]
H_s = significant wave height [m]
$\Delta = (\rho_c / \rho_w) - 1$ [-]

The stability number of 2.8 has been determined by extensive testing against wave loading in 2-D and 3-D models at Delft Hydraulics and other reputable hydraulic laboratories, like the Danish Hydraulic Institute.

2.2.6 Placement pattern

The unit placement pattern has a major influence on the hydraulic stability of the armour layer, as more than half of the hydraulic stability is generated by *interlocking*.

Staggered grid

The basic idea of the placement grid is the use of a staggered grid, this result in a diamond-shaped pattern, as shown in Fig. 2.1. A diamond-shaped pattern can be characterized by two values, horizontal distance and upslope distance, these distances are crucial in the design of a placement grid.

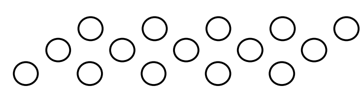

Fig. 2.1 diamond shaped grid

For a number of situations the normal diamond-shaped pattern does not fit anymore, for example at curved sections and by toe level variations. In these situations the placement grid should be modified in such a way that will maintain proper interlocking.

Packing density

The designed placement grid should contain the proper packing density. When the achieved placement deviates from the design grid it is possible to directly see the influence on packing density and it can then be decided to replace the unit or a whole section.
This placement grid will be focused on extensively thought out this study.

2.3 Construction

2.3.1 Placement

Equipment

The placement of armour units onto a breakwater is mostly done by a crawler crane, see Fig. 2.2. The crawler crane can be operated from the breakwater crest or from a barge. The benefit of placement from the crest is the stable basis from which the crane operates. This stable basis makes placement easier and has a positive influence on the accuracy of the achieved placement. The disadvantage for placement from the crest is that the units have to be lifted a large horizontal distance (at the trunk). This results in a larger crane needed than placed from a barge. Another limiting condition is the width of the crest, the crest must have sufficient width to be usable for the crane and the transport equipment.
If placed from a barge the sea conditions plays a major role in the ease and accuracy of the placement.

Fig. 2.2 crawler crane with Xbloc attached by sling

For small sized units a hydraulic excavator can be used instead of a crawler crane for the placement of armour units. The differences of a hydraulic excavator in relation to a crawler crane are:

- Higher operating speed
- Lower operating costs
- Lower lifting capacity

For smaller units the use of hydraulic equipment has only advantages in comparison to cable based equipment.

Traditionally, armour units are placed by sling. With a sling an armour unit can easily be attached to the hoisting cable. However a sling can get stuck between the armour units on the breakwater resulting in a difficult release of the sling.
Another solution can be the use of a clamp. Using this the hoisting equipment can never be jammed between two armour units, which reduce the change of delay. The disadvantage of a clamp is that it is a special tool and therefore not commonly available by contractors.

Operating procedure

The building sequence of units is determined by two aspects, gravity and the equipment used. Gravity determines that the armour layer is built from the toe towards the crest.
If a crawler crane is used the placement will be done in horizontal rows instead of diagonal rows to the crest of the breakwater. This is done because the adjustment of the boom (needed for placement closer tot the crest) is more time consuming than moving a little sideward. Another benefit of this way of placement that after the first row is placed a diver can inspect the achieved placement before the rest of the slope is built, which reduces the change of rebuilding the entire section.

Accuracy

Little is known on the achievable accuracy during placement. It is known that weather and sea conditions have a large influence on the accuracy achieved. Another unknown subject is the influence of placement quality on hydraulic stability. The prescribed placing grid with the allowable deviations is based on experience and expertise of the designers. To determine the location of the individual units during placement instruments are used such as land surveying equipment (theodolite) and DGPS (Differential Global Position System). With the DGPS receiver directly mounted onto the tip of the boom, the accuracy in the position with DGPS is in the order of 10-50 cm.
A less known phenomenon is the influence of the orbital motion of the water due to waves on the submerged armour unit. If the response of the armour unit turns out to be significant, it is important that this effect is taken properly into account with a downtime study for the construction of the armour layer. If the movements of the units are too extreme, another way of placing should be applied to ensure correct placement.

2.3.2 Quality control

To ensure a proper working of the armour layer the interlocking must be good. This will only be the case if the armour unit is placed on its correct position. The position of each unit has been designed in the detailed design.
To check the quality of the armour layer, all units are controlled on their placed position in comparison with their designed location, above water this can be done with land surveying equipment. The units below the water level are more difficult to measure, this can be done with divers, see Fig. 2.3.

Fig. 2.3 diver checking Xbloc position

The location of the first row of armour units are the most important because they determine the position of all the units placed above.
Each unit will be logged on their horizontal position (x, y) when placed. If this placement does not fulfil the specifications for the given armour unit the unit or whole section has to be replaced.

3 Analysis of placement grid

3.1 Introduction

A predefined placement grid is the basis of every single layer armour layer which has to be constructed. The most important parameter of an armour layer is the packing density, if the required packing density is reached it is almost certain that there are no major faults in the armour layer.
A high packing density will result in good *interlocking* between the units. Proper interlocking is reached by placing an armour unit in the middle between 2 *base units*. The quality of interlocking is difficult to measure and is visually checked by experienced engineers, an objective way of measuring the interlocking will be presented in 3.3.4

To achieve proper interlocking the placement grid of single layer armour units have to comply with the following requirements: horizontal rows have to be approximately parallel with the contour line of the slope and the distance between the base units must be in a proper range (not to wide not to small).

The horizontal placing distances is an important limitation for the design of placement grid. The influence of placing distance on achieved density and interlocking is presented in section 3.3.5. The results of this study are used to optimize the placement grid.

3.2 Placement guidelines for the Xbloc armour unit

In October 2002 the first hydraulic tests were performed at Delft Hydraulics. For the placements of Xbloc no specifications existed at that moment. The placement was done by the people of Delft Hydraulics, based on experience gained from other single layer armour units and experience from preliminary tests on the Xbloc unit.

The first placement section built had a horizontal placing distance of 1.39*D (D = unit size) and an upslope placing distance of 0.63*D. These placing distances resulted in a packing density of $1.13/D^2$. After the first hydraulic test significant settlements had occurred, resulting in a decreased upslope distance of approximately 0.58*D and as a result the packing density increased to approximately $1.225/D^2$.

In the following tests the horizontal placement distance was decreased to prevent the settlement experienced in the first test. From these tests a horizontal placing distance of 1.30*D and an upslope placing distance of 0.64*D is recommended. This placing distances results in a packing density of $1.20/D^2$.

These recommended distances are included in the specifications. With these distances the packing density is also prescribed by the specifications. For the whole breakwater the achieved packing density should be within 98% and 105% of this packing density.

The placement distances found will be used for small (up to $5m^3$) Xbloc units. For larger Xbloc sizes a larger placing distance is prescribed due to the more difficult placement, see Table 3.1.

This increased placement distance is based on experience gained with other single layer armour unit projects. As long as there is no data available from Xbloc projects in prototype, this is the best assumption for the time being, see section 3.3.7.

Table 3.1 placing distances versus unit size

Unit size	Dx [along the slope]	Dy [up the slope]
$V \leq 5m^3$	1.30*D	0.64*D
$5m^3 < V \leq 12m^3$	1.33*D	0.655*D
$12m^3 > V$	1.36*D	0.67*D

With these ideal placing distances a theoretical placement density can be calculated with the given formula: $\frac{1}{Dx} \cdot \frac{1}{Dy} = {}^{Xbloc}/_{m^2}$ resulting in:

Table 3.2 packing density versus unit size

Unit size	Packing density
$V \leq 5m^3$	$1.20/D^2$
$5m^3 < V \leq 12m^3$	$1.15/D^2$
$V > 12m^3$	$1.10/D^2$

The different placing distances for different Xbloc sizes have to be further investigated because the requirement of the achieved packing density is quite stringent. But the packing density required for larger Xbloc units drops by almost 10 percent. This decrease in packing density has been without any compensation for the loss in hydraulic stability, which is probably not realistic. The achieved packing density versus hydraulic stability is an important subject but lies outside the scope of this study.
Another interesting fact is that placements with low packing densities are likely to encounter settlements. The settlements continue until the density reaches a normal density of $1.20/D^2$, this has been observed in model tests.

The packing densities listed in Table 3.2 are given in the specifications for the Xbloc. These densities are derived from placement test on a straight section of breakwater. The same density specifications are extrapolated to curved sections of breakwater. This extrapolation has to be checked because the placement pattern will also change.

3.3 *Empirical knowledge and theoretical relations*

All fundamental principles for positioning and placement of a unit are used for the design of a placing grid. This means that all principles have to be incorporated into one method to automatically design a placing grid.
Therefore the principles will be treated on their background, importance and implantations for the design of a placement grid.

3.3.1 Historical development of armour unit shape

Over the years various shapes of armour units have been developed. The first concrete armour unit applied was a cube, which was the first alternative for natural rock. The design of an armour layer with concrete cubes was very similar to an armour layer with natural rock, as the units are randomly placed in a double layer.
In the last 50 years a number of other shapes have been introduced, see Table 3.3. The main objectives of these units are to maximize hydraulic stability and to minimize concrete consumption, which results in an economical attractive breakwater design. An overview of some of the units is given in Table 3.3.

Table 3.3 historical development of selected armour units

Armour unit	Country	Year	Armour unit	Country	Year
Cube	-	-	Seabee	Australia	1978
Tetrapod	France	1950	Shed	UK	1982
Tribar	USA	1958	Accropode	France	1980
Modified cube	USA	1959	Haro	Belgium	1984
Stabit	UK	1961	Hollow Cube	Germany	1991
Akmon	NL	1962	Core-Loc	Usa	1996
Tripod	NL	1962	A-Jack	USA	1998
Dolos	South Africa	1963	Diahitis	Ireland	1998
Cob	UK	1969	Samoa Blocks	USA	2002
Antifer Cube	France	1973	Xbloc	NL	2003

The basic idea how to maximize hydraulic stability can be divided in three stability mechanisms: own weight, interlocking, friction or a combination of these mechanisms.
A general observation is that the more a unit depends on interlocking or friction the more important the placement will be on the hydraulic stability. This importance of placement requires a proper placement grid. The units can be classified by shape, stability mechanism and importance of placement as presented in Table 3.4

Table 3.4 an overview of armour units with their corresponding stability machanisms

Placement Pattern	Number of layers	Shape	Stability mechanism			Importance of placement
			Own weight	Interlocking	Friction	
Random	Double layer	Simple	Cube Antifer Cube modified Cube			minor
		Complex	Tetrapod, Akmon, Tribar, Tripod			average
				Stabit, Dolos		
	Single layer	Simple	Cube	A-jack, Xbloc		important
		Complex		Accropode,Core-Loc		
Uniform	Single layer	Simple			Seabee, Hollow Cube, Diahitis	very important
		Complex			Cob, Shed	

3.3.2 Shape of single layer armour units

Nowadays most rubble mount breakwaters are protected by randomly placed single layer armour units. The hydraulic stability of these single layer armour units is affected by the way they are placed. Therefore this section is focussed on single layer armour units.

Before the orientation of a unit will be addressed more attention is paid to the shape of a single layer armour unit.
Most units are composed of bars, these bars together create a 3-D shape unit, but the bars itself can be placed in two directions or three direction. For example Accropode and Core-Loc have bars placed in two directions, two bars in the same direction and one perpendicular to these bars, whereas A-jack and Xbloc have three bars in perpendicular directions. This results in a centre-based construction for A-jack and Xbloc, see Fig. 3.2, and a stacked bars construction for Accropode, see Fig. 3.1, and Core-Loc.

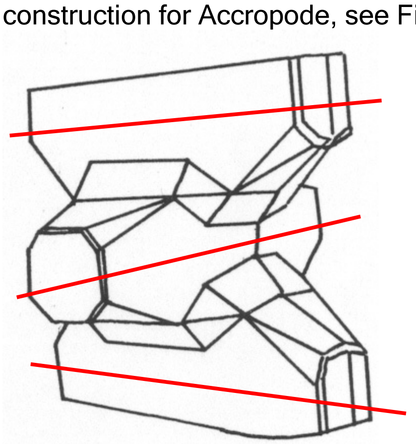

Fig. 3.1 bars of Accropode

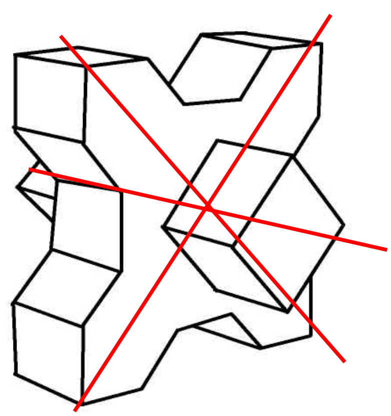

Fig. 3.2 bars of Xbloc

The benefit of the centre based unit in comparison with a stack based unit is that it has no anvils. The anvils of a stack-based unit make it more difficult to place, where as a centre based unit has more evenly distributed notches, which ensure more ease of placement and proper interlocking.

To be more specific about the orientation of an Xbloc, different parts of the Xbloc has been named, as shown in Fig. 3.3. These names will be used through out the report.

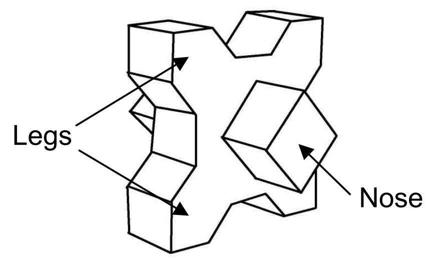

Fig. 3.3 definitions of parts of an Xbloc

Besides the difference in orientation, the stack- and centre-based units will both use the centre of gravity to determine the position. A placement grid will only give the centre of gravity of each unit and not the orientation, therefore it is possible to design a placement grid for any single layer armour units. Off course each unit has its own density and placing distances but the basic principles are the same. This study is focussed on Xbloc only and design parameters will be applicable for the Xbloc.

3.3.3 Packing density

The packing density is expressed in the number of units per square metre, which is relative easy to measure in prototype. The packing density is a quantitative parameter for the quality of the armour layer, which will be used in prototype.

The method to measure the packing density is done by measuring the distances between the units. This can be done for each unit individually but also with a number of units at the same time by the following formula: $PD = \frac{(N_x - 1)(N_y - 1)}{L_x L_y}$

PD = packing density [1/m^2]
N_x = horizontal number of units [-]
N_y = number of horizontal rows [-]
L_x = horizontal length of the section [m]
L_y = length up the slope along the slope [m]

If the packing density is too low it is probably caused by skewness in the staggered grid. A unit is placed in the middle between two units it will sink further in between the two units than when the placement is skewed, this results in larger placing distance upslope and thus a lower packing density, see Fig. 3.4. This phenomenon will be addressed in section 3.3.9.

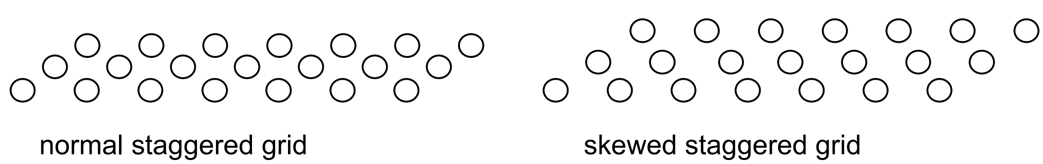

Fig. 3.4 normal and skewed grid

If the packing density is too high it is probably caused by units placed partly onto each other, this overlapping is not wanted because it will distort the placement pattern and this can weaken the armour layer. Beside the distortion in the placement pattern another unwanted side effect is a higher concrete consumption. Therefore attention has to be paid that no units are placed on top of each other, as shown in Fig. 3.5.

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Fig. 3.5 unit placed partly onto other unit

3.3.4 Potential interlocking coefficient

The Xbloc has been designed based on the principle of interlocking. This means that for hydraulic stability the Xbloc is depending on its neighbours. To optimise interlocking a diamond-shaped pattern is the best solution. With this pattern each unit is in contact with four other units, two units below and two units above.

The hydraulic stability of an armour unit can be predicted by the potential interlocking. The quality of interlocking is dependent on position and orientation of the surrounding units. The larger the overlap with the surrounding units the better the interlocking will be. This is the reason that the packing density is already an indication of the quality of the armour layer. The improvement of the PIC over packing density is the possibility to spot deformation in placement pattern with the same packing density.

In the design phase the orientation of the unit is not known and can therefore not be used by prediction of interlocking. To predict the interlocking capacities of the armour layer a potential interlocking coefficient (PIC) is be suggested. This potential interlocking is based only on the position of the surrounding units. Each unit will interact with four other units, left and right above and left and right below, see Fig. 3.6.

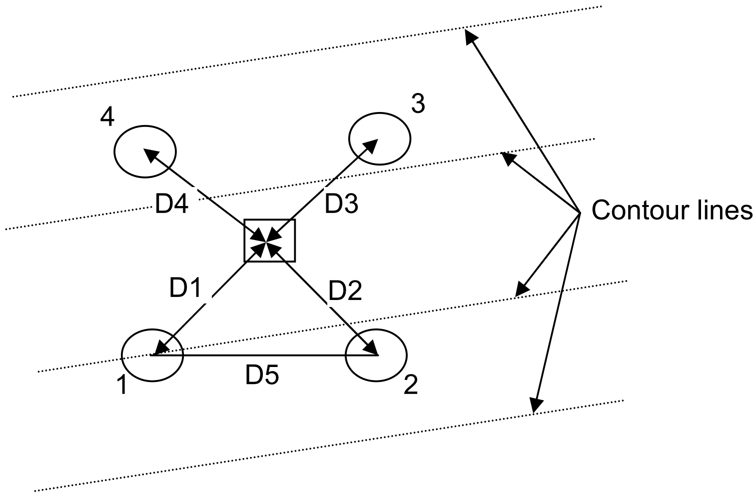


Fig. 3.6 potential interlocking coefficient

To quantify the potential interlocking coefficient a scale of 0 to 10 is used. The mark 0 is given to a unit without any interaction with other units and the mark 10 is given for a unit which is interacting with 4 units in a perfect diamond-shaped pattern.
The mark is built up by five separate factors, the four distances to the surrounding units and the skew between the two *base units*. If the two base units are not level the unit will receive less stability from these two units, this is accounted for in the mark for potential interlocking by applying a reduction factor.
The distance to each surrounding unit in a perfect diamond-shaped pattern is 0.91 D, if the actual distance is equal to this distance the unit will receive 2.5 points, if the distance is 1.41 D or larger the unit will get 0 point. The distance of 1.41 D is chosen because this it is the largest diameter of an Xbloc. For any distance larger than 1.41 D it is impossible to have any interaction. So the maximal number of point is 10.

The formula to calculate the potential interlocking coefficient is given by:

$$\text{PIC} = \left(1 - \left|\arctan\left(\frac{z.2 - z.2}{D5}\right)\right|\right) \cdot \sum_{1}^{4}\left(2.5 - 5 \cdot \left(Di - \sqrt{(0.5 \cdot dx)^2 + dy^2}\right)\right)$$

z.1 = Z coordinate of unit number 1
z.2 = Z coordinate of unit number 2
D5 = distance between unit 1 and 2
Dx = recommended horizontal placement distance
Dy = recommended upslope placement distance
Di = distance 1 - 4

The formula is built-up in two parts, first part is the reduction factor for possible skewness and the second part is the summation of the individual points collected from the four surrounding units.

3.3.5 Theoretical placing distance versus packing density

An imported requirement for the placement of single layer armour is packing density. The packing density is directly related to the placing distances. The relation between horizontal placing distance and upslope placing distance is the main subject of this section.

The packing density is calculated by the horizontal distance and the upslope distance [3.3.3]. With a relation between horizontal distance and distance upslope the packing density can also be expressed in the horizontal placing distance.

To derive the theoretical relation between de horizontal placing distance and the distance upslope two hypotheses have been made:

1. The distance between two units which are in contact is constant
2. The minimum upslope distance is determined by the unit two rows below

The first hypothesis is based on the fact that a newly placed unit is supported by two units one row below. The distance between two units which are in contact with each other is assumed to be constant, see Fig. 3.7. As a result the distance up slope decreases if the horizontal distance increases.

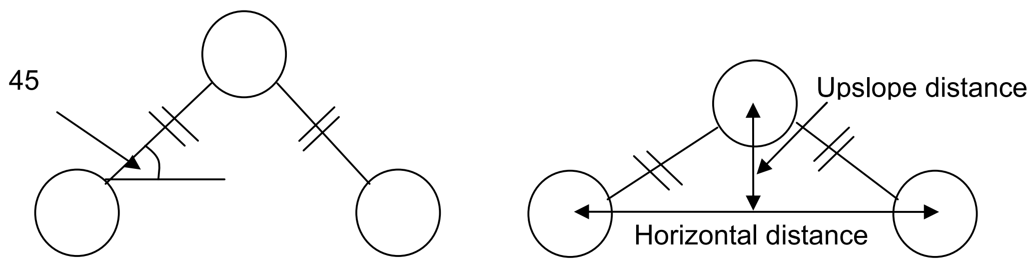


Fig. 3.7 constant distance between units which are in contact with each other

With given horizontal and upslope placing distances for the Xbloc the angle between the baseline and constant distance line is approximately 45 degrees resulting in an almost constant packing density around the ideal horizontal distance, see Fig. 3.8.

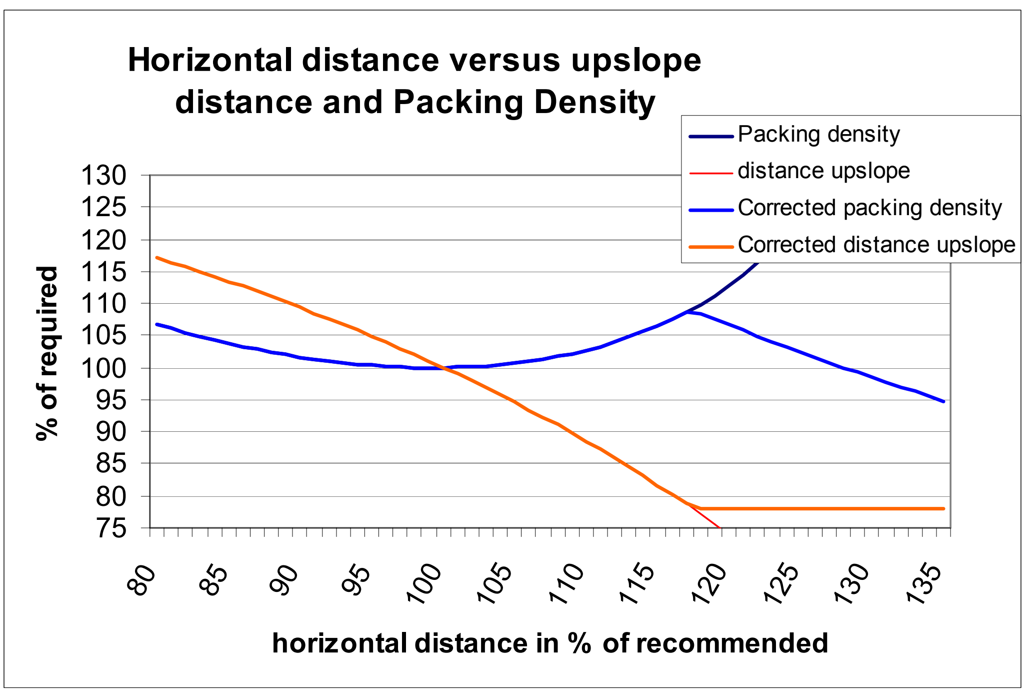


Fig. 3.8 placing distance versus density

The hypothesis also predicts that for small and large horizontal distances the packing density will increase. This is because with an angle larger or smaller than 45 degrees the upslope placement distance does not react linearly with the horizontal placement distance.
This hypothesis is not true for large deviations in horizontal placing distance because there are other limiting conditions such as more difficult placement with small horizontal distances and touching the unit two rows below with large horizontal placement distances.

The second hypothesis is based on the physical limitation of the minimum distance upslope. The minimum distance between these two units is 1.0 D, see Fig. 3.9. As a result the distance upslope can never be smaller than 0.5 of the unit size.

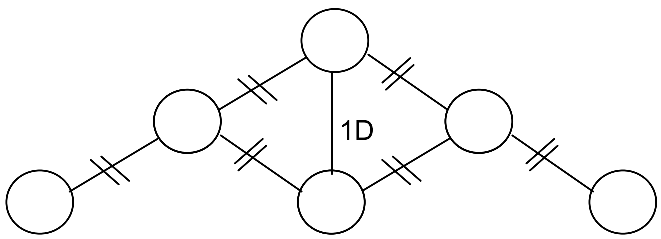


Fig. 3.9 limited vertical distance

With the second hypothesis implemented in the model and as a result the upslope placement distance will get constant around 120 % of the horizontal placing distance. As a result of this packing density will decrease, see Fig. 3.8.

3.3.6 *Experimental placing distance versus packing density*

Model description

These hypotheses have been verified by model tests. The model test has been performed with 4.3 cm Xbloc units on a smooth surface (no underlayer). The smooth underlayer is chosen to get instant settlement, in prototype the armour layer will settle a little due to moderate waves.

The first row of Xbloc units has been placed on accurate horizontal placement distances. After the first row the next rows have been placed by hand in a diamond-shaped pattern.
The horizontal placement distances tested vary from 85% up to 135% of the recommended placement distance by DMC. The step size in horizontal placement distance is 5%. The results are given in Fig. 3.10. To filter out the individual results each horizontal placement distance has been tested three times.

To measure the achieved density, the upslope distance has been measured on 9 different vertical rows and then averaged. With this average upslope distance and known horizontal distance the density has been calculated.

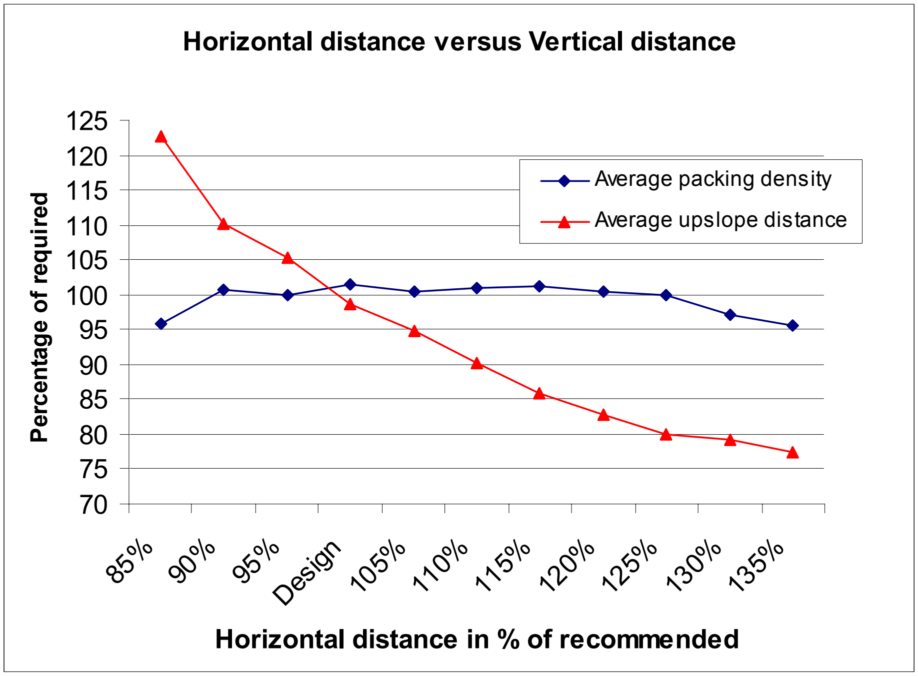


Fig. 3.10 X-distance versus Y-distance and density model tests

Results

From Fig. 3.10 it can be seen that the relation between horizontal distance (X-distance) and density is constant in a large range (90% up to 125%). The reason for this constant density is that with increasing horizontal distance the upslope distance decreases.

The 85%, 130% and the 135% placements did not reach the required density and are therefore rejected as acceptable horizontal distances.
The 90% placements did fulfil the density specification but it was difficult to place the armour unit between the two units in the row below. As this placement is already difficult, it will almost impossible to place in prototype. Because of the difficult placing this horizontal distance will also not be used in an Xbloc grid design.
The 125% placement did fulfil the density requirement but the unit did not interlock properly with its neighbours. Instead of interlocking with its neighbours it leans onto the unit 2 rows below. This can reduce the hydraulic stability and is therefore not used in the Xbloc grid design.
The 95% up to 120% the placement pattern and density were good. This range can by used to overcome curved sections of breakwater and toe level variations.

In the model tests the packing density is even more constant than the hypotheses predicted, see Fig. 3.11. The loss in packing density with large placing distances coincides pretty well with the model. Only the peak in packing density predicted around 115 % with the model does not appear in the model tests, which can be explained by the fact that the unit touches the unit two rows below much earlier than expected, reducing the density. This early touching of the units can be explained by the fact that it is placed with 1 leg pointing downwards, in this orientation the unit has its largest diameter, 1.41 D instead of the 1 D used in the model. To describe the area around 115 % a non linear function has to be applied for the minimum distance to two rows below.

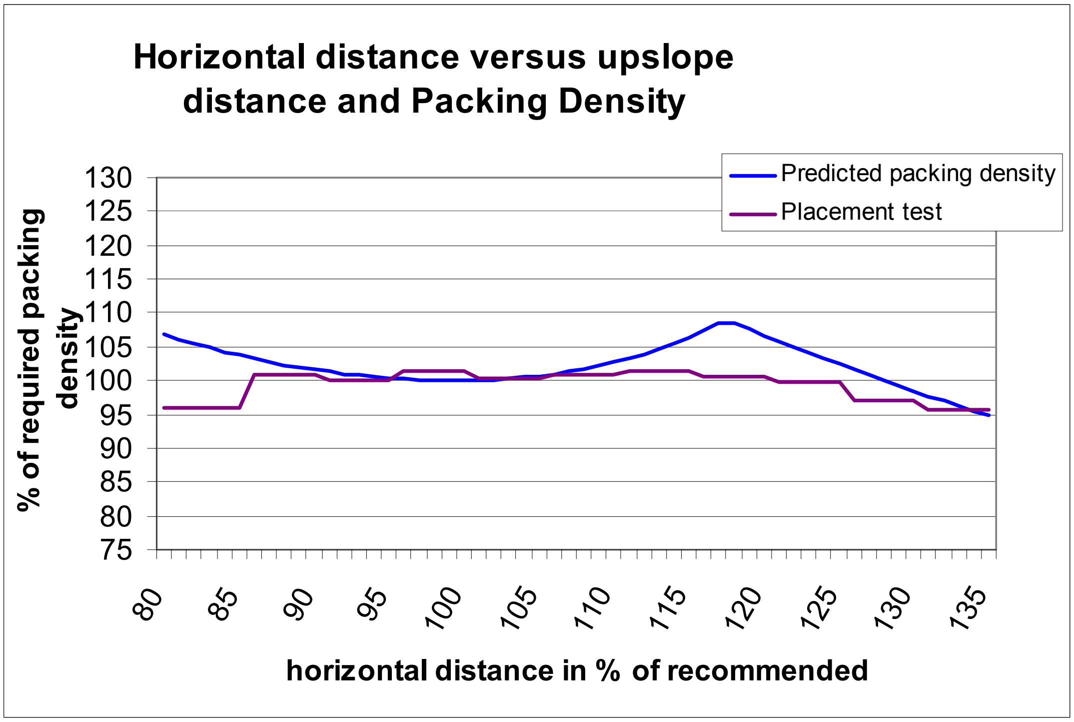


Fig. 3.11 comparison between predicted and measured packing density

3.3.7 Influence of block size on packing density

Single layer armour units have in general a lower packing density when the unit size increases. This is an effect of the more difficult placement of larger units. This lower packing density is important to know because it should be accounted for in the design, both in hydraulic stability as well as for the placement drawings.

The predicted hydraulic stability using the potential interlocking coefficient for a straight section of breakwater covered with 20 m^3 Xbloc units is maximal 8.5. Therefore a loss in hydraulic stability of about 10 % is anticipated, (see section 3.3.4).

A benefit of this reduction in packing density is that the total number of unit needed for the armour layer is decreased in comparison with small units. This reduction has economical benefits for selection of the type of armour unit. However the requirements for some units have become more stringent in recent years, this has been done to prevent settlement of the armour layer after the first storm. This result in less reduction in packing density for large units, this has been done by Core-Loc international and Sogreah (Accropode). See Fig. 3.12

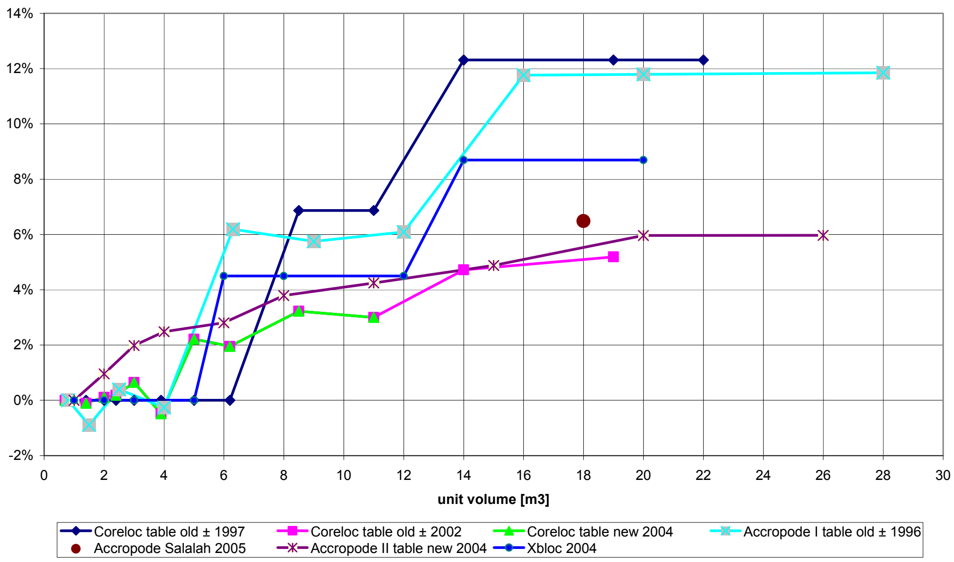


Fig. 3.12 reduction in packing density for larger armour units

The latest Core-loc specifications give a reduction in packing density for the largest unit ($11m^3$) of 3% which was 7% in 1997.
The Accropode had a reduction for the largest unit ($26m^3$) of almost 12 % and for the new Accropode II the reduction is only 6% ($26m^3$).

The latest model tests executed in South Africa represents 15 ton Xbloc units. The units were placed on a horizontal distance according to their placing distance in prototype of 1.33*D which is 2.3% larger than normal. The distance upslope should also be 2.3% larger than normal. This was not the case instead the larger horizontal placing distance led to smaller vertical distances. This effect was reached directly after placement.
The reduced upslope distance corresponds with the relation found in placing distance versus packing density. This is the result of small scale model units but it has to be monitored in prototype.

It seems that all single layer armour units have a natural packing density just like granular material like sand and gravel. Armour units can be loosely packed just as sand but it will settle to its natural density after some wave action.

With the knowledge about settlement and economical benefits a delicate balance has to be found between constructability, hydraulic stability and economical benefits (fewer units).

3.3.8 Placement of submerged units

The difference between submerged placement and placement in the dry is the visual information which is not available under water. As result of this limitation the units must be placed on position by a pre-established position of the crane.
Another difficulty of submerged placement is that the orientation of the unit also has to be determined on information which is not available, such as position and orientation of the already placed units.
It has to be tested if centre based units can be placed on basis of their position only, if this is the case it will make submerged placement a lot easier. These tests are performed in the laboratory at TUDelft and the results are presented in section 5.6.

3.3.9 Off centre placement of units

Normally single layer armour units are positioned in the middle between two units below. On a breakwater head this pattern is not sustainable because of the decrease in radius length higher up the slope.
If the units are kept in the centre position until the horizontal distance becomes so small that the next row of units do not fit anymore. So the next row would contain half of the original units. This is because for every other unit one unit has to be left out. To solve this problem if the units are shifted a little towards the side before the unit is left out.

The mechanism to shift the unit is driven by the distance between the horizontal neighbour, u3 and the new unit N, see Fig. 3.13. If distance d3 becomes too small the units can shift a distance Δx along a straight or curved line to give more space for the new unit.
Using the hypothesis of constant distance between two units which are in contact with each other, see section 3.3.5, the curved line should be used to shift a unit. However to keep the shifted distance *off centre distance* Δx comprehensible a simplification is made to use a straight line.

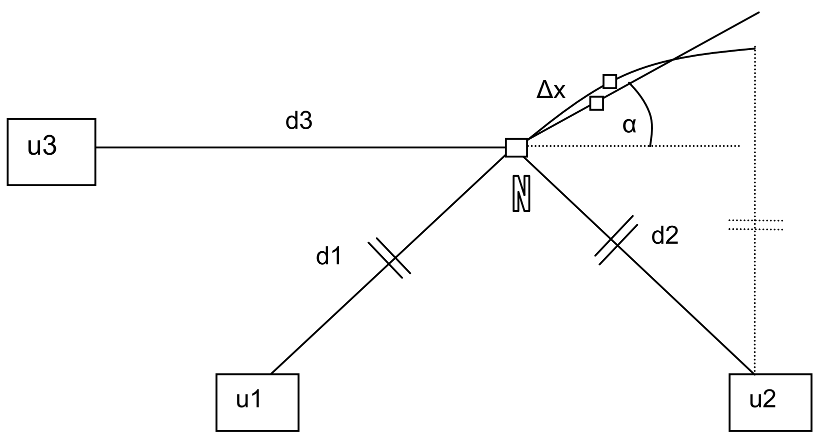


Fig. 3.13 shifting a unit by Δx

If the unit has to be shifted over a too large distance Δx the unit is left out. The distance Δx shifted is calculated by a nonlinear error function of distance d1, d2 and d3. A small deviation the distances d1, d2 and d3 will has almost no effect on Δx but when the distances becomes smaller than a minimum distance between two units Δx will almost linear.

The exact function for shifting the new unit and the maximum deviation of this unit has to be studied carefully. This should be verified with model testing in a laboratory.

With the hypothesis of constant distance between two units which are in contact, the unit adjust angle α is depended of the distance shifted. With the straight line simplification a fixed angle will be used as shown in Fig. 3.13. This angle will be slightly smaller than the start angle of the arc. As a first estimate the angle will be set to 30 degrees, if necessary the angle will be adjusted after the model tests.

3.3.10 Self correcting behaviour of misplacement

The placement of an armour unit will be done on basis of the two units in the row below (basis units). In this way the new unit is properly interlocking with the two already placed armour units. Another important benefit of this placement pattern is that the deviations from

the ideal placing position are automatically corrected higher up the slope, this effect is only reached if the average horizontal placing distance is correct.
In each row the individual placing error becomes half of the original placing error, this effect is reached because the horizontal distance in the new row is depended of two horizontal distances in the row below. See Fig. 3.14, here the first row is placed irregular but the rows higher up the slope the horizontal distances become more regular.

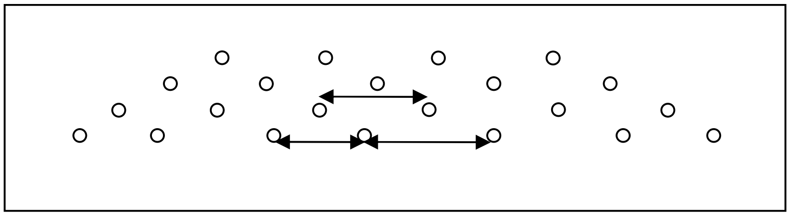


Fig. 3.14 self correction behaviour of misplacement

4 Placement of an Xbloc

4.1 Methods to place an Xbloc unit

To ensure a proper interlocking and ease of placement the orientation of the hanging armour unit is of great importance. A hanging unit should be both safe and stable, the term safe relates to the possibility of a unit falling out of its hoisting equipment.
The most common technique used for placement of armour units is by sling. Various types of sling techniques have been tested. For the Xbloc only two orientations are recommend, one for the units placed in the first row and one for all units placed upslope.
The most important property for the units in the first row is the horizontal placement distance. This distance is most accurately reached with the unit hanging with three points pointing downwards, see Fig. 4.1. In this orientation the unit does not topple over when touching the filter layer. If a unit in the first row is placed with one leg pointing downwards like the units upslope the unit will topple over and its centre of gravity can deviate from its hanging position by 0.5 D.
Xbloc units upslope are placed with one leg of the X pointing downwards as shown in Fig. 4.2, in this orientation the unit can be easily placed between two units the row below ensuring proper interlocking.

Fig. 4.1 Xbloc with three points pointing downwards

Fig. 4.2 Xbloc with one leg pointing downwards

The orientation of a hanging unit is depending on the *sling path* and sling length. The sling path is the route the sling follows around a unit, see Fig. 4.3

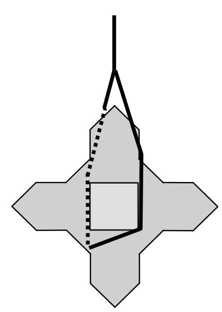


Fig. 4.3 sling path

The sling length is determined by the lifting procedure while lifting the unit it rotates from a storage orientation into the hanging orientation, see Fig. 4.4. If the sling length is too long the unit will not rotate enough resulting in a less favourable orientation.
With the sling paths used for the Xbloc, the sling length has a little to no influence on safety and stability of the hanging unit.

Fig. 4.4 rotation by lifting of the unit

From experiments it turns out that the ideal sling length for both orientations is three times the characteristic diameter.

After a unit is place onto the slope the sling has to be released. To ensure an easy release of the armour unit a quick release hook is used, see Fig. 4.5. With a quick release hook one end of the sling can be released by a secondary cable opening the hook. The benefit of this method is that no diver is needed to release the sling.

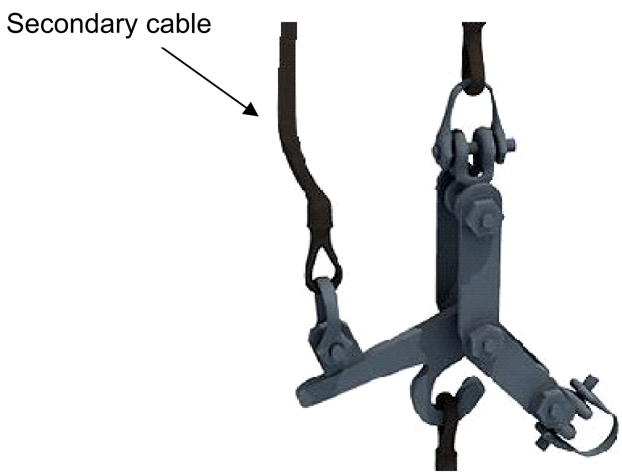


Fig. 4.5 quick release hook

4.2 Influence of waves during placement

4.2.1 Introduction

From experience in prototype it is known that a unit can swing during placement due to waves. Since there are almost always waves during construction of the armour layer it is important to understand and quantify this phenomenon. When the waves are harmonic with long periods (swell) a hanging armour unit can become in resonance causing large motions in the armour unit. This swinging motion will has significant influence on the achievable accuracy of the placement.
This resonance phenomenon will be schematized by a pendulum. This schematizing is justified by the fact that the mass of the unit is much larger than the weight of the hoist cable and that the drag and inertia forces on the cable are also negligible in comparison to the forces working on the unit.

4.2.2 Water motion due to waves

The waves produce orbital water motion. The horizontal motion of this orbital motion is the interesting part, whereas the hanging unit has the freedom to move in the horizontal plane.
With the horizontal water motion the hydraulic forces acting on the unit are calculated. There are three formulas to calculate the horizontal water motion, all three formulas have their own area of validity depending on water depth over the wave length, see Table 4.1 maximal horizontal velocity Table 4.1.

Table 4.1 maximal horizontal velocity

	Deep water $\frac{h}{L} > \frac{1}{2}$	Shallow water $\frac{h}{L} < \frac{1}{20}$	Transition between shallow and deep $\frac{1}{20} < \frac{h}{L} < \frac{1}{2}$
Max horizontal velocity	$\hat{u} = \frac{1}{2}\omega H e^{ka}$	$\hat{u} = \frac{1}{2} H \sqrt{\frac{g}{h}}$	$\hat{u} = \frac{1}{2}\omega H \left(\cosh\left(\frac{2\pi(h+a)}{L}\right) \Big/ \sinh\left(\frac{2\pi(h)}{L}\right) \right)$

With the typical values for waves (swell) and water depth at the toe of a breakwater the formula needed is the formula for transitional water.

For example, with a depth of 8 meter and swell with a period of 8 seconds the wave length is 64.9 meter resulting in an h over L of 1 over 8. This h over L requires the formula for the transition. With a wave period of 12 sec the wave length becomes 103 meter resulting in an h over L of 1 over 13, with this h over L the same formula is still applicable.

4.2.3 Forces acting on a submerged Xbloc

The water motion will apply a dynamic force onto the unit. To calculate the forces on the unit the Morison equation for a stationary object in oscillating flow (Keulegan and Carpenter, 1958) is used.

$$f = C_m \rho \frac{\pi}{4} D^2 \frac{\partial u}{\partial t} + C_d \frac{\rho}{2} D|u|u$$

The coefficients C_m and C_d in the Morison equation should be in the order of 0.5 to 1.5 according to various shaped found on the internet [http://www.grc.nasa.gov/WWW/Wright/airplane/Images/shaped.gif]. Due to the rough shape of the Xbloc the coefficient are likely to be on the high end of this estimate but the actual coefficients are fitted by model tests.

4.2.4 Pendulum

The large mass of the Xbloc in comparison to the hoisting cable makes the system ideal to schematize as a pendulum. Due to the external force it is schematized as a forced pendulum, see Fig. 4.6.

For the fact that a hanging Xbloc unit is not stationary but free to move the Morison equation is slightly adjusted.

Instead of the velocity and acceleration of the water, the difference in velocity and acceleration between the water and the unit are used in the adapted Morison equation.

$$f = C_m \rho \frac{\pi}{4} D^2 \frac{\partial \Delta u}{\partial t} + C_d \frac{\rho}{2} D|\Delta u|\Delta u$$

The restoring force of the pendulum is the acceleration due to gravity. The gravitational force of a submerged unit is reduced by Archimedes' principle. This reduced gravity and damping results in a longer Eigen period than with a free surface pendulum which is given by:

$$Period = 2\pi \sqrt{\frac{l}{g}}\ .$$

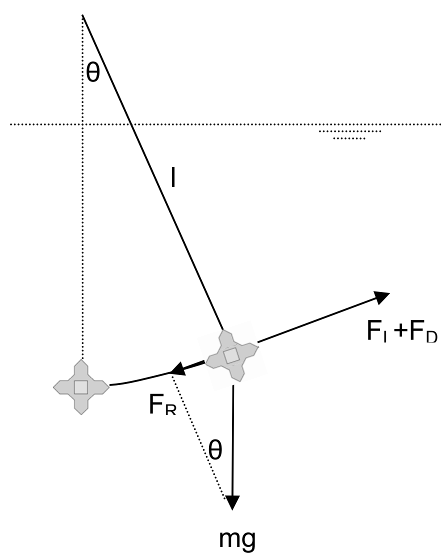


Fig. 4.6 forces acting on unit

4.2.5 Numerical solution

To predict the behaviour of a submerged Xbloc unit hanging on a crane the equation of motion is solved by a computer program using the Runga-Kutta scheme. To make sure no programming errors have been made in the numerical solution is be checked with the much easier to construct but less accurate Euler scheme.

The time step used is 0.03 seconds. This time step is chosen to get reasonable number of data points for the simulation period of 30 seconds. Test runs with a time step of 0.003 seconds didn't show any improvements in the model results so it can be concluded that 0.03 is small enough to get reliable results.

The input form of the numerical model is given in Fig. 4.7. The parameters given in this form are also used in model tests. The drag coefficient [C_d] of 1.2 and the inertia coefficient [C_m] of 1.5 are the best fits given the model test results.

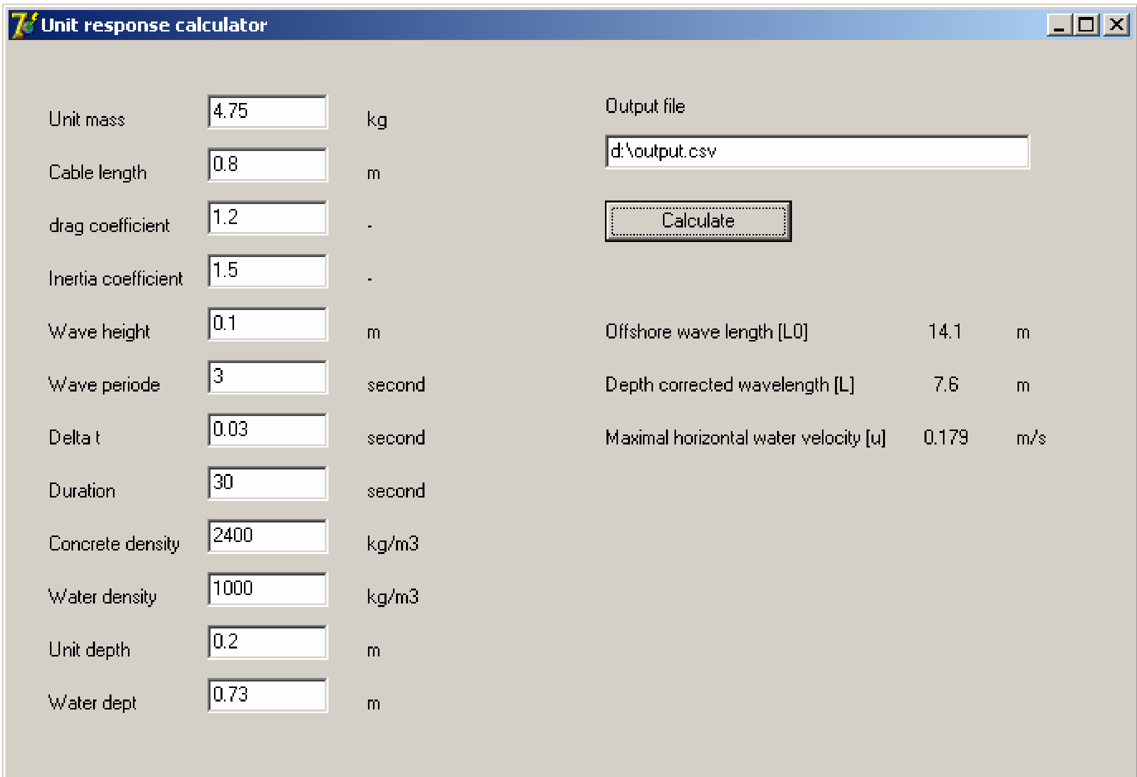


Fig. 4.7 input form

Calculation of the forces and response of a unit

The calculation is done in two phases, the First phase is the calculation of the water movement, this is given in the right side of the input form by u in [m/s]. In the second phase the forces and movement of the unit are calculated and written to an output file.

On t = 0 the location of the unit and the acceleration and velocity of both water and unit are known (Initial values). With these values the hydraulic and gravitational forces acting on the unit are calculated. The gravitational force is calculated by: $\Delta mg \cdot \sin(\theta)$.
The total force and thus the acceleration of the unit is calculated by the equation of motion. With the calculated acceleration and initial velocity the new velocity and position of the unit are calculated on t+Δt. This loop repeats until the given end time.

An example of a calculation is given below. The example is a prediction of the model test performed in a wave flume with a 4.75 kg Xbloc unit (18.2 cm).

The numerical model gives beside the amplitude of the unit also the hydraulic forces acting on the unit, see Fig. 4.8. These forces are used to check if no calculation errors have been made in the simulation.

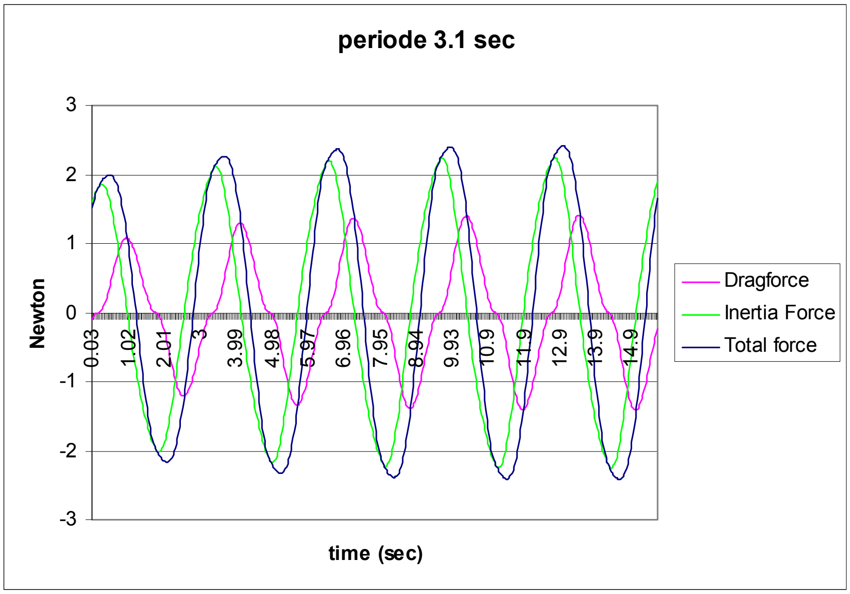
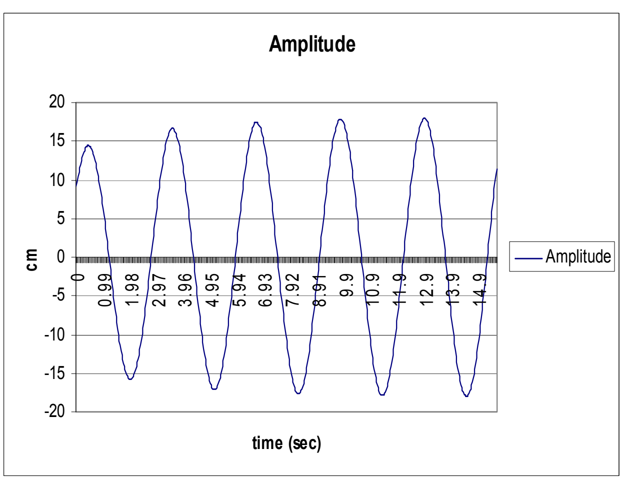


Fig. 4.8 forces acting on a unit

Besides the check on calculation errors the figure can also give insight information on the behaviour of a submerged unit. The observations are given below.

- The inertia force is out of phase with the drag force by ¼ of the period. This is explained by the fact that the inertia force is generated by the acceleration which is the first derivative of velocity which is also ¼ of the period out of phase.
- The inertia and drag force are of the same order of amplitude.
- The response of the armour unit is directly connected with the water motion, the wave period and the response period of the unit are exactly the same.
- The response of the armour unit is at full amplitude after approximately three waves, this means the full amplitude has developed before a unit is placed onto the slope.



In the numerical model at T = 0 the unit has no velocity and acceleration and is hanging straight down. These are the same conditions as when a unit is lowered into the water.
To compare the calculated unit response with the measured unit response in the wave flume the first 1.7 wave periods has been removed from the calculation to get the same time interval.
The unit response calculated by the numerical model is given in Fig. 4.9.

Fig. 4.9 calculated unit response of model test with a period of 3.1 sec

Model tests to validate the numerical model

The numerical model predicts a large dependency on wave period, therefore the model tests are designed to check two parameters. Firstly the dependency on wave period and secondly the amplitude of the swing motion, this is tested by a series off tests with different wave periods and the two different wave heights, see Table 4.2.
The length scale has been $\frac{1}{10}$ of prototype which results in a time scale of $\frac{1}{\sqrt{10}}$

Table 4.2 tests performed

Wave period Model test	Wave period Prototype	Wave height	
		5 cm	10 cm
1.0 sec	3.16 sec	X	X
2.0 sec	6.32 sec	X	X
2.5 sec	7.91 sec	X	X
2.8 sec	8.85 sec		X
2.9 sec	9.17 sec		X
3.0 sec	9.49 sec	X	X
3.1 sec	9.80 sec		X
3.2 sec	10.12 sec		X
3.5 sec	11.07 sec	X	X
4.0 sec	12.65 sec	X	X
5.0 sec	15.81 sec	X	X

The model test has been done at the TUDelft in wave flume. The characteristics of the experiment which were constant for all tests were:

- still water level was in the wave flume which was 73 cm
- cable length which was 80 cm
- depth of the centre of gravity of the unit which was 20 cm

To measure the amplitude of the unit the experiments were recorded by a digital video camera positioned perpendicular to the wave flume. Afterwards the video has been split in separate pictures every 0.2 second. With these pictures the position of the unit is logged 5 times per second creating a time series of the position of the unit, see Fig. 4.10. An example of a picture taken from a test video is given in Fig. 4.11.

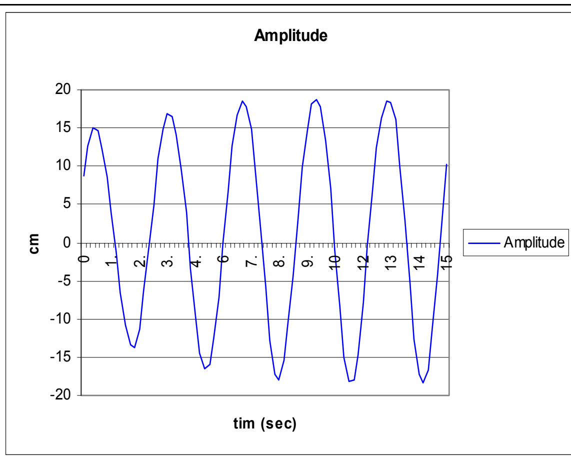


Fig. 4.10 measured units response of model test with a period of 3.1 sec.

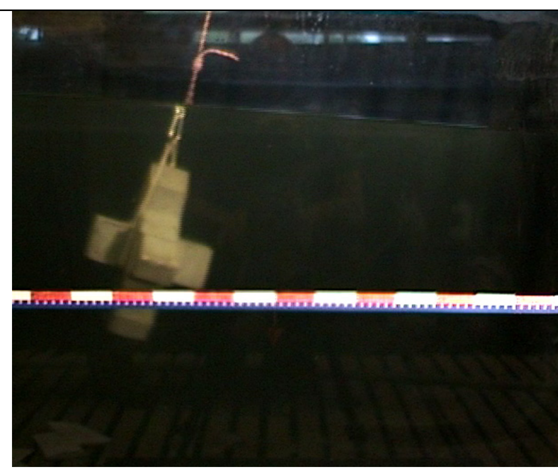


Fig. 4.11 picture captured from video

From all model tests a time series like Fig. 4.10 have been made. The maximal amplitude of each time series (model tests and numerical model) have been put together in one figure, see Fig. 4.12
The amplitude calculated by the numerical model is similar to the amplitude measured in the model tests. Only the tests with long wave periods differ significant. This is probably due to the reflection of surging waves on the model breakwater located a few wavelengths down the wave flume. The reflecting wave was clearly visible in the response of the unit.

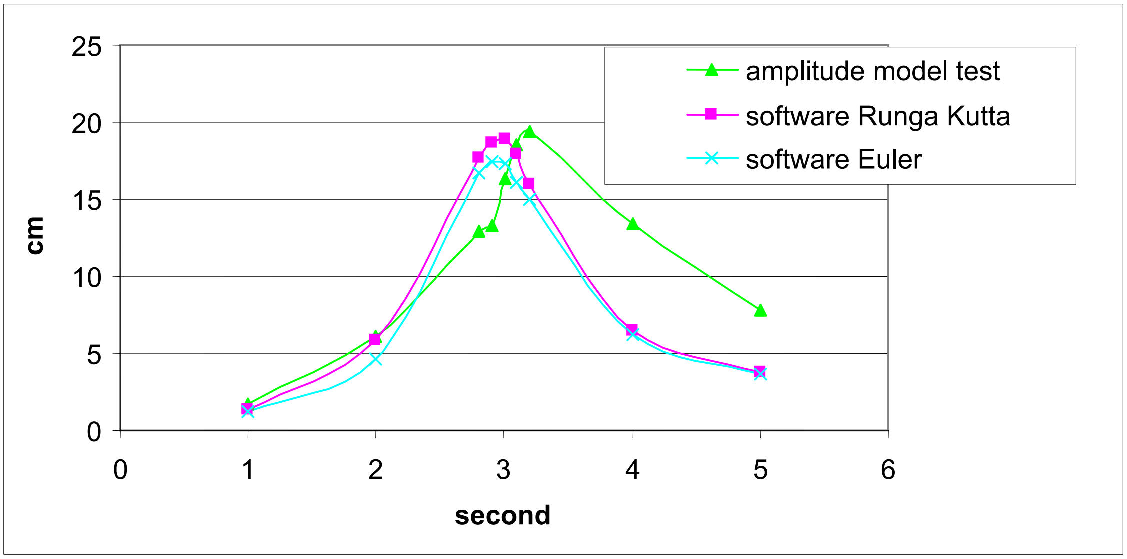


Fig. 4.12 unit response diagram

5 Placement tests

5.1 Objective and approach of the placement tests

The placement tests are designed to check the theoretical relations presented in chapter three. The parameters checked are packing density, horizontal versus upslope placement distance and the off centre placement behaviour.
The packing density required in prototype is determined by small scale Xbloc units placed by hand, this is verified with large scale Xbloc units (18 cm) placed in a realistic manner.
The horizontal versus upslope placement distance is checked indirectly by measuring all individual horizontal and upslope placement distances.
The off centre placement is tested to determine *unit adjust angle* and the usable *off centre distances*.

These relations are tested in six different experiments as given below:
- Standard grid placed with guidance
- Standard grid placed without guidance
- Standard grid submerged placement
- 0.1 D off centre placement
- 0.2 D off centre placement
- 0.3 D off centre placement

The standard grid tests are used to determine the packing density and the relation between horizontal versus upslope distance. Whereas the off centre placement are used to determine de unit adjust angle and the possible off centre distances.

All six placement tests have been executed multiple times to create larger and more reliable data sets. From each placement all units are measured on position (X- and Y-coordinates). From the coordinates other parameters, like deviation on the designed position and packing density are calculated.

Besides testing the theoretical relations the placement test will also give valuable information on the achievable accuracy of Xbloc placed by sling.

During placement in prototype the quality control is mostly based on pictures of the placement. Therefore it is important to provide a link between the visual information and quantifiable data. To give this link each placement will be described visually and on measured position. All measured positions and pictures taken of the placements are included in appendix I. [The included CD-ROM]

The orientation of Xbloc is not prescribed, therefore the orientation of the individual units is not recorded. The orientation of the placed units is only recorded by pictures taken of the placement.

5.2 Description of the test facility

In this section the common features of the test facility are described.

5.2.1 Test basin

The placement tests have been performed at the laboratory of the TU Delft department of Civil Engineering. The test basin used is 2.5 m by 2.5 m by 2 m (Width, Length, depth), see Fig. 5.1. In this test basin only placement in the dry and in still water placement is simulated as no waves can be produced in this basin. The response to waves during placement has been tested in a wave flume as presented in chapter four.

Fig. 5.1 test basin

5.2.2 Hoisting equipment

The hoisting equipment was mounted on a moveable platform on top of the basin, see the top view schematisation in Fig. 5.2. To reach the whole basin area, the platform can be turned around on the bridge by 180 degrees, positioning the "crane" to any position in the basin. The position of the crane is determined by measuring tape on the side of the basin and on side of the bridge, creating a 2D grid.

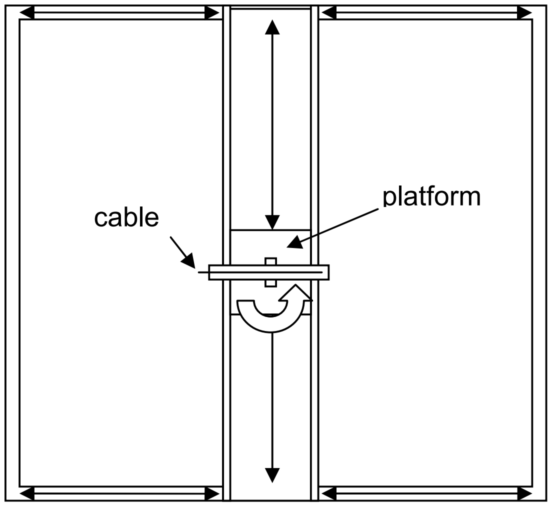


Fig. 5.2 schematisation of hoisting equipment on top of basin [top view]

The accuracy of the crane positioning is 0.5 cm. This is determined by comparing the position of the crane and the position of a plumb line at the bottom of the basin. To achieve this accuracy on both sides of the bridge, the bridge had to be made exactly level. The moveable platform and crane are shown in Fig. 5.3.

Fig. 5.3 moveable platform with “crane” mounted on top

5.2.3 Measuring equipment

After the units are placed their position has been measured (x,y). This measurement can be done with a plumb line from the crane but a more efficient method is using a laser pointing straight down, as shown in Fig. 5.3.
The accuracy of the laser measurement is 0.5 cm. The laser dot can be moved on the centre of the unit by moving the platform, see Fig. 5.4

Fig. 5.4 laser dot pointing at centre of Xbloc unit

5.2.4 Units

The units used for the placement test are made at the TUDelft. The concrete units have been made in reusable formworks of PVC, see Fig. 5.5.
The concrete mixture is adapted for the small size units. The aggregates are smaller than normal, the gravel has a D_{50} of 8 mm, and a high water cement factor is used. This is to make sure that the concrete mixture is poured into every corner of the formwork.

Fig. 5.5 reusable formworks of PVC

The formworks could be dismantled every day. After striking the units were placed under water to cure for another week.

The characteristic unit size of the model units is 182 mm which results in a volume of $2.0 \cdot 10^{-3}$ m^3. With an average unit weight of 4.75 kg the concrete density is 2,375 kg/m^3. This is a normal concrete density so it will not influence on the placement behaviour.

5.3 Model set-up for straight section of breakwater

5.3.1 Breakwater profile

The core of the breakwater in the test basin consists of a steel frame with a wooden surface, the slope of this frame is 3:4 [V:H]. The toe of the breakwater consists of a wooden structure with a height of 10 cm.
On top of this frame and toe an underlayer of rock is placed. The rock size is scaled down to match the scale model Xbloc units. The dimensions of this breakwater are given in Fig. 5.6

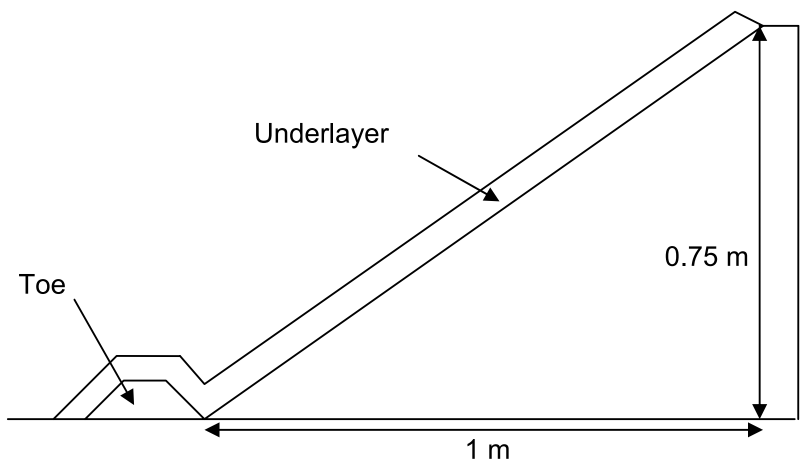


Fig. 5.6 profile of the test breakwater

5.3.2 Underlayer

The W_{50} of the underlayer should be between $W_{Xbloc}/9$ and $W_{Xbloc}/11$, see chapter 2.2.3. This means that the W_{50} should be approximately 0.48 kg.
The largest rock available at the laboratory had a W_{50} of 0.2 kg. Although this is significantly lighter, the D_{50} is only 20 % smaller. The influence on placing of Xbloc units is therefore believed to be minimal.

5.4 Test 1: Standard grid placed with guidance

5.4.1 Description

Objective

This standard grid test is used to determine the achievable packing density and the relation between horizontal and upslope placement distances in practice. Secondly the accuracy results will be used as a benchmark for achieved accuracy of all other placement tests.

Standard grid

The standard grid is a triangle shaped grid with the recommended horizontal and upslope placement distances as shown in Fig. 5.7. The recommended placing distances results in a perfect diamond-shape placement grid.
Due to the limited size of the basin, the maximal number of units in 1 row is 8, which results in a total of 36 units.
To enlarge the dataset this placement test has been performed four times.

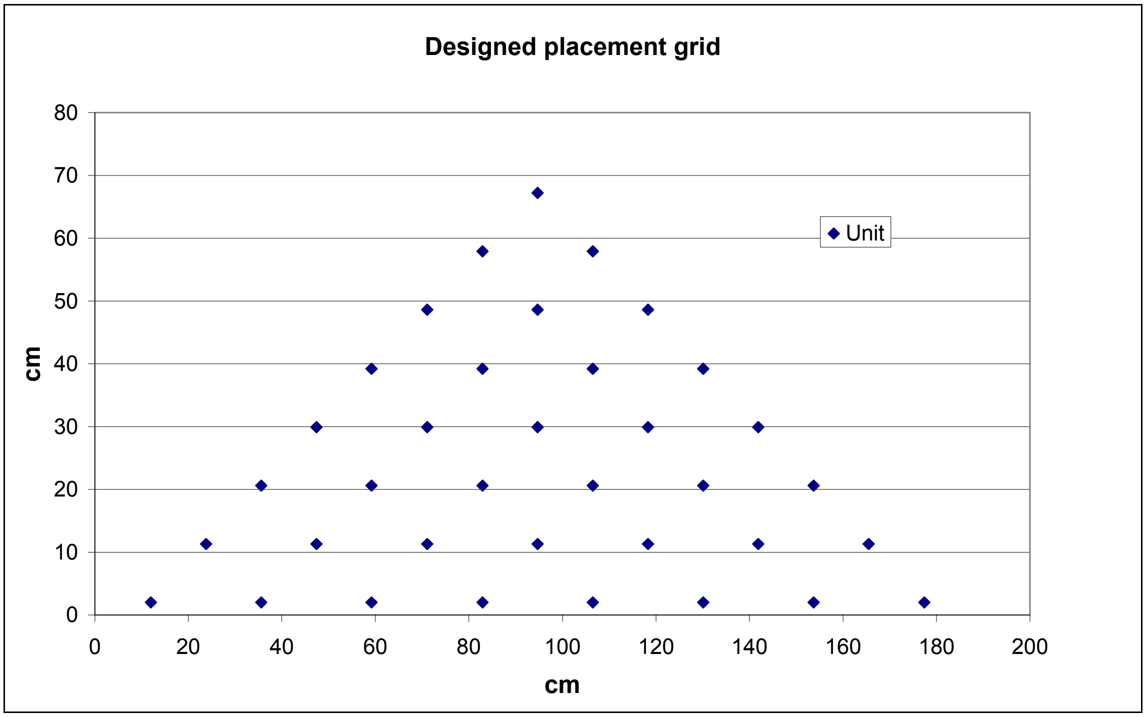


Fig. 5.7 topview of the designed grid

Guidance of a unit

All units are lowered at their predefined position onto the slope. During placement the units have the standard orientations in the sling, as described in section 4.1. The orientation in the sling is only dependent on the location of the unit on the slope. The units in the first row are placed with three points pointing downwards and the units higher upslope are placed with one leg pointing downwards.

The only remaining degree of freedom is rotation around the axis of the hoisting cable. This rotation can be used to fit a unit properly into the gap between two base units, this is called guided placement. The guided placement should prevent early touching of one of the horizontal legs onto the already placed units. This can topple over the unit and prematurely jam it, resulting in a less favourable position.

5.4.2 Visual description of placement

In this section the link between the visual description and the measured data is presented. The measured positions of placement test two are shown in Fig. 5.8. In this figure the units marked red differ significant in their position compared to the designed grid in Fig. 5.7. However in Fig. 5.9 a picture of the same placement is shown. In this picture it is difficult to find these “misplaced” units. So visually the placement looks better than when the units are schematized to points.

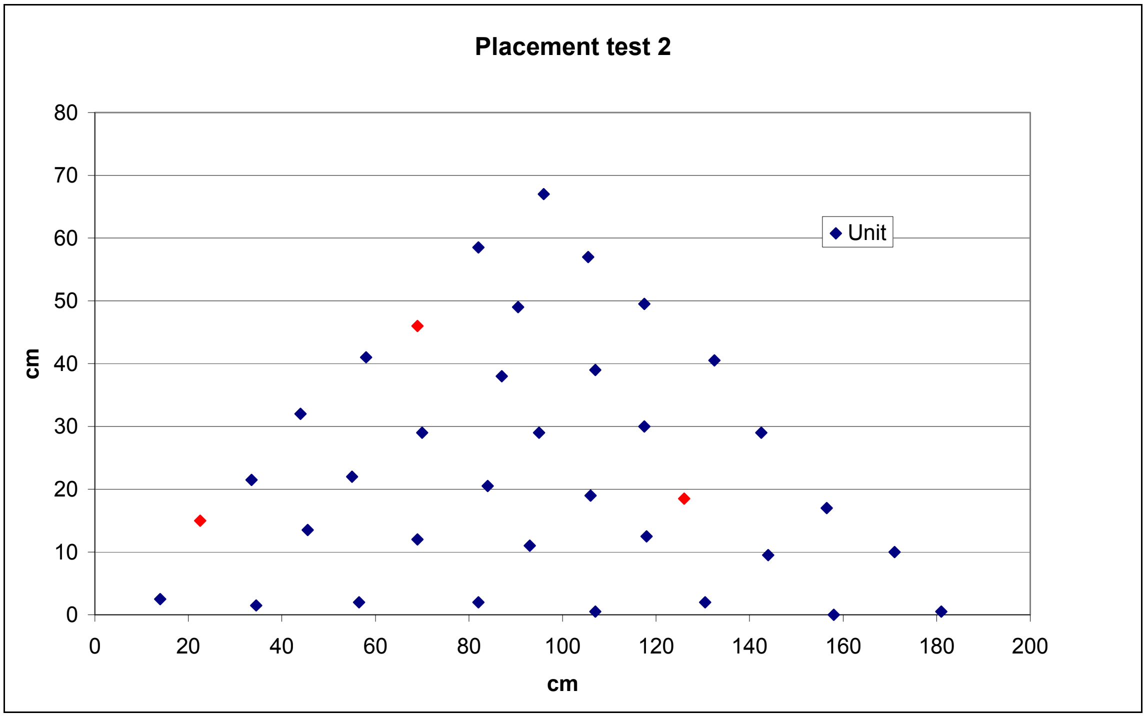


Fig. 5.8 measured positions of placement test number two

Orientation

The orientation is only depending on the gap into which the unit has to be placed. As a result of this fitting the orientation around the axis of the hoisting cable is completely random. This randomness means there is no preferred orientation on which the units can be placed and guiding is needed.

Cumulative placement errors

The individual misplaced units [marked red] do not affect the entire placement pattern. The units higher up the slope can still be placed on their predefined position. So there is no cumulative placement error by guided placement. The quality of the placement higher upslope is as good as at the first few bottom rows.

Fig. 5.9 picture of placement test number two

Loose units

When a unit is not interacting with all its neighbours this is called a loose unit. Loose units are not accepted in prototype placement.
During these guided placement tests no loose units were found at all. The newly placed units were already properly locked up. As a result guided placement is not likely to encounter large settlements.

5.4.3 Results based on coordinates

Deviation of designed position

Due to the achievable accuracy during placement the units will always be a little off position. A proper placement is characterized by a small individual deviation and an average deviation close to zero. When the placement is biased it can give problems during execution, especially at the edges of the placement grid.
For this guided placement the average deviation in position is very close to zero. The average horizontal deviation is -0.008 D with a standard deviation of 0.132 D and the average upslope deviation is -0.002 D with a standard deviation of 0.099 D.
The deviation from the theoretical placement grid for each individual unit is presented in Fig. 5.10. A relation between the horizontal and upslope deviation can be seen.
When the horizontal deviation is close to zero the upslope deviation is also limited. When the horizontal deviation is larger, the upslope placement distance increases resulting in an increased upslope deviation, see V-shape in Fig. 5.10. This corresponds approximately with the units adjust angle of the off centre placement, see section 3.3.9.

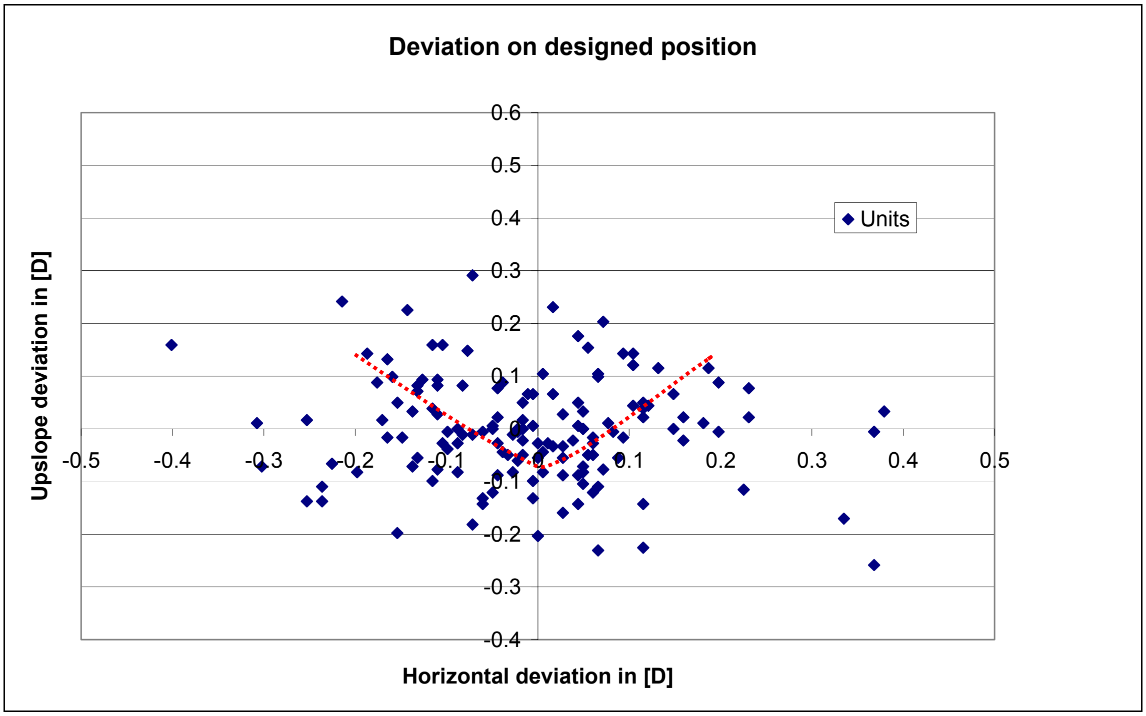


Fig. 5.10 deviation on designed position

Relation between horizontal placement distance and upslope distance

The deviation in position leads to varying horizontal and upslope placing distances. These distances should show the correlation as found in section 3.3.5.
The placement positions were based on a upslope distance of 0.64 D but the actual achieved upslope distances are dependent on the horizontal placement distance, see Fig. 5.11.

To emphasize the relation between horizontal and upslope placement distance a linear regression line is printed in Fig. 5.11. This regression line indicates a constant packing density, see function of the regression line below.

$y = -0.4815 \cdot x + 1.2873$ [regression line]

y = upslope placement distance
x = horizontal placement distance

The horizontal distance is twice the upslope, this means that a 10% increase in horizontal placing distance means a 10% decrease in upslope distance.

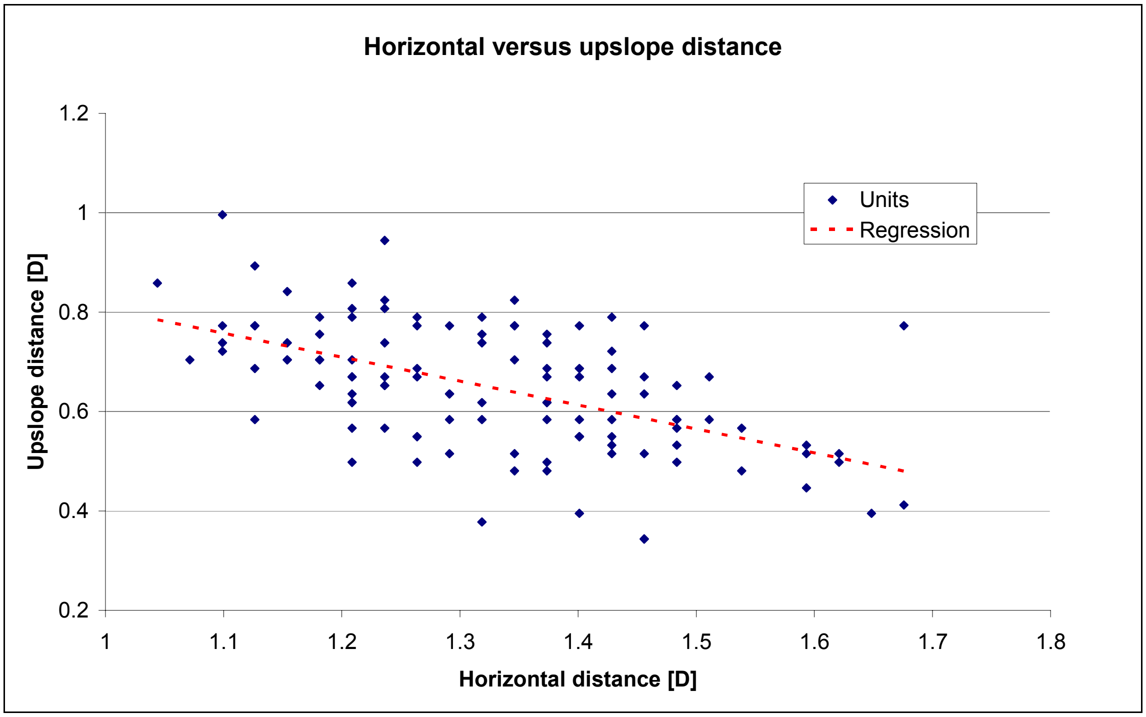


Fig. 5.11 horizontal placing distance and upslope distance

Packing density

The theoretic packing density for the 18.2 cm Xbloc units is 36.4 units per square meter. The individual packing densities vary a little, but the average achieved packing density is 36.6 units per square meter, which is 100.5 % of the required packing density.
This packing density is achieved by a realistic way of placement, which is promising for the achievable packing density in prototype.

The standard deviation on individual packing density is 6.9 units per square meter, so the majority of all individual packing densities are within two times the standard deviation, which is 22 to 50 units per square meter, see Fig. 5.12. The individual packing density is one over the surface area of each individual unit, as described in section 7.2.2.

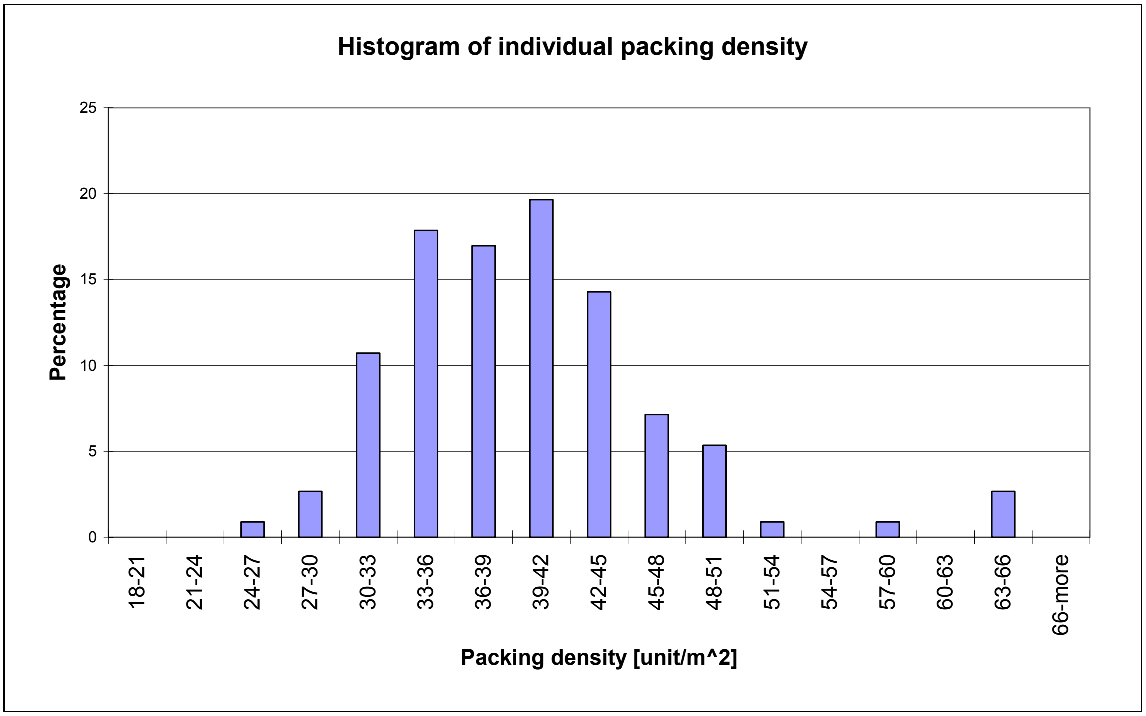


Fig. 5.12 histogram of individual packing density

Placement used by hydraulic model testing

A commonly used method to check the hydraulic stability of a breakwater design is by model testing in a laboratory. These test slopes are built by hand. To check if this is realistic for prototype placement and thus representative for the hydraulic stability in prototype a hydraulic test slope is analysed. This slope is given in Fig. 5.13.
All units in the green triangle are measured on their position and plotted as a dot in Fig. 5.14. This pattern is visually compared with Fig. 5.8 and no significant differences in accuracy are found.
Comparing the pictures of both placements one difference can be seen, which is in the orientation of the units. The picture of the hydraulic model test is one of the first model tests done. At that time the preferred orientation in the sling has not been implemented in the model. As a result a number of units is positioned with their nose pointing upwards, this orientation is not possible with the current sling methods.

In the hydraulic test slope units with their nose pointing upwards look like loose units. So the placements reached by the placement tests are as least as good as in hydraulic model testing.

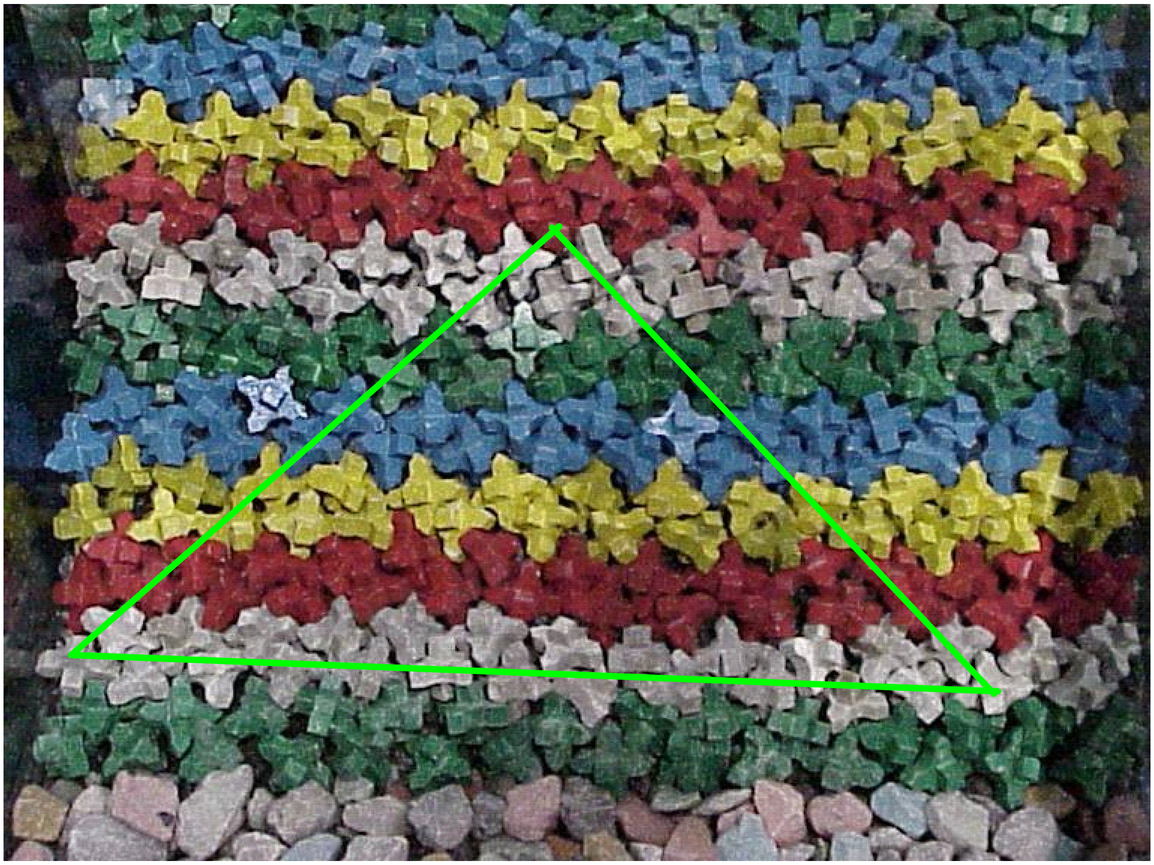


Fig. 5.13 hydraulic test slope (picture perpendicular to the slope)

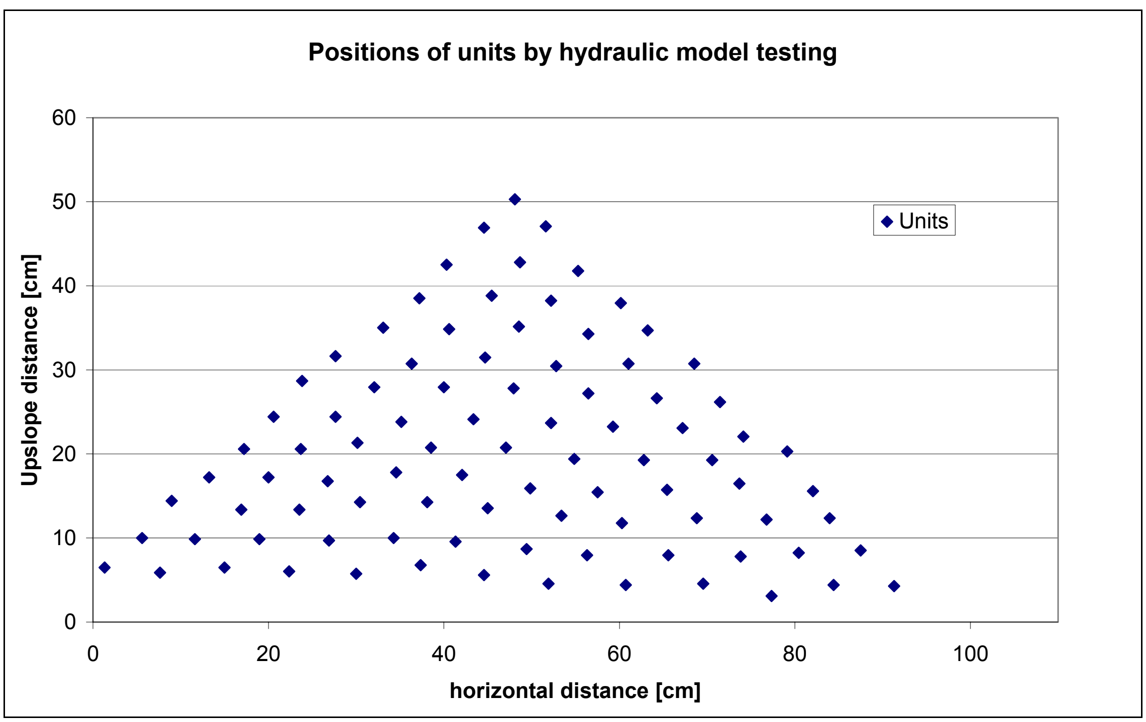


Fig. 5.14 positions of units of slope used in model testing of hydraulic stability

Conclusions

- The achievable packing density corresponds with the packing density found with small scale model units.
- The achieved placement is as good as the hydraulic tested placements. Therefore the data from these standard placement tests provide a benchmark for a good placement.
- From this realistic placement tests it is likely that under favourable sea conditions the quality of these placements is also achievable in prototype.

5.5 Test 2: Standard grid placed without guidance

5.5.1 Description

Objective

In prototype not all submerged units can be seen from the crane position. Therefore the standard grid is tested without guidance to determine if units can be correctly placed without looking to the already placed units.

Standard grid

The designed placement grid used is the same as by placement test 1, see section 5.4.1. This test is been performed 3 times to enlarge the data set.

Guidance of a unit

The same sling technique has been used as in placement test 1. The difference compared with the guided placement is the rotation around the axis of the cable. In this placement test the unit is given a random rotation and lowered blind in between the two base units instead of using the rotation to fit the gap.

5.5.2 Visual description of placement

The accuracy of unguided placement was significantly worse than the placement with guidance. The result of the third placement is shown in Fig. 5.15. The quality of placement differs significantly between units in the first few rows and higher up the slope. The units higher upslope do not even have the diamond-shaped pattern anymore.

Fig. 5.15 picture of third placement of test 2

Orientation

The surrounding units did not guide the newly placed unit into a preferred orientation/position resulting in a loosely packed placement. During unguided placement one of the horizontal legs often gets stuck on one of the base units causing it to topple, creating a less favourable gap for the unit positioned above.

Cumulative placement errors

During the placement tests is was clear that unguided placement lead to cumulative errors. This cumulative error is caused by the fact that a unit leans on only one unit and does not roll in between the two base units creating large error on position. This error can not be overcome by the next unit creating a cumulative error, see Fig. 5.16. In general a cumulative error is clearly visible.

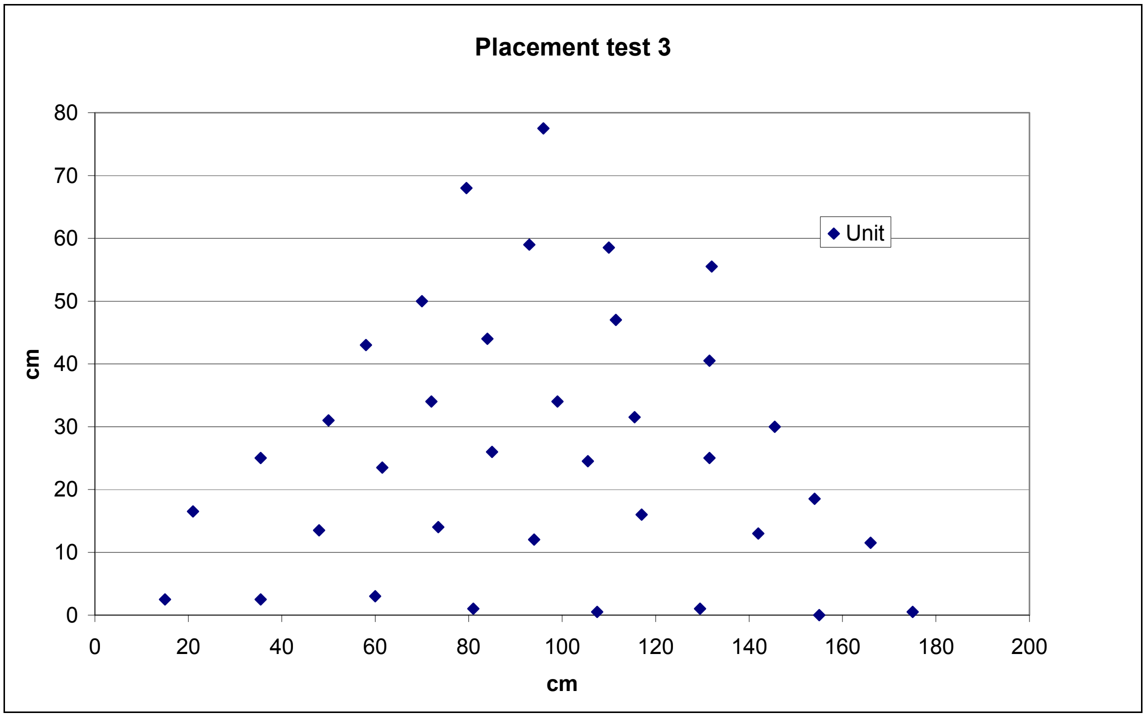


Fig. 5.16 measured positions of the third placement

Loose units

With this unguided placement there are several units which are only connected to one other unit. This is not acceptable in prototype, therefore unguided placement is not recommended in prototype.

Density

Visually the packing density of these placements is significantly lower than with the guided placements, so the placement is likely to encounter large settlements.

5.5.3 Results based on coordinates

All data of the three placement tests have been put together to create a larger and more reliable data set, in total 107 units have been placed [one unit could not be placed].

Deviation of designed position

The average deviations should be close to zero but this is not the case, especially in the upslope direction. The average deviation in upslope direction is 0.097 D, which is 15 % of the recommended upslope placement distance. The average horizontal deviation is -0.013 D which is relative small. But the standard deviation is with 0.200 D which is significant larger than in the guided placement. The horizontal and upslope deviations are shown in Fig. 5.17

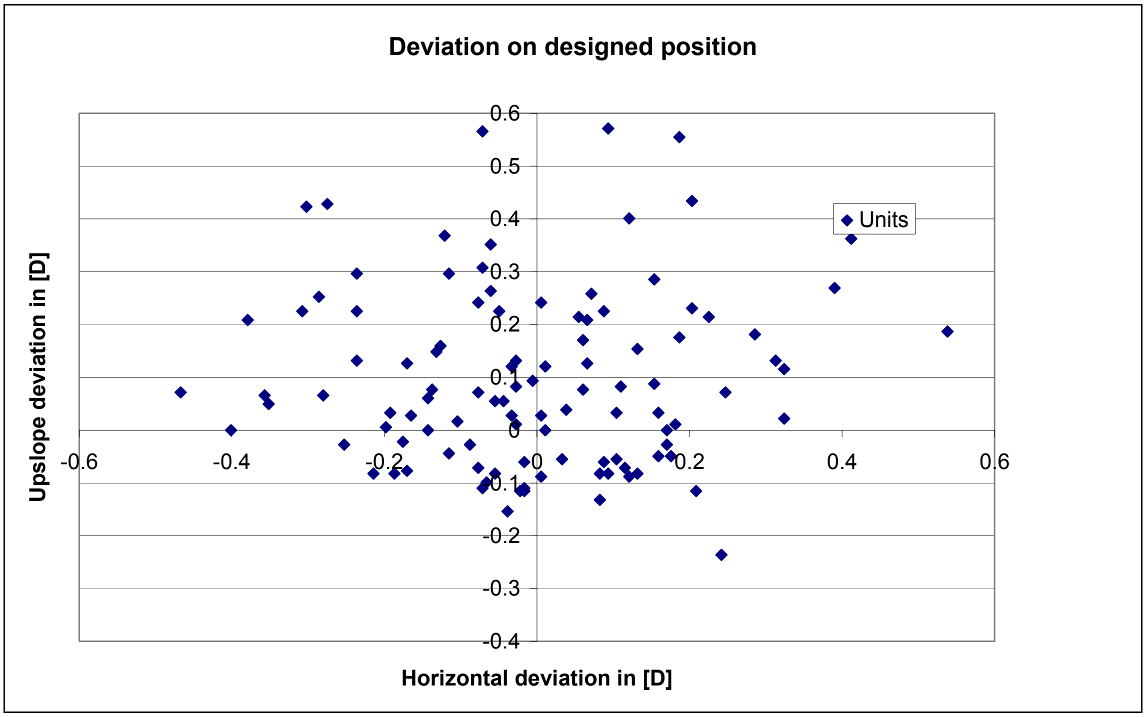


Fig. 5.17 deviation on designed position

To highlight the upslope deviation the spreading in upslope deviation is shown in a histogram, see Fig. 5.18.

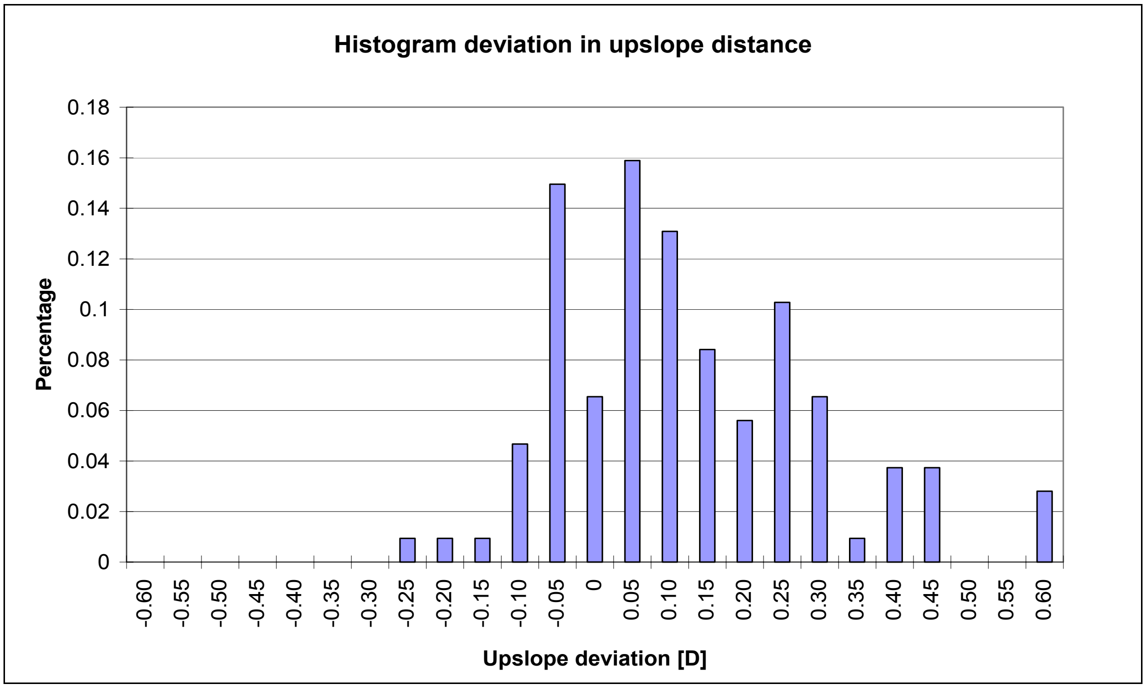


Fig. 5.18 histogram deviation in upslope direction

Relation between horizontal distance and upslope distance

Despite the large deviations to the designed placement grid the relation presented in section 3.3.5 is still valid, see Fig. 5.19. The gradient in the trend line is almost the same as with the guided placement tests. As expected from the deviations in upslope positions the average upslope distance is slightly larger.

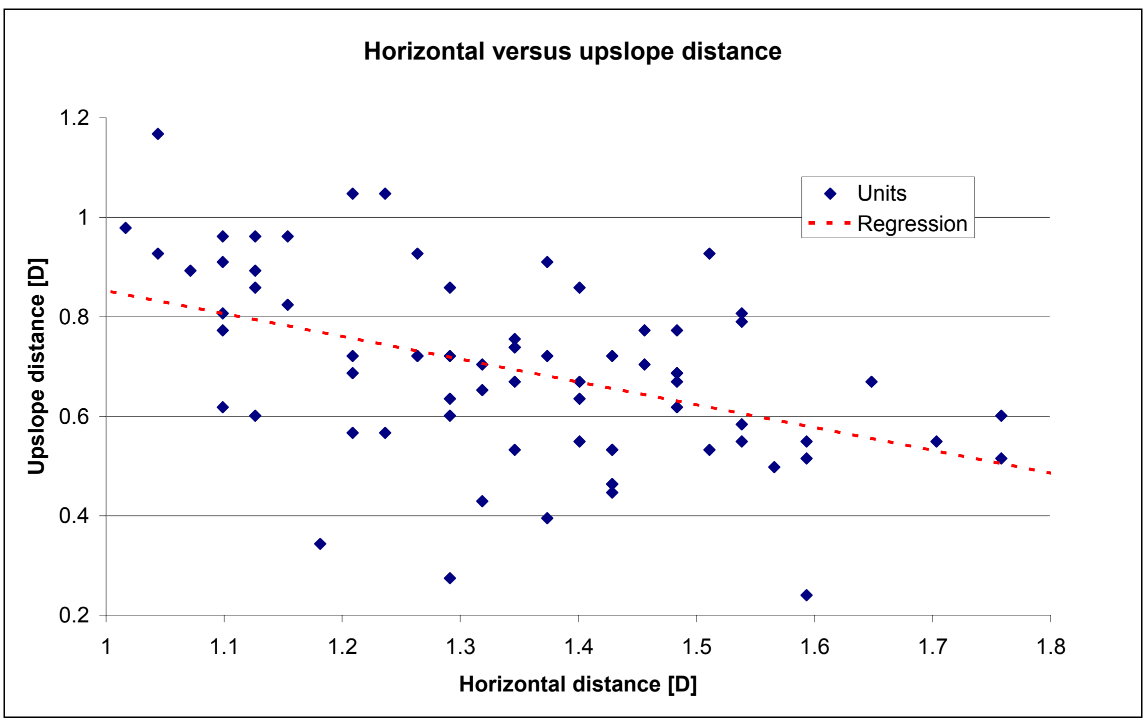


Fig. 5.19 horizontal distance versus upslope distance

Packing density

The average achieved packing density is 34.3 units per squire meter, which is 94.2 % of the required packing density. This low packing density is not accepted in prototype.
The standard deviation on packing density is 9.2 unit per square meter. This is significantly larger than with guided placement, see spreading in individual packing density in Fig. 5.20. This low packing density and large spreading show that the guidance is necessary to achieve the required packing density.

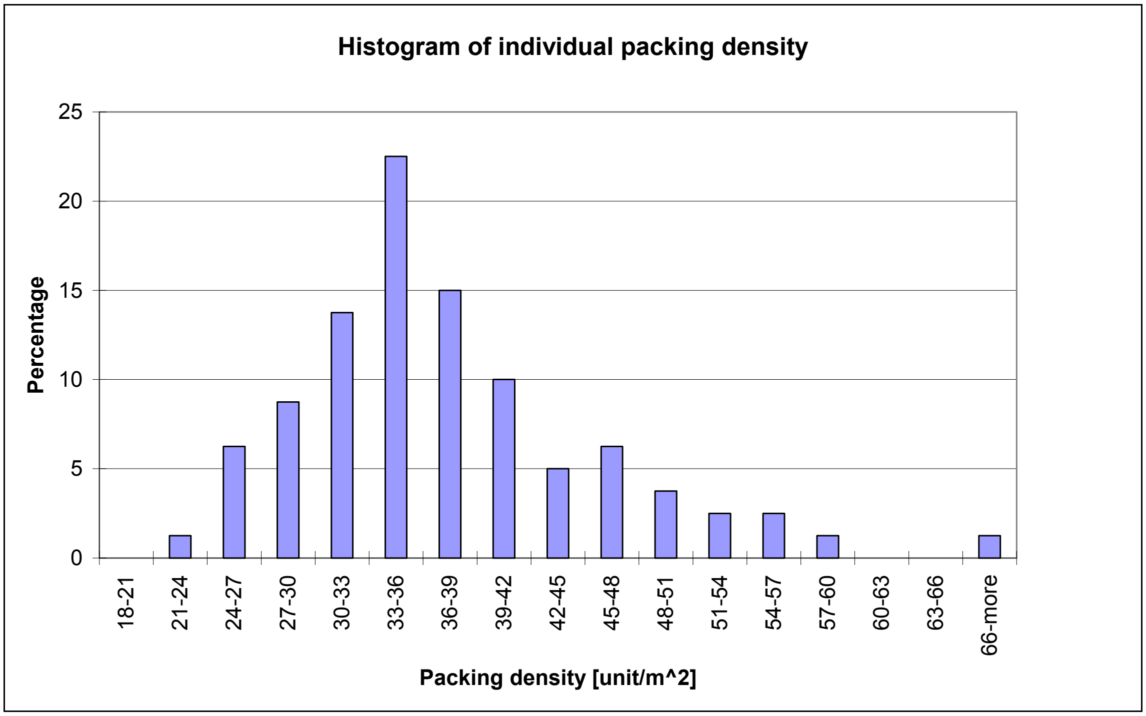


Fig. 5.20 histogram individual packing density

Conclusions

In general the quality of unguided placement is significantly worse than of the guided placement. A cumulative placement error exists, higher upslope the placement becomes worse than the first few rows.
In prototype is recommended to deploy divers to guide/check the units fit properly between the base units below.

5.6 Test 3: Standard grid submerged placement

5.6.1 Description

Objective

The submerged placement tests are used to check if the reduced gravity has influence on accuracy and packing density.

Standard grid

The placement grid used is the same as by placement tests 1, see section 5.4.1. This test is been performed 2 times to enlarge the data set.

Guidance of a unit

The guidance of a unit is the same as by test 1, see section 5.4.1. A benefit of submerged placement is that the units are less susceptible to swing due to the drag of the water.

5.6.2 Visual description of placement

Submerged placement under good visibility (guided) is as easy to place as placement in the dry. This easy placement results in a visually proper placed armour layer, see Fig. 5.21. The submerged placement is visually the same as the placement tests placed in the dry.

Fig. 5.21 picture of submerged placement test number two

5.6.3 Results based on coordinates

Deviation of designed position

The deviation on average position of the submerged units is a little bit larger than the units placed in the dry, see Fig. 5.22. This probably caused by the fact that only two submerged placement test have been done instead of the four in the dry.
The horizontal standard deviation is 0.140 D and the upslope standard deviation is 0.080, this is approximately the same as the guided placement in the dry.

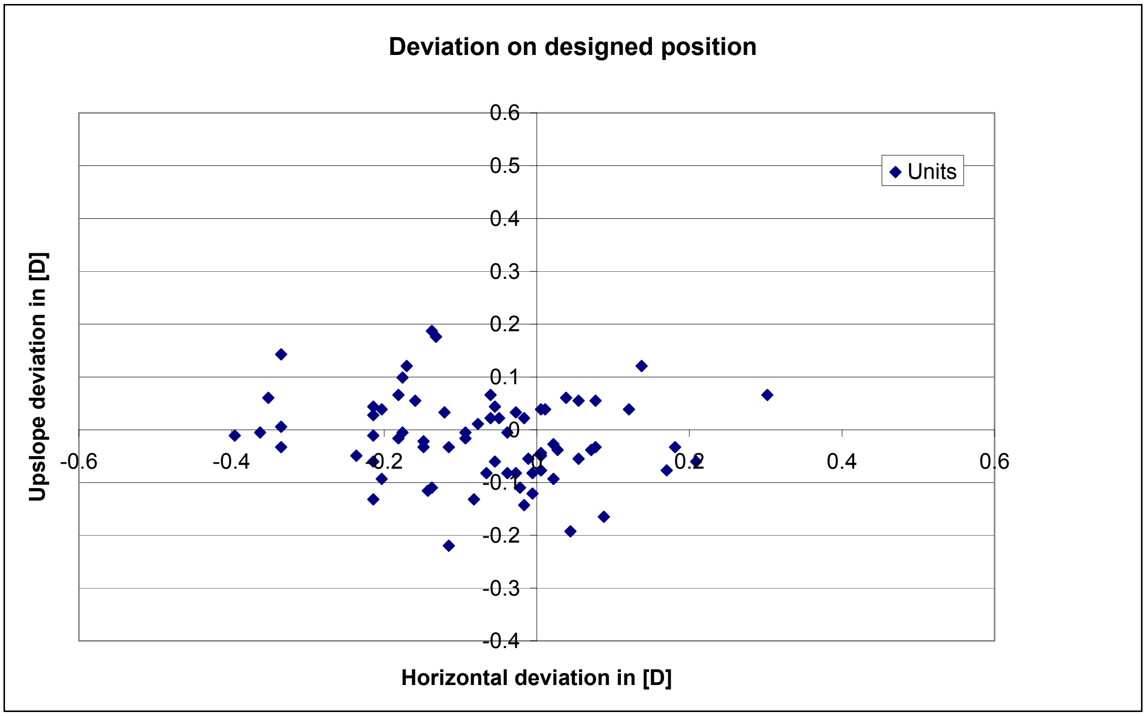


Fig. 5.22 deviation on designed positiion

Relation between horizontal and upslope placement distance

By submerged placement the relation between horizontal and upslope placement distance is weaker than in the dry, this is probably due to reduced gravity. Gravity is the driving force for the unit to sink in between the two base units. Therefore the units are more likely to stay on their placed position than sinking in between the base units. This results in more constant upslope distances as shown in Fig. 5.23.

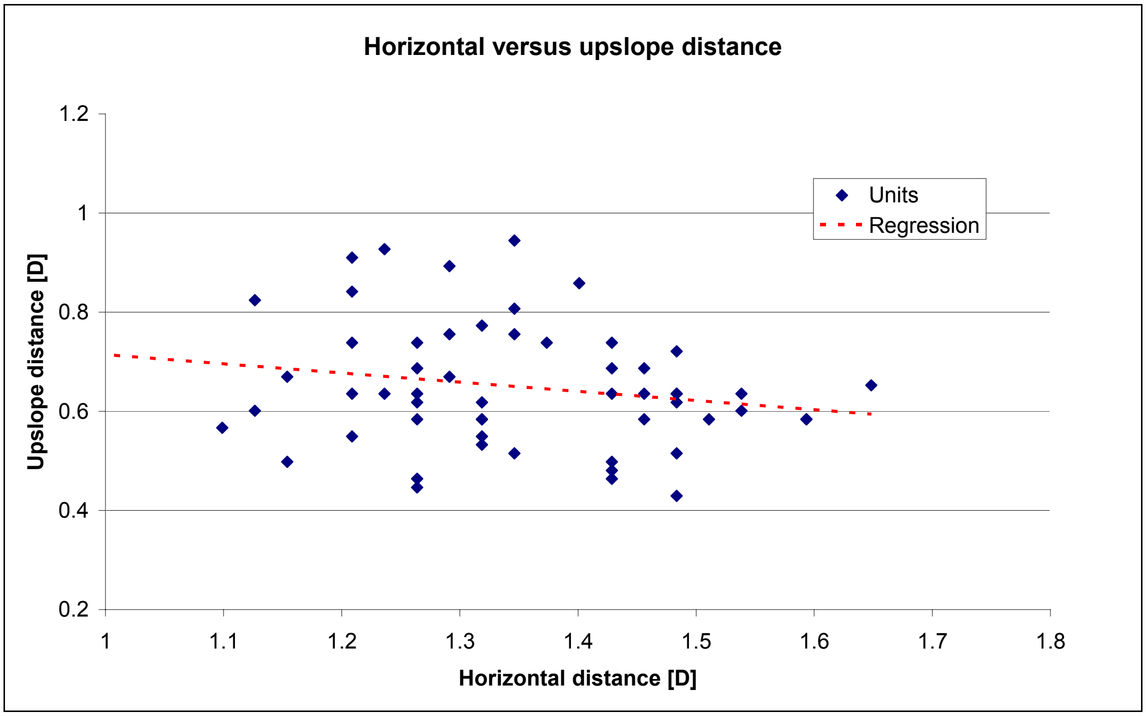


Fig. 5.23 horizontal versus upslope distance

Packing density

The average achieved packing density is 36.1 units per squire meter, which is 99.1% of the required packing density. This is a bit lower than in the dry but still acceptable for placement in prototype. The standard deviation on individual packing density is 7.3 units per square meter which is approximately the same as for placement in the dry.
The spreading in individual packing density has a dip around 40 units per square meter which can not be explained from a placement related view, see Fig. 5.24. This is probably also an effect of small data set.

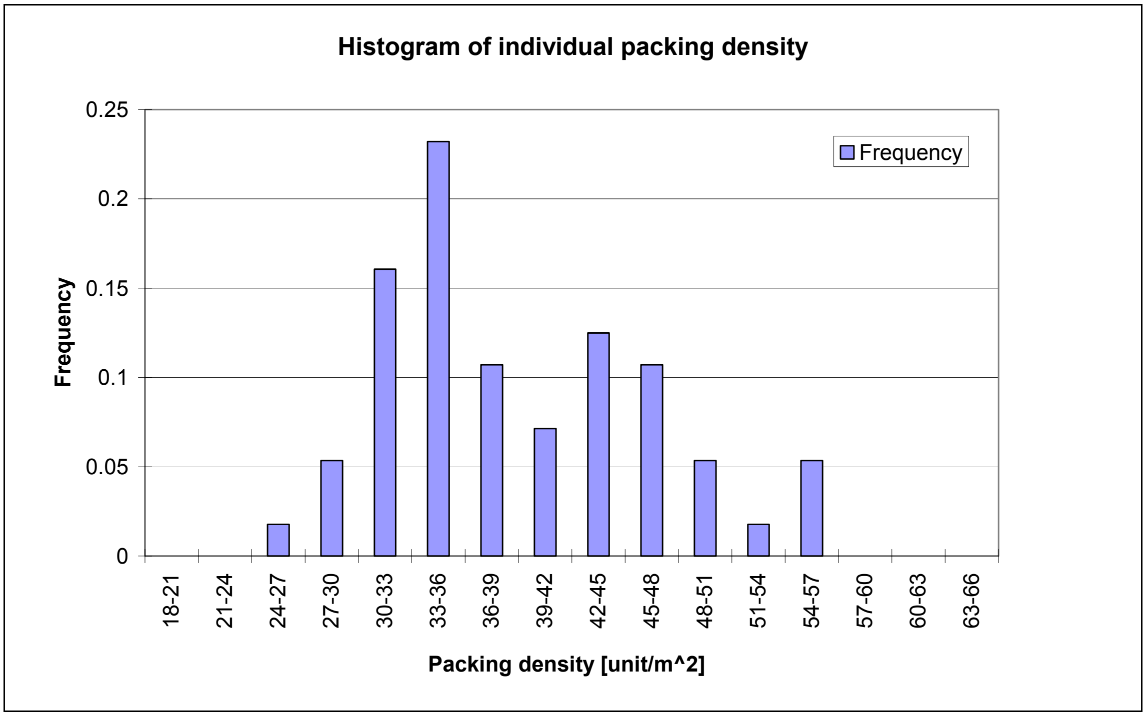


Fig. 5.24 histogram individual packing density

Conclusion

There are no specific problems with submerged placement. The only point of attention is the packing density. Due to the reduced gravity the unit should be guided with even more precision in between the base units.

5.7 Test 4: Possibility to place a unit off centre

5.7.1 Description

Objective

Determine the *unit adjust angle* and the usable *off centre distances.*

Designed off centre grid

The off centre placement will normally be used when the horizontal distance becomes too small. To represent this small horizontal distance the tests should be done at a breakwater head. Due to the extensive scope of the study, tests on a breakwater head is agreed to be out of the scope of this study. Instead conservative tests on a straight section of breakwater have been done. These tests are considered conservative because the small horizontal distance which drives a unit off centre is not present.
Thus if it is possible to place a unit off centre without support of the small horizontal distance it is certain that the units can be placed off centre with the horizontal support.

To overcome curved sections of breakwater different off centre placement distances are used. Therefore three different *off centre distances* have been tested. The off centre distances tested are: 0.1 D, 0.2 D and 0.3 D. The off centre distance is defined as the distance along the *unit adjust line*. Each designed placement grid is shown at the visual description of the placement.
All three distances have been tested three times to enlarge the dataset and increase the reliability. The off centre placements are only 3 or 4 rows to avoid cumulative errors during placement.

Due to the *unit adjusting angle* and the *off centre distance* the upslope distance of an off centre placement is larger than a placement in the middle. For a straight section of breakwater with off centre placement this results in a lower packing density.
For a breakwater head the larger upslope distance is partly compensated by the reduced horizontal placement distance.

Guidance of a unit

The guidance of a unit during placement is the same as in test 1 and 3, see section 5.4.1.

5.7.2 Visual description of placement

In this section the three different off centre distances are presented separately by looking at one placement per test per off centre distance. All other placement tests are included on CD-ROM.

0.1 D off centre placement

For this placement test the distinction between the second row and the higher is made. In the second row most units are positioned to the left instead of the designed right, as shown in Fig. 5.25. The reason for this large deviation is that the newly place unit touches the right base unit first and than rolls off to the left, resulting in a position to the left.
Due to the unit positions in the second row, the off centre distance in the third and fourth row is larger than originally designed. A surprisingly result of these units is that they have less problems rolling back to the left.

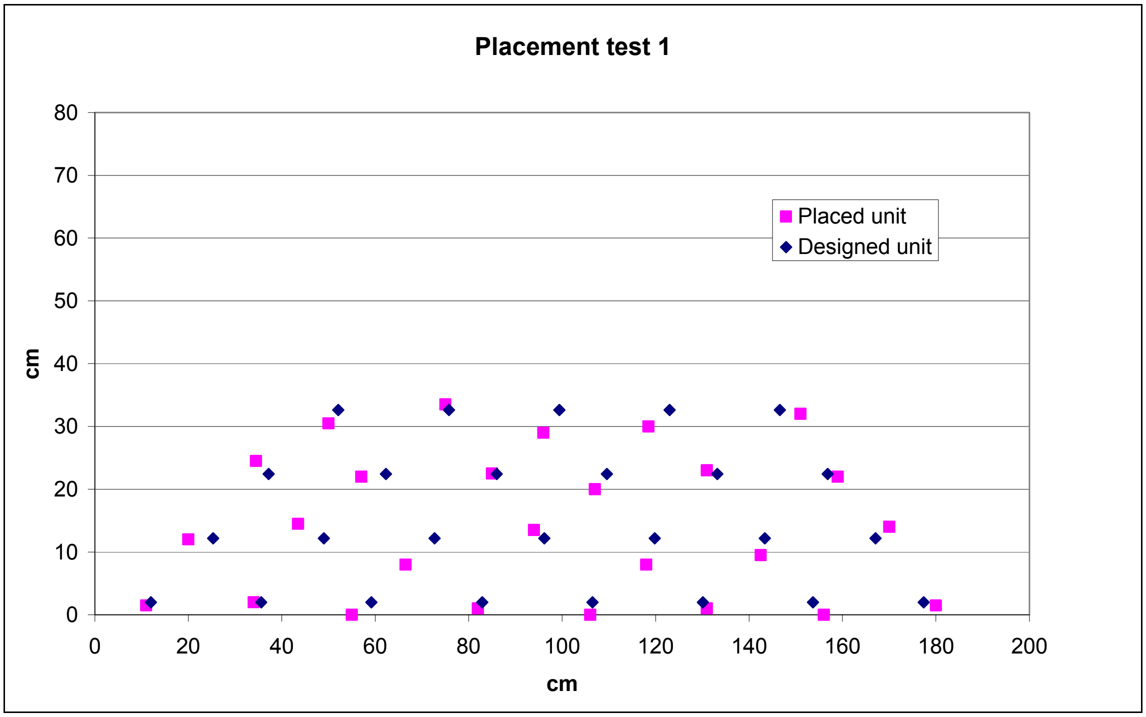


Fig. 5.25 designed off centre grid and first 0.1 D off centre placement

In Fig. 5.26 it can be seen that the upslope distance is larger than with the standard placement, resulting in a lower packing density. Another interesting observation is that the orientation of units reveal in which direction the unit has toppled on placement. When the leg pointing upwards is pointing slightly to the left the unit has rolled back to the middle.

Fig. 5.26 first 0.1 D off centre placement

0.2 D off centre placement

With an off centre distance of 0.2 D less units roll back as described in 0.1 D off centre placement. In the second row two of the seven units rolled back, see Fig. 5.27.

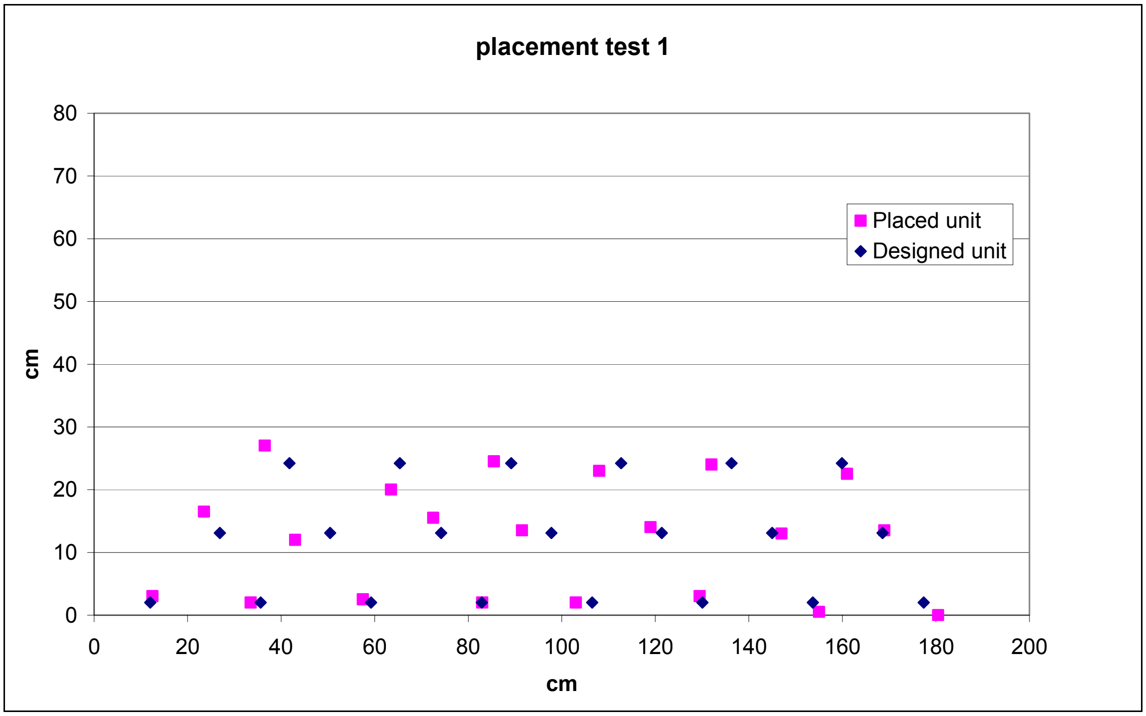


Fig. 5.27 designed grid and first 0.2 D off centre placement

The off centre distance of the units in the third row are already very depending on the unit position in the second row. The units left above the units which rolled back to the middle have a larger off centre distance. Therefore these units lean meanly onto this unit, see the marks in Fig. 5.28.

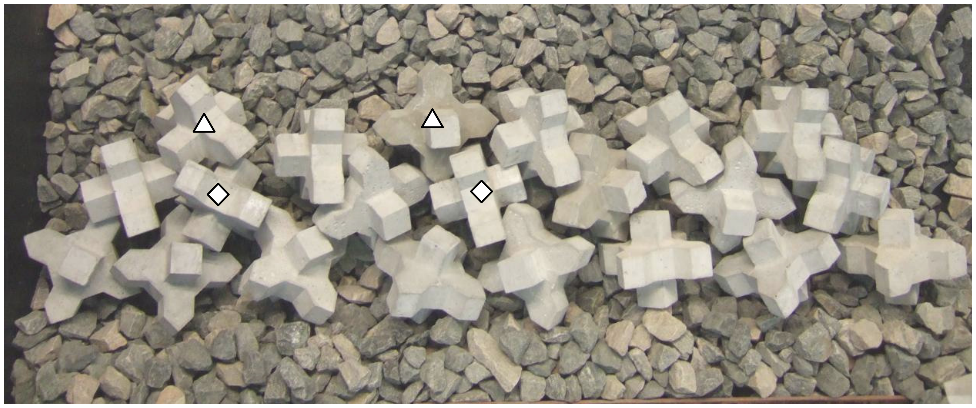


Fig. 5.28 first 0.2 D off centre placement

0.3 D off centre placement

With 0.3 D off centre distance tests almost all units are placed properly off centre. The units lean onto only one unit, the unit right below, and they do not roll back to the centre position. From Fig. 5.29 is seen that the upslope distance is also predicted quite well.

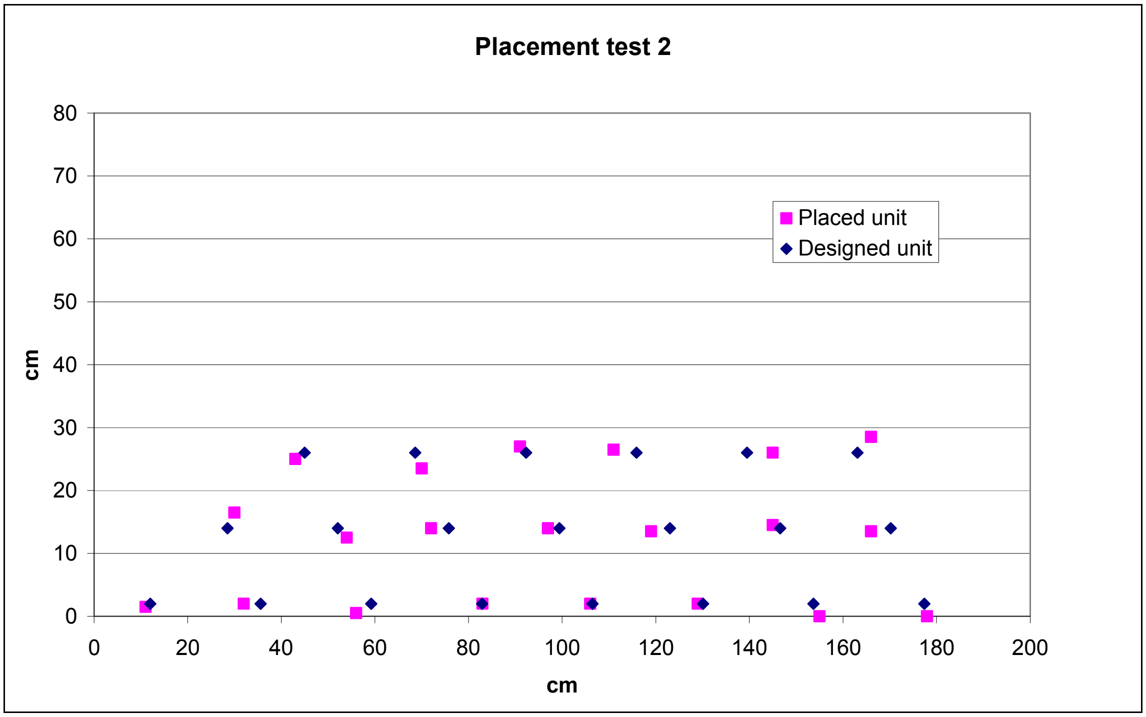


Fig. 5.29 designed grid and second 0.3 D off centre placement

The 0.3 D off centre placement looks very skewed. To achieve this skewed pattern the off centre units require even more attention during placement than normal units. This prevents the units from rolling back into the gap between the two base units. Despite the guided orientation around the axis the orientation of the units looks still completely random, see Fig. 5.30.

Fig. 5.30 second 0.3 D off centre placement

5.7.3 Results based on coordinates

The parameters of interest are accuracy of placement and the unit adjust angle. The accuracy of placement is used to look at the feasibility of off centre placement and the unit adjust angle is used to calibrate the calculation constants in software design tool.
The unit adjust angle of off centre placement is studied in further detail, this is done by looking at the achieved distances d1 and d2, see Fig. 5.31. From these distances the angle α can be calculated which is used in the software design tool for the optimization of the unit position.

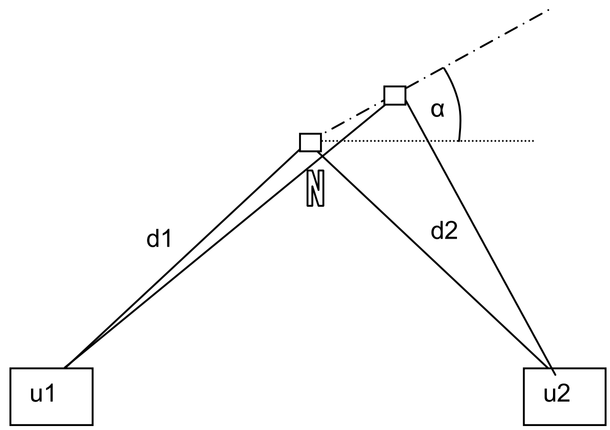


Fig. 5.31 definition sketch

The packing density of a skewed placement pattern is lower than a diamond-shaped pattern. Due to the larger upslope placement distance and the same horizontal placement distance.

For the three different off centre placement distances the following parameters will be presented separately:

- Packing density
- The placement accuracy compared with the standard placement tests.
- Distances d1 and d2 and the *unit adjust angle* α

0.1 D off centre placement

For a 0.1 D off centre placement the designed packing density drops from 36.40 to 33.64 units per square meter. The achieved packing density for these 0.1 D tests was 33.37 units per square meter, which is 99.2% of the designed value.

The accuracy on individual position is comparable with the standard placement described in section 5.4.3. The only difference is the average position, which is not on the designed position. This is caused by the fact that units tend to roll back to the centre position. As a result the average deviation in the position of a unit is horizontally 0.06 D back to the middle and 0.013 D lower than designed. In Fig. 5.32 the individual deviations are shown. In this figure the bias in position is clearly visible.

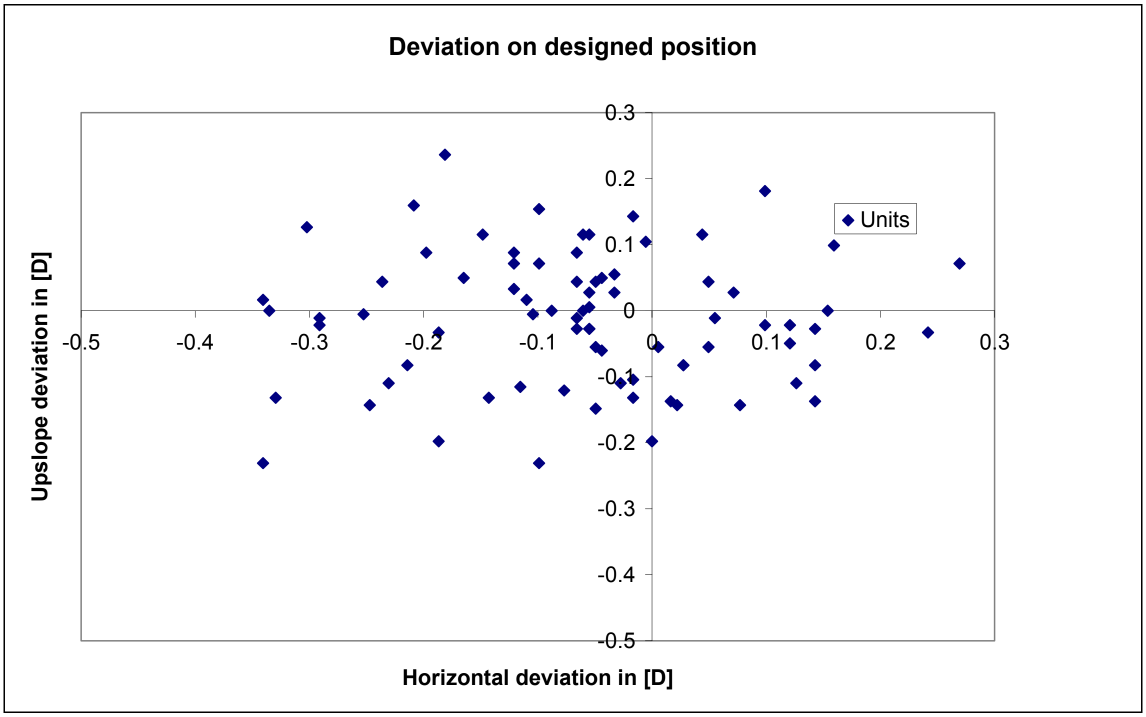


Fig. 5.32 deviation on designed position

To calculate the *unit adjust angle* the position of the placed units is compared with the theoretical *centre position*. The angle of the line from centre position to placed position should be equal to α, this is done for each individual unit, see N in Fig. 5.31.
Due to the accuracy of placement of about 0.2 D and the 0.1 D off centre distance the angle varied between 0 and 360 degrees and was of no use to determine the *unit adjust angle*.

Another method to determine the *unit adjust angle* is by using distances d1 and d2. The average distances d1 and 2 can be used to calculate an average unit position.
This calculation method is only allowed if there is no correlation between d1 and d2. Physically there is no reason why d1 and d2 should be correlated. To show they are really uncorrelated, the deviation of d1 versus deviation of d2 has been plotted in Fig. 5.33. If d1 and d2 are correlated all data point should be on one line or at least at a small range, this is clearly not the case.

From this calculation the *unit adjust angle* should be 47 degrees. This is corresponding with the starting angle of the arc described in section 3.3.9.

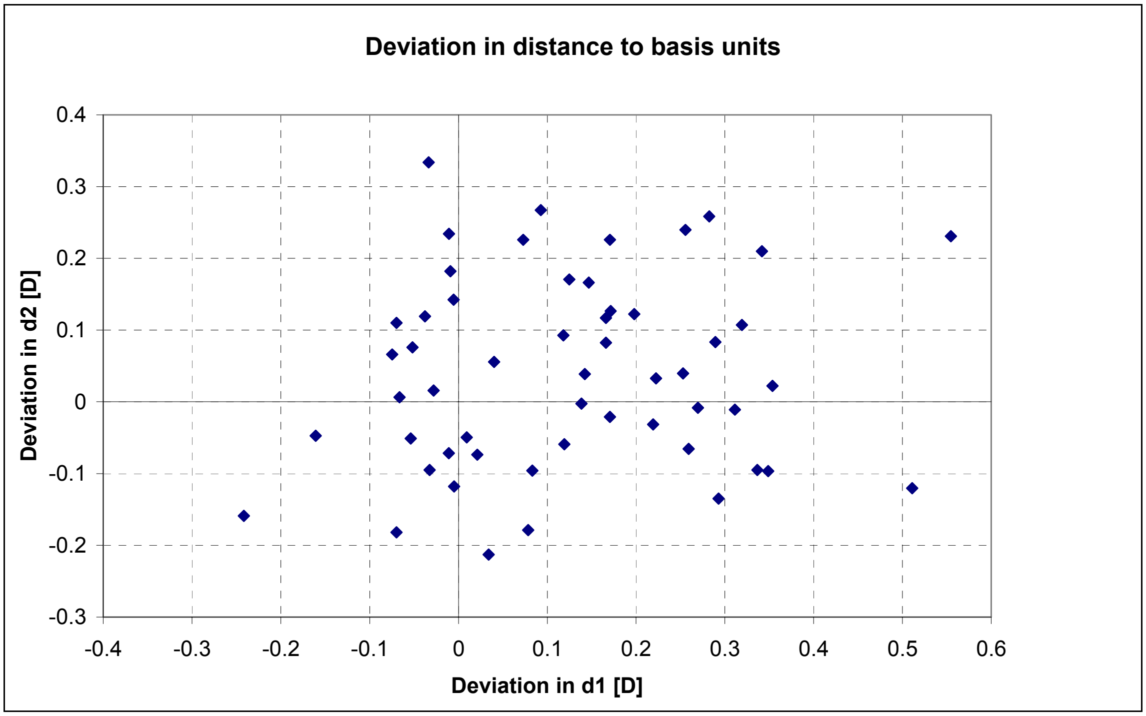


Fig. 5.33 deviation in distance tot base units

Another observation from Fig. 5.33 is that the units with a negative deviation in d1 are the units which have been rolled back. This means that approximately one third of the unit placed 0.1 D off centre rolls back to the centre position.

0.2 D off centre placement

For a 0.2 D off centre placement the designed packing density drops from 36.40 to 31.38 units per square meter. The achieved packing density for these 0.2 D tests was 31.30 units per square meter, which is 99.7% of the designed value.

The accuracy on position is approximately the same as with the standard placement described in section 5.4.3. The only difference is the average position, which is not on the designed position. This is caused by units rolling back to the centre position. As a result two concentrations are found, marked by two circles as shown in Fig. 5.34.
The average horizontal deviation is 0.097 D back to the middle and the upslope deviation is 0.009 D lower than designed. This horizontal average is caused by the fact that approximately half of the units have rolled back to the middle.

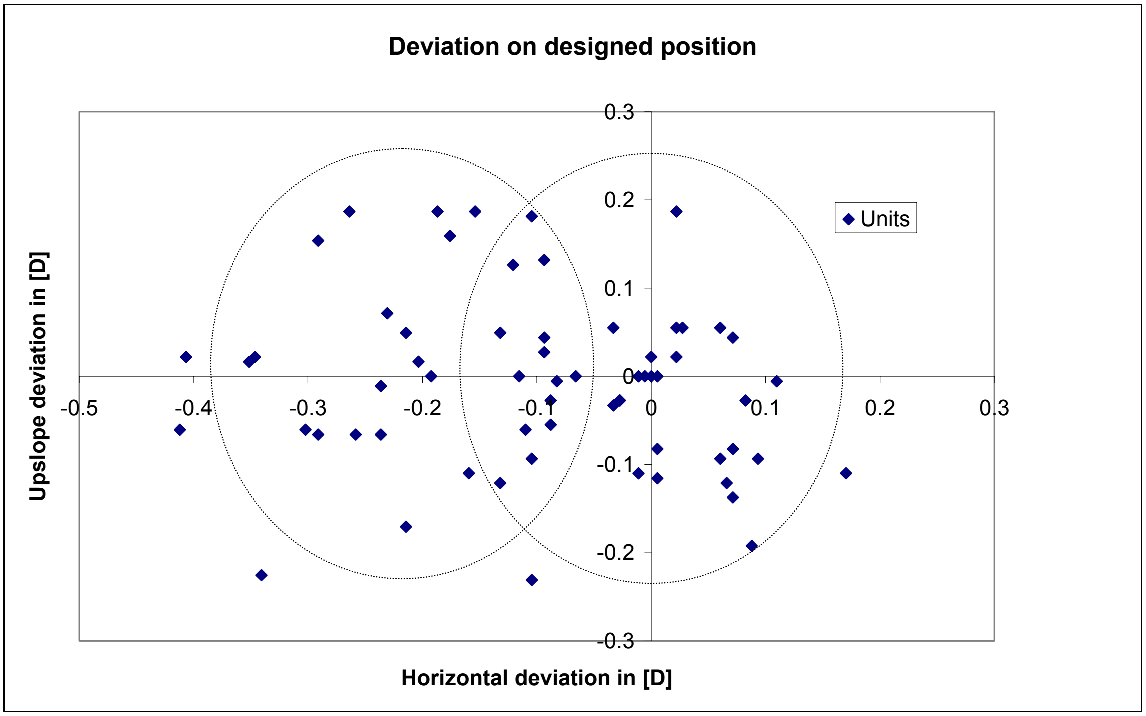


Fig. 5.34 deviation on designed position

To calculate the unit adjust angle by the individual *unit adjust angle* is not possible because the 0.2 D is still relatively small in comparison with the standard deviation in position. To calculate the *unit adjust angle* the distances d1 and d2 are used.

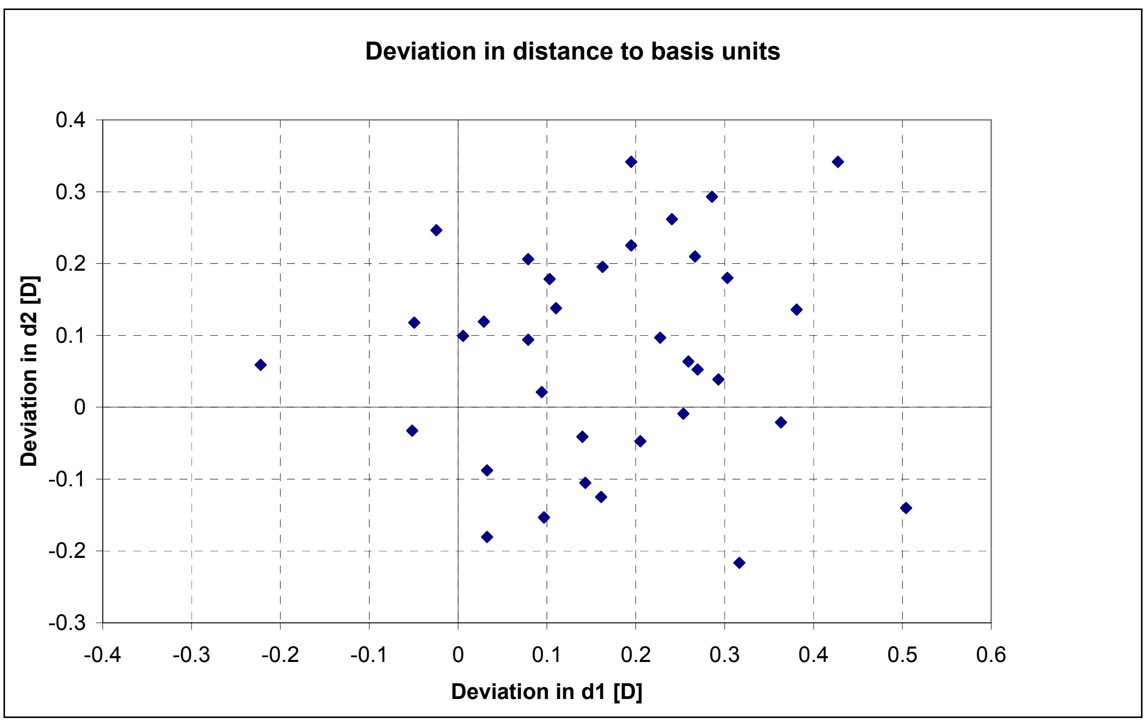


Fig. 5.35 deviation in distance tot base units

From the calculation with d1 and d2 the *unit adjust angle* for 0.2 D off centre placement is 44 degrees.
This is smaller than with 0.1 D off centre placement but still larger than the straight line described in section 3.3.9. A reason for this larger angle is found by the fact that unit rolling back do not settle properly between two base units, which is cause by the rotation in orientation.

0.3 D off centre placement

For a 0.3 D off centre placement the designed packing density drops from 36.40 to 29.40 units per square meter. The achieved packing density for these 0.3 D tests was 30.44 units per square meter, which is 103.5% of the designed value.

The accuracy on individual position is slightly less than by the standard placement described in section 5.4.3. The horizontal standard deviation is 0.169 D in comparison with 0.132 D for the standard placement. The upslope standard deviation is 0.127 D in comparison with 0.100 D for the standard placement. The spreading of individual deviation is given in Fig. 5.36. It is clear that a few units left below [marked red] have rolled back to the centre position. These units influence the standard deviation quite a lot because they are far off position. If these units are excluded in the standard deviation, the standard deviation is approximately the same as for the other tests.

A great benefit of this larger off centre distance is that the units have less tendency to roll back. As a result the average deviation in the position of a unit is less than with 0.2 D off centre placement. The average horizontally deviation is 0.086 D back to the middle and 0.06 D lower than designed.

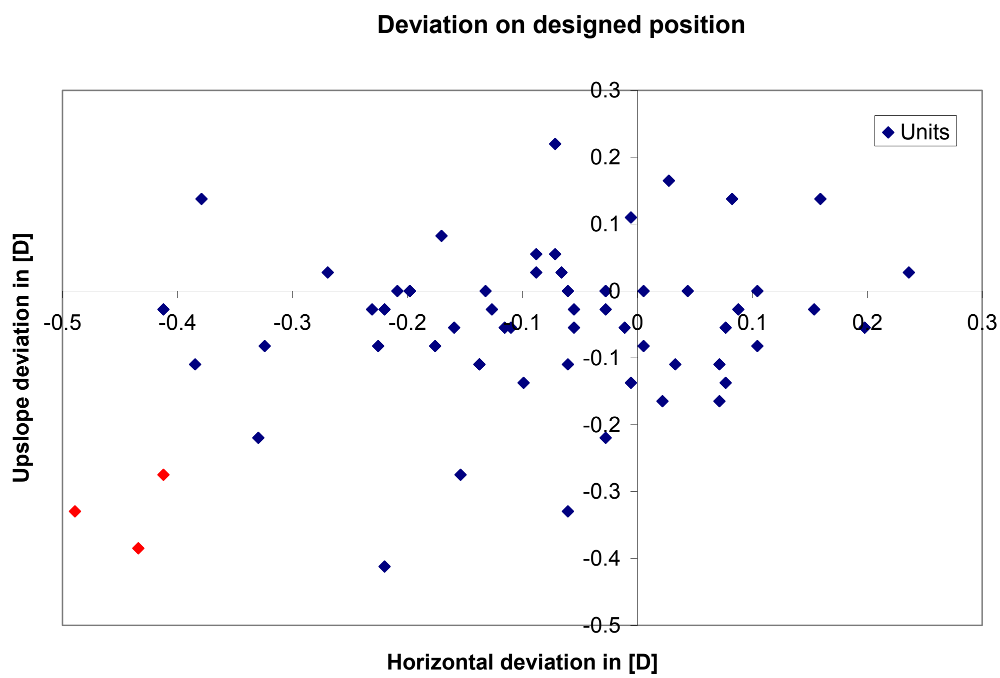


Fig. 5.36 deviation on designed position

Determine the unit adjust angle

The 0.3 D off centre placement distance is approximately two times the standard deviation on placement position. So the average individual unit adjustment angle should give a tendency towards the average *unit adjust angle* α.
The spreading of individual unit adjust angle is given in Fig. 5.37. In this histogram a peak is found around 50 and -130 degrees, which is the same line. So from this method the average unit adjust angle is approximately 50 degrees

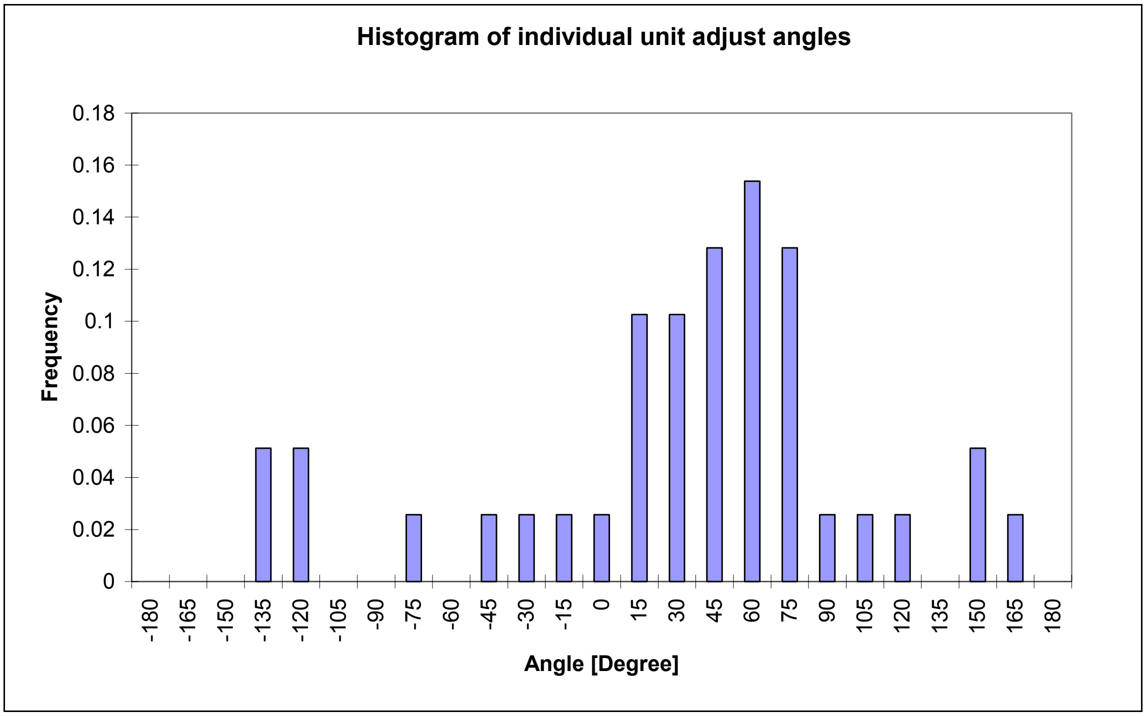


Fig. 5.37 histogram of individual unit adjust angles

The unit adjust angle is also calculated on basis of d1 and d2 as in the 0.1 D and 0.2 D tests. The *unit adjust angle* for 0.3 D off centre placement calculated by d1 and d2 is 45 degrees. This is equal to the tendency found by the individual unit adjust angles.

5.8 Analysis and conclusions of model tests

5.8.1 Accuracy of placement

The measured deviation of individual units is larger than a picture suggests. Therefore, to retrieve reliable information on the quality of armour layer units must be measured on their location based on the centre of gravity of the units.

The achievable accuracy in position using guided placement in favourable conditions is about 0.2 D. The achieved accuracy was almost constant for all guided placement tests. The direction of the individual deviation in position is completely random resulting in an average deviation close to zero. This property makes the position on average well predictable.

The individual deviation does not influence the placement of other units in such way that the deviation accumulates. So the designed placement grid does not have to be adjustable to the already placed units.

5.8.2 Calculation parameters for the computer design tool.

In chapter 6 a computer design tool to calculate an Xbloc placement grid is presented. For a systematic calculation of a placement grid a number of parameters are needed. The parameters are presented below.

Placement distances

The placing distances recommend by DMC and used in the software design tool are predicted correctly. Therefore the recommended horizontal placement distance remains 1.3 D and the upslope distance remains 0.64 D. With these placing distances the required packing density also remains unchanged on $1.20/D^2$.

Off centre criteria's

On a curved section of breakwater the unit's position is optimized based on the surrounding units. After the optimization each unit has an ideal off centre distance, this off centre distance should be within the applicable range. Some units placed with an off centre distance smaller than 0.2 D roll back to the centre position. Due to this unpredictability all units with an ideal position smaller than 0.2 D off centre are designed and placed in the centre position.
The maximal off centre distance used is set to 0.4 D. With the individual deviation in position of 0.2 D, any larger off centre distance and the unit can be placed precisely on top of one base unit. This is not desirable for the placement pattern and stability of the armour layer.

Therefore a unit with an off centre distance smaller than 0.2 D is positioned in the centre position and a unit with an off centre distance larger than 0.4 D is left out.

Unit adjustment angle

The unit adjust angle has been tested with three different off centre distances. The angle was found to be almost constant for all three tests, approximately 45 degrees. This constant angle suggests a straight line for the unit adjustment line.
The usage of a straight line fits better than based on the theoretical analysis, see section 3.3.9, this is probably caused by the orientation of the units. Therefore a straight line with 45 degrees is used in the design model.

Randomness in error coefficient

The randomness on left out criteria was set to 20 % of the maximal error. The value of 20 % was chosen visually, based on designed placement grids. With the standard deviation on position of 0.13 D, the 20 % randomness is approximately half this standard deviation. So the designed randomness is significantly smaller that the accuracy achieved in prototype. Therefore the value of 20% will be kept to ensure a random left out pattern.

Coefficient error function

The optimization function has not been calibrated due to the absence of a test breakwater head. Therefore the coefficient of the error function is left unchanged on 1.5, which was determined on visual interpretation of different test runs.

5.8.3 Prediction for placement in prototype

The placement tests performed with 18.2 cm Xbloc units have given confidence in good placement behaviour of Xbloc in prototype. A summary of the predictions for placement in prototype have been made:

- Xbloc is suitable unit for placement on basis of a predefined placement grid
- The two sling methods are enough to place all units correctly
- Guidance of orientation along the vertical axis is necessary to fill up the gap in between the base units. Submerged units should be checked in order to fill in the gap.
- Realistic placement with significantly larger units than hydraulic test units resulted in a similar packing density. So the assumption of reduction in final packing density due to large units is not likely to occur
- Swell can cause problems for accurate placement. When swell with a long period is present the units must be guided horizontal as well to prevent swing of the unit

6 Description of the software design tool

6.1 Introduction

The objective was to develop software that generates a placement grid which includes all variables encountered in the analysis of a placement grid for single layer armour layer. This means that the software should be capable of calculation a placement grid on any breakwater lay-out and cross section while maintaining the empirical knowledge and theoretical relations found in section 3.3. This led to a program structure as shown in Fig. 6.1.

A second objective in the development is the user friendliness of the software design tool. A complete description how to use the software design tool is given in the user manual. This is a separate document on the CD-ROM. Besides this the complete source code and validation files of the software tool are also given on the CD-ROM.

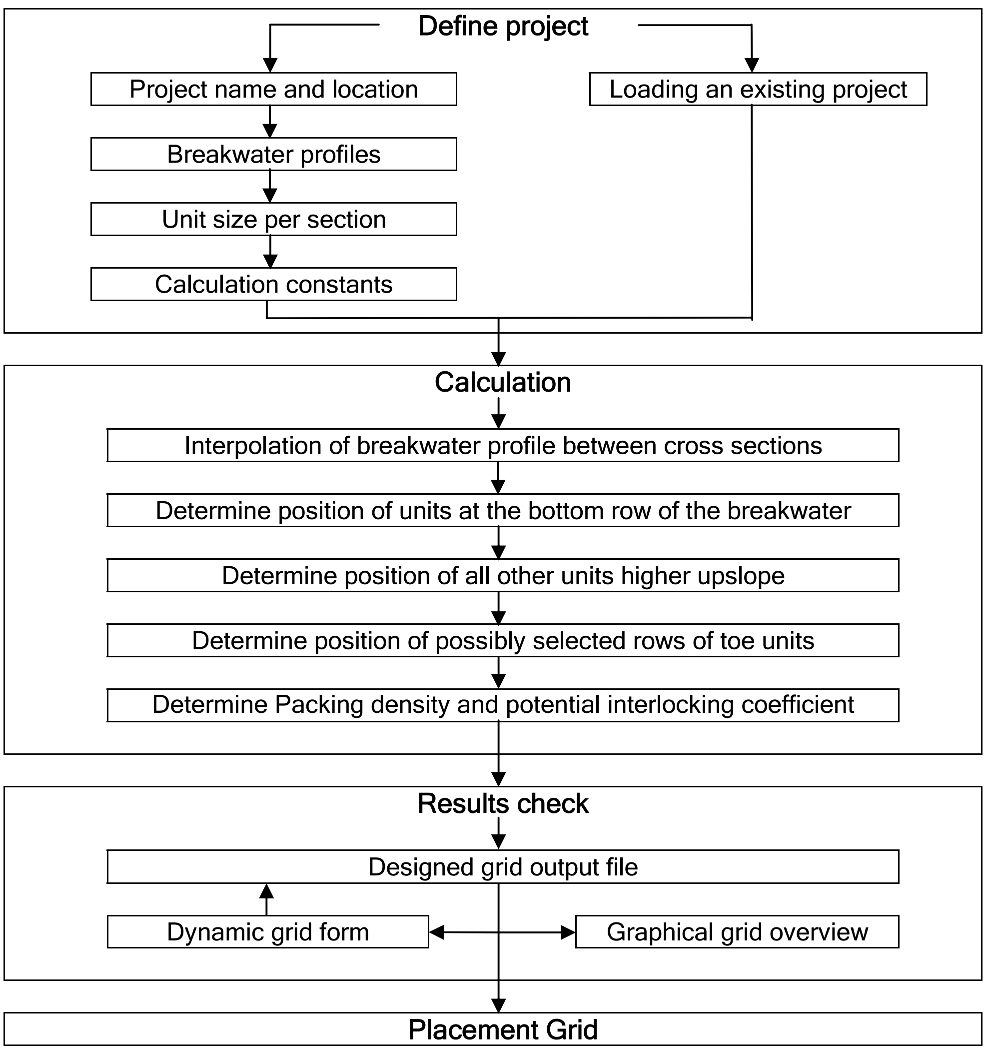


Fig. 6.1 Program structure

6.2 Project definition

6.2.1 Project name and location

A grid calculation can be started by defining a new project or loading an existing project. If a new project is started, a form, see Fig. 6.2 appears asking a project name and number and a base point.
The project name will be used as file name of the output file, in this case the output file will be "Port Oriel.CSV". The project number can be used as an identification number which is stored but never used for any calculation.
The base point can be used to connect a local co-ordinate system to any global co-ordinate system, this function is not jet operational in this version.

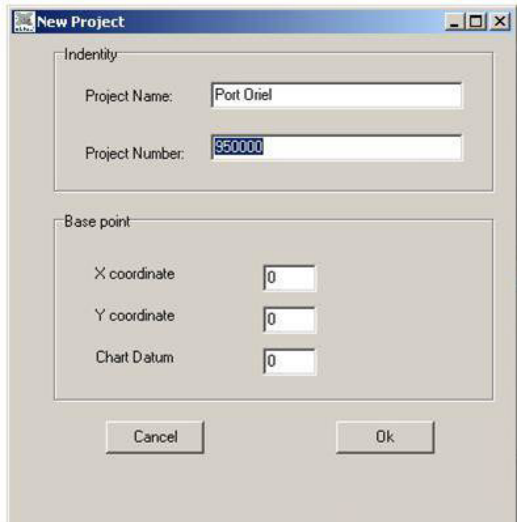


Fig. 6.2 project sheet

6.2.2 Definition of a breakwater profiles

The location of the breakwater is defined by the X and Y coordinate at the centre point of the breakwater. The "Angle" is defined as the angle between the longitudinal-axis of the breakwater and the X-axis of the spatial grid. (CCW)

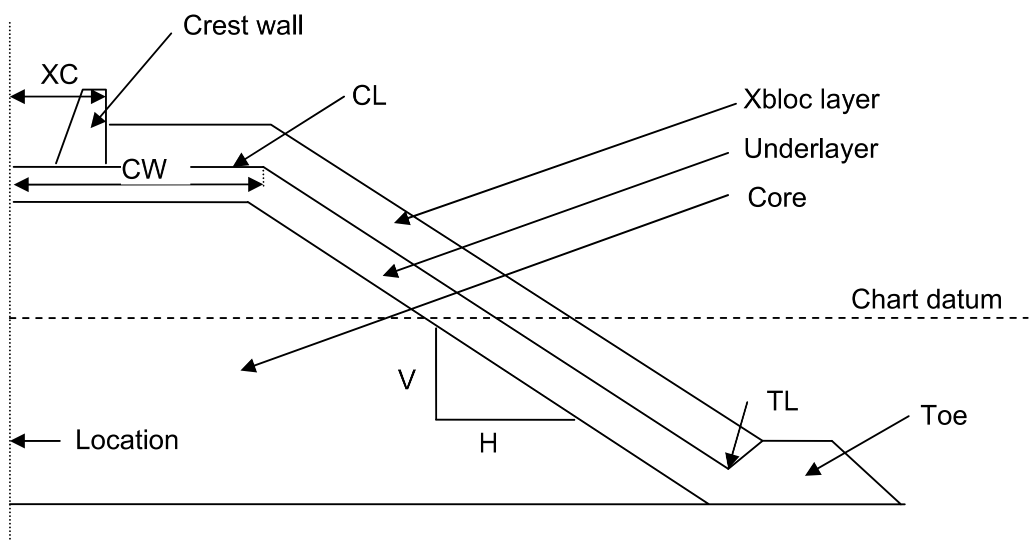


Fig. 6.3 definition on dimensions of a breakwater cross section

Definitions on the dimensions given in Fig. 6.3

- *The crest level* (CL) is defined as the height of the underlayer at the crest in relation to Chart Datum.
- *Crest width* (CW) is the distance between the centre of the crest and the outer point of the crest.
- *Xbloc crest* (XC) is the distance from the centre of the crest till the point of which the Xbloc units are placed.
- *The Toe level* (TL) is defined as the height of the underlayer at the toe in relation to Chart Datum.
- *The Slope* is defined as the relation vertical (V) stands to horizontal (H).

Xbloc Toe

In the computer model two different toes can be selected, a rock toe or an Xbloc toe. An Xbloc toe can be designed by selecting a number of units placed in front of the slope. Zero units mean a rock toe is applied. If no Xbloc toe is selected the software will automatically select a standard rock toe. The selected toe will be the same for all sections of the breakwater.

6.2.3 Unit size per section

Unit sizes can be selected for all individual sections. These size differences will be automatically accounted for in the calculation module. The unit size is passed on to the unit left above, as shown in Fig. 6.4. In this way in this way no light units are placed onto the head section.
An example of a transition between different size units at the trunk and head is given in Fig. 6.4, for this example a larger difference of 50% increase unit weight is used to emphasize the effect of difference sized armour units. Normally units on a head are 25% heavier than on the trunk.

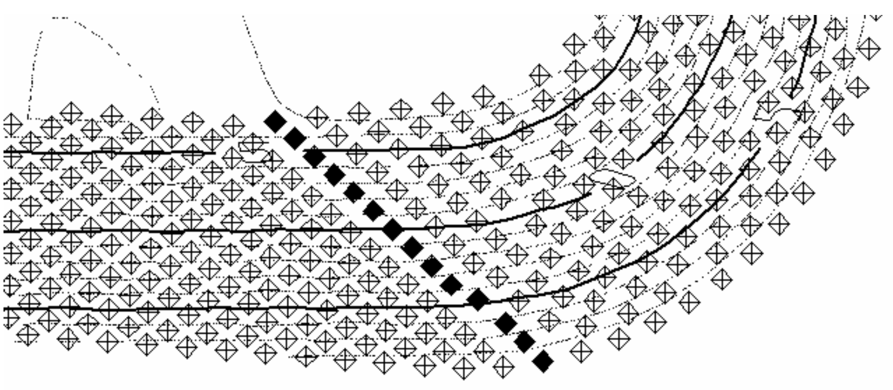


Fig. 6.4transition between two sizes armour units

6.2.4 Parameters used for the calculation

A number of parameters will be used for the calculation of a placement grid. The values as shown in Fig. 6.5 are based on the results of the placement test described in section 5.8.2.

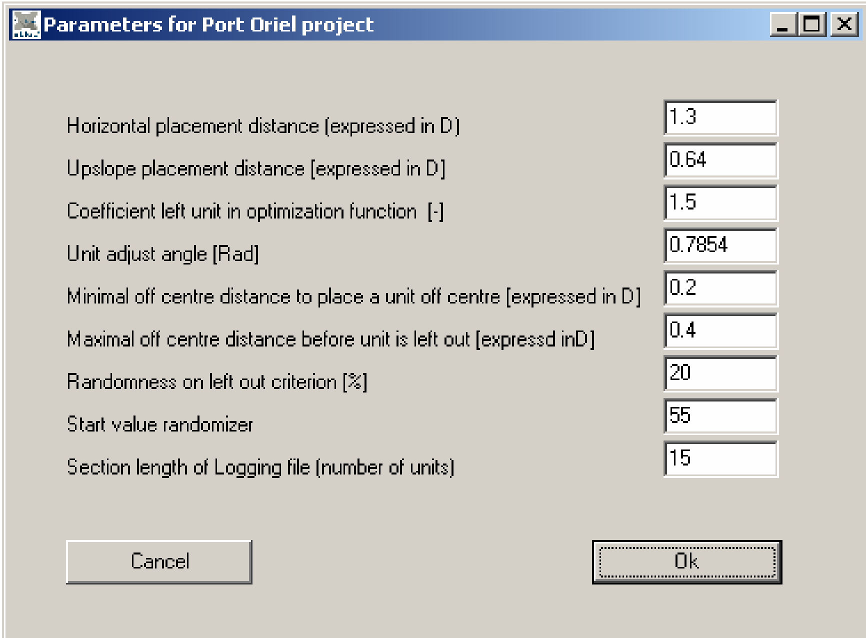


Fig. 6.5 calculation parameters

- *Horizontal and upslope placement distance* can be set depending on the unit size used. 1.3 and 0.64 are standard values for the Xbloc, these factors have to be multiplied by the characteristic unit size to get the placing distance in meters.
- *Coefficient left unit in optimization function,* the optimal position of a unit is based on an error function depending on three other units two below and the unit to the left. This coefficient is used to tune the error function.
- *Unit adjust angle*, this is α in Fig. 3.13 in section 3.2.8.
- *Minimal off centre distance to place a unit off centre,* is the minimal off centre distance Δx expressed in D, see section 3.2.8, before a unit is not placed in the middle anymore.
- *Maximal off centre distance before unit is left out,* is maximal off centre distance Δx expressed in D, see section 3.2.8, before a unit is left out.
- *Randomness on left out criterion,* is built in to prevent a uniform pattern of units which are left out. A repeating pattern of units which are left out can cause weak spots in the armour layer.
- *Start value randomizer*, to reproduce a placement grid the same series of random numbers is needed therefore a special randomizer is built which produce the same series of random numbers with the same start value.
- *Section length of logging file,* is the length of the sections which is saved in 1 logging file which the contractor has to use for the quality control of the placement

6.3 Calculation of individual unit positions

After the interpolation of the breakwater profiles the calculation of a placement grid is done in three phases, the first phase is the calculation of all units in the first row, secondly all units upslope and the last phase are the Xbloc toe units. A completed the calculation contains more information than the position of all units only. A number of parameters like the packing density and potential interlocking coefficient are available.
Some parameters like position and neighbours are directly addressed when the unit is calculated other parameters like potential interlocking coefficient will be assigned in a later stage, as shown in Fig. 6.1.

The parameters that are assigned/ calculated are:
- *Number* is the units unique number which is used as identification of the unit
- *Position (x,y,z)* are the three coordinates fixing its position
- *Surrounding units* are the numbers of the six surrounding units, see Fig. 6.6. These units are used for navigating over the slope and calculation distances

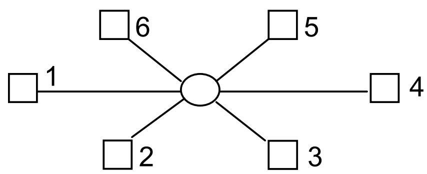


Fig. 6.6 surrounding units

- *Error parameters* are based on the distances between the units and used to determine the best possible location of the unit
- *Packing density* is calculated for each individual unit and also the total packing density which is the average of all the individual packing densities, see section 5.2
- *Potential interlocking coefficient* is a parameter to predict the hydraulic stability of the armour unit. This can be used to locate potential weak spots in the armour layer.
- *Distance to the centre of the crest* is used to determine if a unit placed on the slope or on the crest of the breakwater
- *Unit volume* is given in m^3
- *Characteristic diameter* is calculate on basis of the unit volume and is used to determine placement distances.
- *Row number* is the number of the row the unit is place in counted from the toe.
- *Section* is the number of the section in which the unit is placed.

6.3.1 Interpolation of breakwater profile between cross sections

The breakwater profile between two given cross section is linear interpolated. Almost all data points of the breakwater profile are interpolated, crest level, toe level, crest width and Xbloc crest width, only the slope of the breakwater is constant for whole breakwater.

The input of different slopes for different cross sections will give wrong answers. The error is generated by the fact that the cross sections will be according the given dimensions. whereas the placement module is not capable of interpolation the slope at the location of the unit and will use a constant slope over the section, resulting in discontinuities. In common practice this will be no problem because all single layer armour units are placed on a standard slope used for the whole breakwater which is between 3:4 and 1:1.5 (V:H).

On a straight section of breakwater the interpolation is done on basis of the distance along the breakwater. For a curved section of breakwater the interpolation is done on the basis of the angle of rotation.

6.3.2 Determine position of units in the bottom row of the breakwater

Before the positions of the first row of units can be calculated the given cross sections has to be expressed in global X- Y- Z-coordinates instead of dimensions like crest width and toe level. This is done for all characteristic points of the cross sections.

The coordinates of the first row units can be determined by placing the units per section. When a section is completed the next section will be calculated until all sections have been calculated. To ensure a smooth transition between the succeeding sections the cross sections are shifted a little to align exactly with the position of the last unit of the previous section. The shift of a cross section has little effect on the position of the units itself. With very large gradients in toe level between the cross sections the calculated z-coordinate can differ by a few cm.
For every section it is determined if the slope is curved or straight. For these different sections two different calculation methods are implemented: one for a straight section of breakwater and one for a curved section of breakwater.

Straight section of breakwater

When the actual section is the first section of the breakwater, the first unit is positioned on the coordinates of the toe of cross section 1. If it is a succeeding section then cross section 1 is adjusted to coincide with the last unit of the previous section.
When the first cross section is adjusted the length of the section is calculated again and the number of units in the first row is determined. The units are placed on the ideal horizontal placing distance on the line between the toe of cross section 1 and 2.

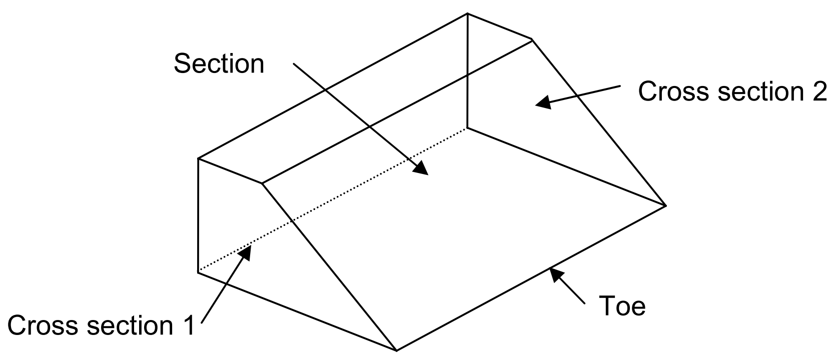


Fig. 6.7 schematic overview straight section of breakwater.

Curved section of breakwater

A curved section is quite similar to a straight section. The only difference is the way the units are divided over the section. By a curved section it is done by an angle of rotation multiplied by the radius instead of a distance. The angle of rotation per unit is determined on the basis of the ideal placing distance and the radius off the curved section. The reason to calculate the first row by angle of rotation is purely mathematical.

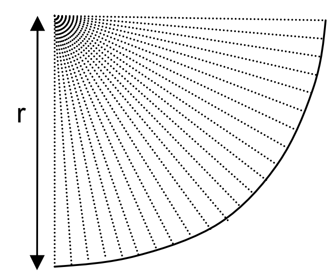


Fig. 6.8 units divided by angle of rotation

6.3.3 Determine position of all units higher upslope

The position of the first row of armour units is calculated based on the cross sections only. All other units are positioned on bases of the already calculated units and breakwater profiles.

To keep the calculation organized the units are calculated row by row until the complete slope is covered with armour units. To determine if a row is completed and where to start the new row of armour units the algorithm uses the unit identification number of the already calculated units. The calculation cycle of one unit is shown in Fig. 6.9 and will be explained in detail in this section.

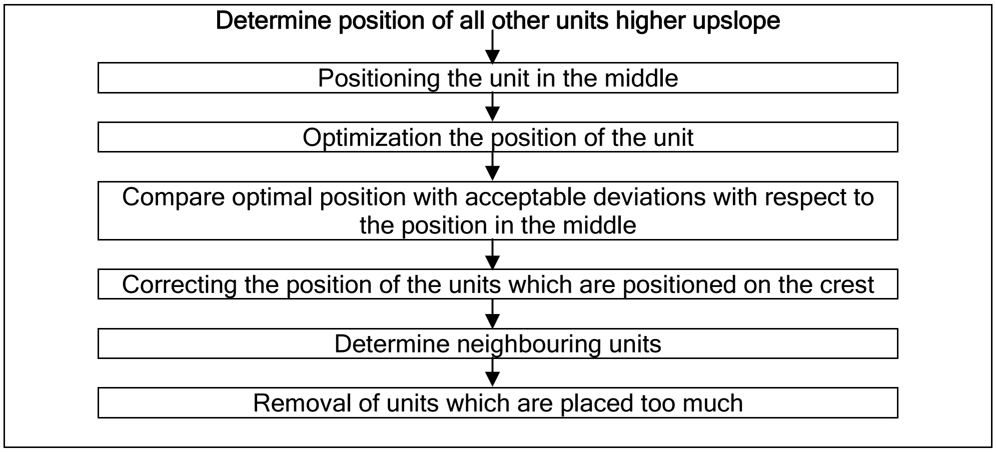


Fig. 6.9 calculation cycle of one unit

Positioning the unit in the middle

The starting point for the calculation of the position of a new unit is to calculate the position in the middle between the two units one row below. This calculation is done in two steps.
The first step is averaging the x, y, z coordinates of both units resulting in the point exactly in the middle between the two units. The second step is to calculate the distance upslope perpendicular to the line between the two units. The distance upslope is calculated on basis of the distance of the two units, see section 3.3.5.
During this calculation all units are assumed to be located on the slope of the breakwater and not on the horizontal part (crest). If it turns out the unit is positioned on the crest, see Fig. 6.11, the position will be corrected later on in the calculation. This centre position is the starting point for the rest of the calculation.

Optimizing the position of the unit and compare this with the position in the middle

The next step in positioning a unit is to check if there is a more favourable position than the position in the middle. This optimisation is done by moving the new unit along the straight line as described in section 3.2.8 and determining for each position the error function. The optimal position is the point on this line where the error function reaches its minimum.
The first proposal for the error function is based on three distances, the distance to the two base units and the distance to the unit to the left in the same row.

After the optimization process, the unit has an ideal position along the unit adjust line and a distance *off centre distance* Δx from the centre position. With this information three options are possible:

1. The distance Δx is smaller than calculation constant PM (placement in the middle); the unit is placed in the middle.
2. The distance Δx is larger than PM but smaller than constant ULO (Unit left out); the unit will be positioned at the new position on the unit adjust line.
3. The distance Δx is larger than constant ULO; the unit is left out and the next unit will be positioned on the next two base units.

An example of a placement grid on a head of a breakwater with shifted units is given in Fig. 6.10. In row number 4, unit 1 is placed in the middle. Unit 2 is moved a little to right above and number 3 is left out. Number 4 is placed in the middle again.

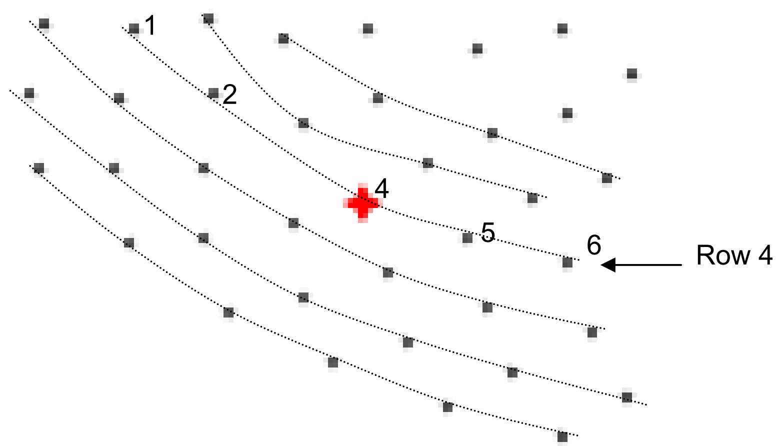


Fig. 6.10 example of a placement grid of a head.

Another important phenomenon is that because of the larger horizontal space between unit 2 and 4 the unit above sinks much further between 2 and 4 than with a normal horizontal placing distance.

Correcting the position of the units which are positioned on the crest

The new position will be checked on its location on the breakwater, this is done to check if the unit is on the slope or crest of the breakwater. This check is performed by comparing the height of the unit with the height of the crest at the unit's location. If the unit's is positioned higher than crest level, the unit should be positioned on the crest.
To place the unit on the crest the unit has to be corrected both to the vertical plane as to the horizontal plane. This correction is done by folding down the unit, see Fig. 6.11.

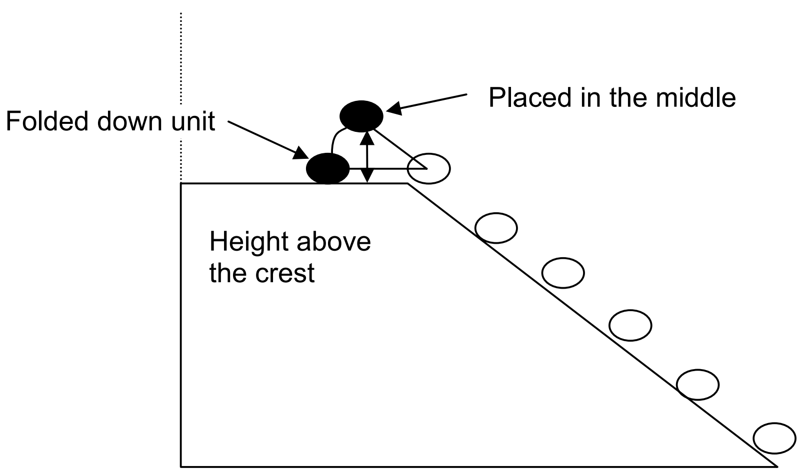


Fig. 6.11 folding down of a unit

Distance to the centre of the breakwater and removal of all units which are to close to the centre of the breakwater

For each unit the distance to the centre of the breakwater is calculated. The placement algorithm calculates row by row, this continues until a complete row is placed beyond the theoretical line of unit coverage (crest wall). In this way it is certain that the whole breakwater is covered with armour units.
To check if a complete row is positioned behind the crest wall the distance to the centre of the breakwater is calculated for each unit. The unit closest to the toe of the breakwater is saved for each row. If this unit and thus all units of that row are placed behind the crest wall the algorithm stops.
The last step in the calculation of the upslope units is the removal of all units which are positioned beyond the crest wall. This is done by comparing the distance to the centre of the crest of each unit with the location of the crest wall at the units location.

6.3.4 Toe units

If an Xbloc toe is selected the units in the toe will be calculated as last part of the whole grid calculation. The Toe units are placed on the basis of the bottom row. The calculation of the toe units uses the same but simplified principles as the calculation of the units upslope, one of the simplifications is that all units are placed in the middle and can not been adjust to optimize the placement. A second simplification is that the Z-coordinate is copied from the first row upslope instead of calculation a new Z-coordinate.
These simplifications are justified because a toe consists only of one or two rows and are placed on a horizontal plane in front of the breakwater.

6.3.5 Results

The computer model is developed to give its results in three different ways, in a dynamical output form, as a graphical overview and in an output file. The dynamical output form and graphical overview can be used to assess and adjust the design, whereas the output file can be used to create CAD drawing of the placement grid.

Dynamical output form

The results of the calculation are given in a table. This table is meant as a check if there are any defects. If it turns out that there are defects it is possible to repair these defects manually by changing the coordinates.
To get a convenient arrangement, the units are divided over the different sections of the breakwater, see Fig. 6.12.
When a section is selected all units located on that section will be put in a list. When a unit is selected from this list the information of the selected unit is given.
The position of the selected unit on the breakwater can be seen in the graphical overview as a red dot, see Fig. 6.13.

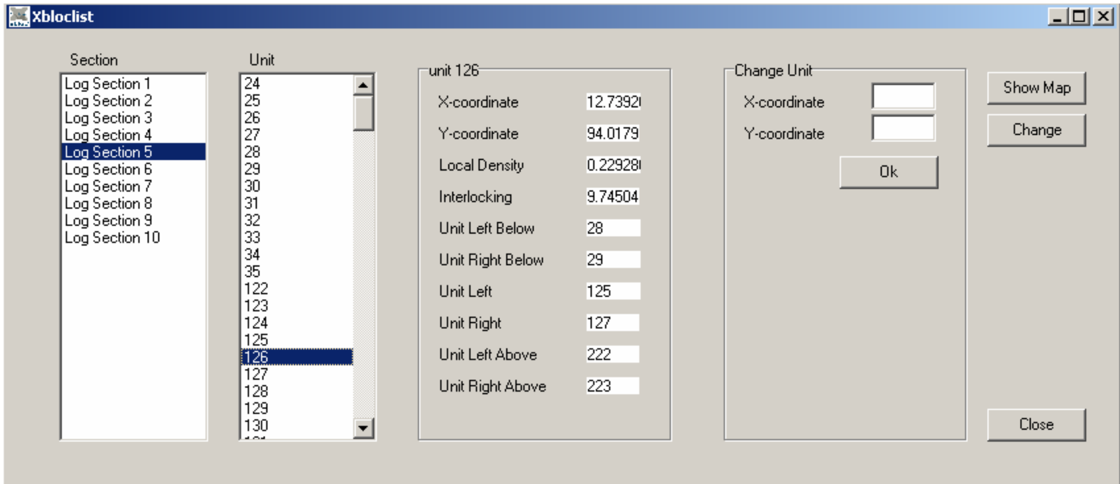


Fig. 6.12 dynamic output form

Graphical overview

The graphical interface is mainly to give a visual impression of the designed placement grid. The graphical overview makes it easy to discover possible errors before the output is processed into a breakwater design.
The graphical overview does not only show the units but also presents the cross sections and a spatial grid. This extra information is presented to improve the clarity of the overview.
To locate a unit easily in the unit in the dynamical output form, it is possible to select a unit in the overview by clicking on the unit, the information of the unit will be presented in the dynamical output form.

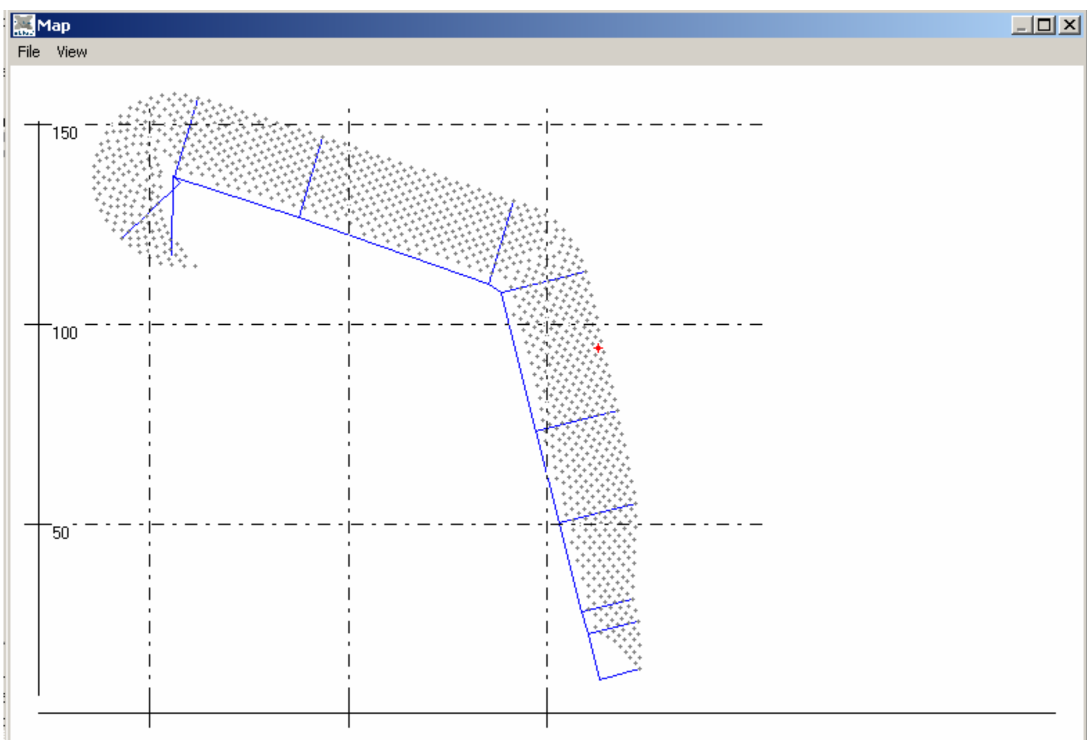


Fig. 6.13 example of graphical output

Output files

Project data

If a breakwater is defined the geometry can be saved. An Xbloc project file contains all information needed for the calculation of a placement grid. An example of an xbp-file is given on CD-ROM, the xbp file is a standard ASCII format which makes it easy to control with any editor. The lay-out of an Xbloc project file is as follows: each row contains a variable followed by a description of the variable.

Designed grid output file

After a calculation of a placement grid the output file will be automatically generated. The output file will be a standard comma separated value file which can be opened with Excel.
At the beginning of the file a resume is given of the constants used in the calculation. The rest of the file is a table containing all information of each unit. Each unit is described in one row with multiple columns. An example of an csv-file is given on CD-ROM.

6.4 Limitation of the software tool

To use the software design tool correctly it is necessary to know the limitations. The limitations of this software tool are summarized in this section.

6.4.1 Curvature towards open sea

At a breakwater most curves are directed towards the sheltered area. The software is based on this shape only. Therefore it is impossible design a proper placement grid for breakwaters with a sharp curvature towards open sea. (is can not put extra units in)

6.4.2 No different slopes per cross section

The software is based on a constant slope of the breakwater.

6.4.3 Small radius

The algorithm used is not capable to position a unit correctly by small radius curvatures (< 2 times D), this can occur on the crest of a breakwater. The reason for this is that position of the new unit is calculated on two base units. When the angle between two succeeding basses is large the newly calculated units cross each other creating a false placement pattern, see Fig. 6.14.

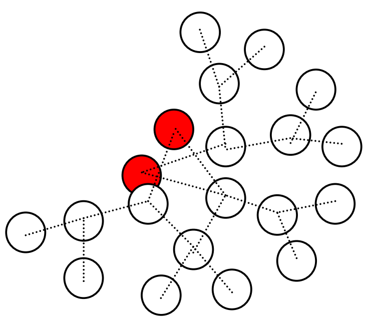


Fig. 6.14 crossed units.

6.4.4 Very small sections

The adjustment of the cross sections to create smooth transition between succeeding sections can shift a cross section by one horizontal placing distance. This shift in position of the cross section becomes relatively large if the distances between the cross sections are small (< 2 time a unit placement distance). The detailed information given with small sections will not be expressed in the placement grid.

6.4.5 Special Toe units

In June 2005 a special Xbloc toe unit has been designed. The modified unit has only one nose, see Fig. 6.15. This special toe unit may require other distances in front of the slope than normal Xbloc units. This is not included in the software.

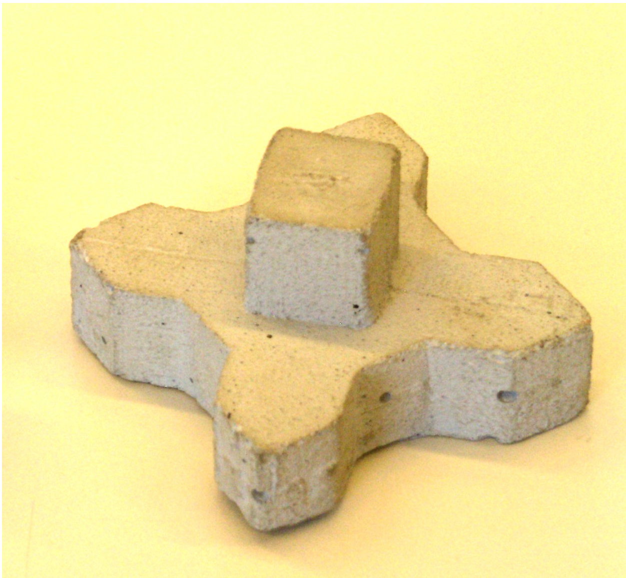


Fig. 6.15 special toe unit

6.4.6 Convert local coordinates into global coordinates

The model is based on local coordinates. To calculate the global coordinates on the basis of the local coordinates and the base point has to be done manually.

7 Testing the Software design tool

7.1 Introduction

To test the software design tool a number of test cases have been created. For all these cases a number of parameters have been tested like; breakwater profile, packing density and potential interlocking coefficient.
In section 7.2 all validation parameters are presented and in section 7.3 the test cases are presented.

7.2 test parameters

7.2.1 Breakwater profile

The breakwater profile is the basis of every grid calculation and should therefore be correct. The breakwater profile is checked on all characteristic points by looking at the coordinates of the unit's position at these characteristic points. This profile checks are performed at different locations along the breakwater to check the interpolation.

The characteristic points of a breakwater profile are:
- The toe the breakwater; this is checked by the coordinates of the units in the bottom row.
- The crest level; this is checked by the Z coordinate of the units placed onto the crest.
- The crest width; this is checked by the positions of the first unit positioned on the crest and the unit directly below the crest level, see Fig. 7.1. The width of the crest at the cross section is calculated by the distance to the crest of the unit below crest level minus delta z time the angle of the slope.

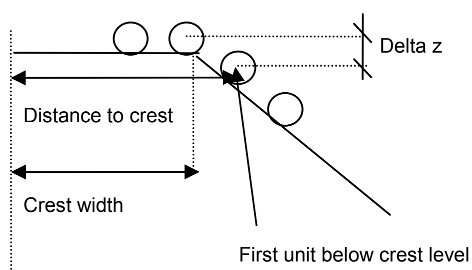


Fig. 7.1 calculation of crest width

7.2.2 Packing density

The packing density is an objective quantity which is verified every calculation. Two different types of packing densities are provided: local packing density and an average packing density. The local packing density is defined as, one unit over surface area [1/m^2]. The surface area of one unit [U4] is defined as the horizontal distance D1 times the upslope distance D2, see Fig. 7.2.

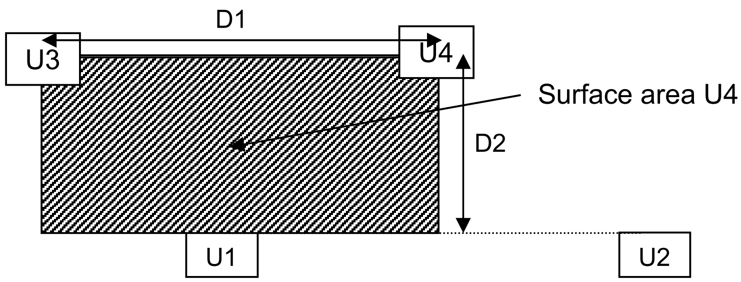


Fig. 7.2 surface area of one unit

The local packing density can not be calculated for all units, units which are positioned in the first row or units with no unit to the left do not have D1 or D2. As a result the local packing density can not be calculated.
The average packing density for the whole breakwater is the arithmetic average of all units which has a local packing density.

7.2.3 Potential Interlocking Coefficient

In Comparison to packing density the potential interlocking coefficient [PIC] gives a more accurate predicting of the hydraulic strength of the armour layer because it also says something about the pattern of the designed armour layer.
In prototype the interlocking on a curved section of breakwater is lower than on a straight section of breakwater, this is due to the change in placement pattern and not in density. The PIC on a curved section is approximately 30% lower than on a straight section.
The hydraulic stability of an single layer armour unit is generated by interlocking and by its own weight. For Xbloc the hydraulic stability is generated for around 75 % by interlocking and 25 % by its own weight. With a reduction of 30% in interlocking the total loss in hydraulic stability is around 20 %.

To compensate this loss of hydraulic stability a standard accepted design rule is applied, this rule says that the units on the head of a breakwater must be 25 % heavier than the unit at the trunk of a breakwater. This compensation of loss in hydraulic stability is in the same order as the loss in hydraulic stability calculated by PIC.

7.3 Test cases

To check if the software design tool is capable of calculating all kind of breakwater layouts, all kind of simple layouts have been tested. And the last test case is a complex layout with a combination of straight and curved sections, as shown in Fig. 7.5.
The simple layout tests are divided in two categories constant profiles and changing profiles between two cross sections. An overview of all test cases is given in Table 7.1.

Table 7.1 test scheme

Straight section of breakwater with constant profiles	Correct profile	Proper interlocking	Packing density
Direction 30 degrees	V	V	100%
Direction 90 degrees	V	V	100%
Direction 120 degrees	V	V	100%
Direction 180 degrees	V	V	100%
Direction 210 degrees	V	V	100%
Direction 270 degrees	V	V	100%
Direction 320 degrees	V	V	100%
Curved section of breakwater with constant profiles			
Curvature 50 degrees	V	V	100.25%
Curvature 90 degrees	V	V	99.54%
Curvature 130 degrees	V	V	100.42%
Curvature 180 degrees	V	V	100.65%
Curvature 240 degrees	V	V	99.97%
Interpolation of depth gradients			
Straight section	V	V	99.98%
Curved section	V	V	102.08%
Interpolation of crest level gradients			
Straight section	V	V	100%
Curved section	V	V	99.10%
Interpolation crest width gradients			
Straight section	V	V	100%
Curved section	V	V	99.35%
Combination of straight and curved sections, including interpolation	V	V	100,29%

7.3.1 Section of breakwater with constant profile

The tests with constant profiles are designed to check the goniometric formulas used to define the position of the breakwater. All straight tests cases looks quite similar with only the direction of the breakwater changing but this is needed to test the behaviour of the goniometric formulas in all four quadrants.

The straight section of breakwater has a length of 100 meter and a constant profile as shown in Fig. 7.3. The profile used for the curved sections of breakwater is almost similar to the profile of the straight sections. The only difference is the position of the crest wall which is positioned at 3 m instead of 2 m from the centre of the breakwater. This to avoid small radius curvatures as described in section 6.4.3.

All tests with constant profiles were successful. The sections are calculated at their proper position and direction which shows that the goniometric formulas work correctly in all four quadrants.
The placement grid calculated for these sections is calculated without any errors, resulting in the correct packing density and proper interlocking.

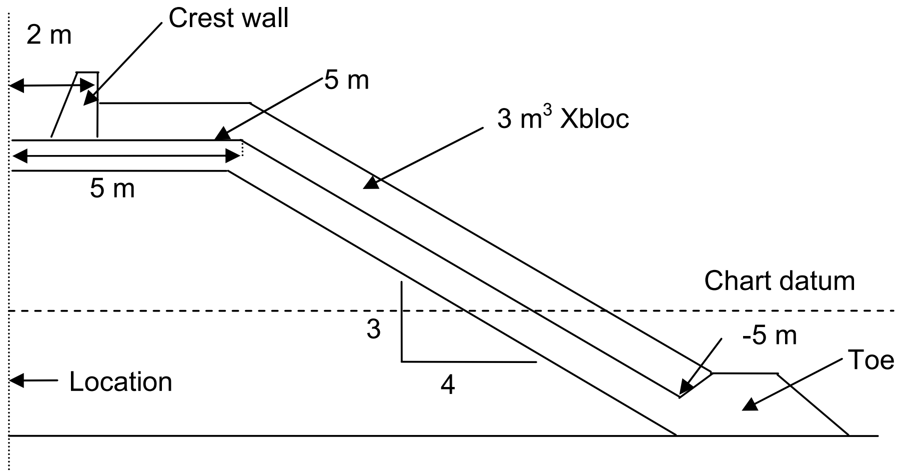


Fig. 7.3 breakwater profile used by straight section with constant profiles

7.3.2 Interpolation of profile along a section of breakwater

Due to bottom variations and variation in wave loads the cross section of the breakwater changes along the axis of the breakwater. Therefore parameters such as depth, crest level and crest width can vary along a section of breakwater, these parameters have been tested individual. Because different formulas are used by straight and curved sections of breakwater each parameter has been checked two times.

Cross section 1 has the same profile as shown in Fig. 7.3. In cross section 2, see Fig. 7.4 one parameter is changed at the time:

- toe depth is changed form -5 m to -7 m
- crest level is changed from +5 m to +7 m
- crest width is changed from 5 m to 10 m

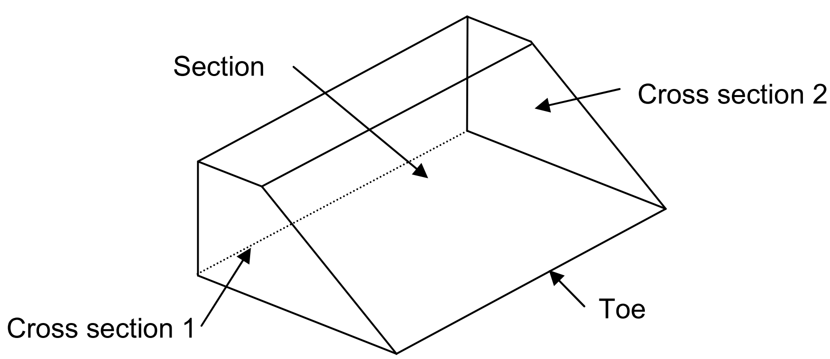


Fig. 7.4 definition cross sections

All these interpolation test cases were calculated correctly.

7.3.3 Combination of straight and curved sections, including interpolation

The final test to check the software design tool is a combination of different sections creating a complete breakwater profile. This breakwater should include straight sections, curved sections and interpolation between cross sections.
The first Xbloc breakwater project, Port Oriel Ireland, fulfil these test requirements. Therefore Port Oriel is a good test case.
The breakwater layout of Port Oriel has been defined by 11 cross sections, see blue lines in Fig. 6.13. The geometry of the breakwater is represented correctly and the is no visible transition in the placement grid between two sections

Packing density

For the whole breakwater a 4 m^3 unit is used. This unit size requires a packing density of 0.23 units per square meter. The average calculated packing density is 0.23 unit per square meter, thus the software calculates the proper average packing density.
The local packing density is visually given in Fig. 7.5. In the areas with low packing density [red dots] a unit has been left out. Above this low packing density area a high packing density arises. Due to the missing unit a large gap between the units arises resulting in a very small distance upslope resulting in a high packing density.

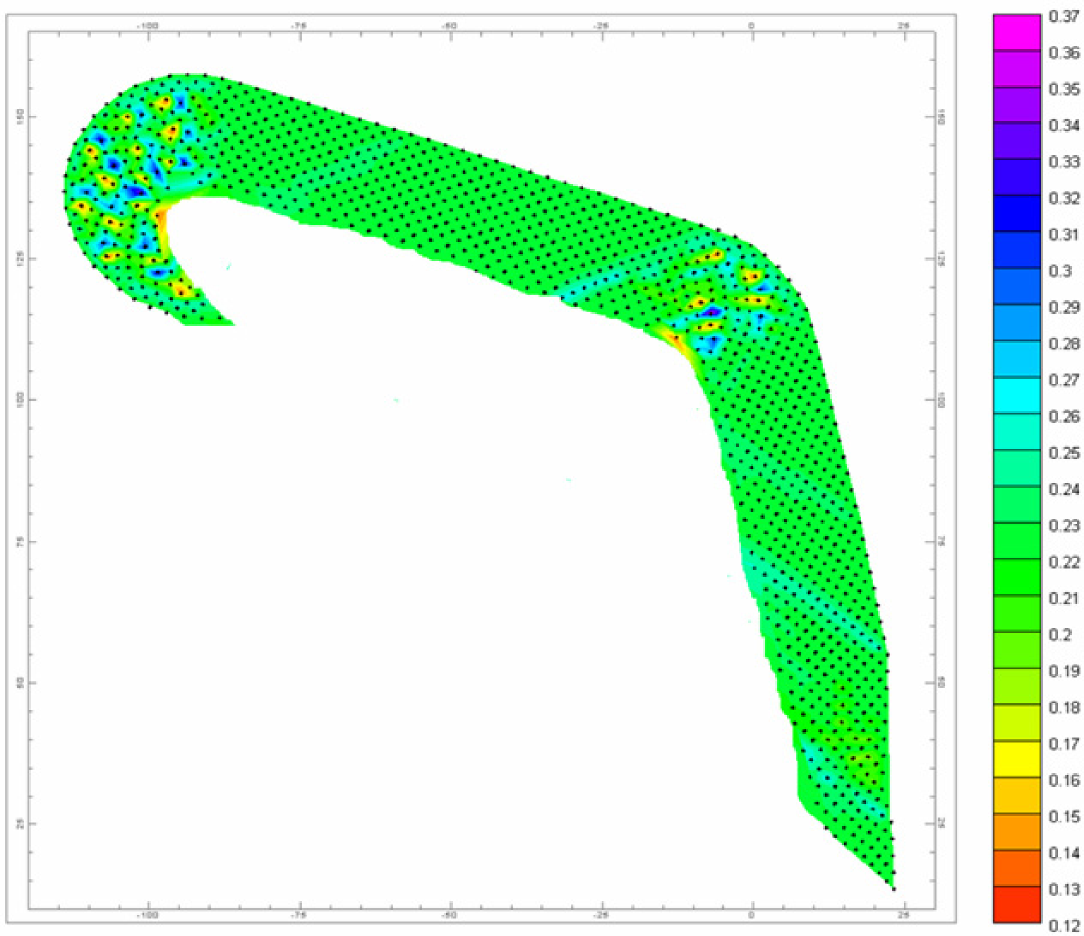


Fig. 7.5 individual packing density

Potential Interlocking Coefficient

The potential interlocking coefficient [PIC] gives a prediction of the hydraulic stability of the designed armour layer. An example of visual representation of the PIC for Port Oriel is given in Fig. 7.6.

From this figure it is clear that at the edges of placement grid the PIC is rather low, in prototype the edges are also the weak points of the armour layer. This low PIC is caused by the fact that these units are only interacting with two units instead of four (section 3.3.4).

On the straight sections the maximal interlocking can be reached because the diamond-shape pattern is in place. At curved sections the diamond-shaped pattern is disturbed but still has a reasonable interlocking potential is reached.

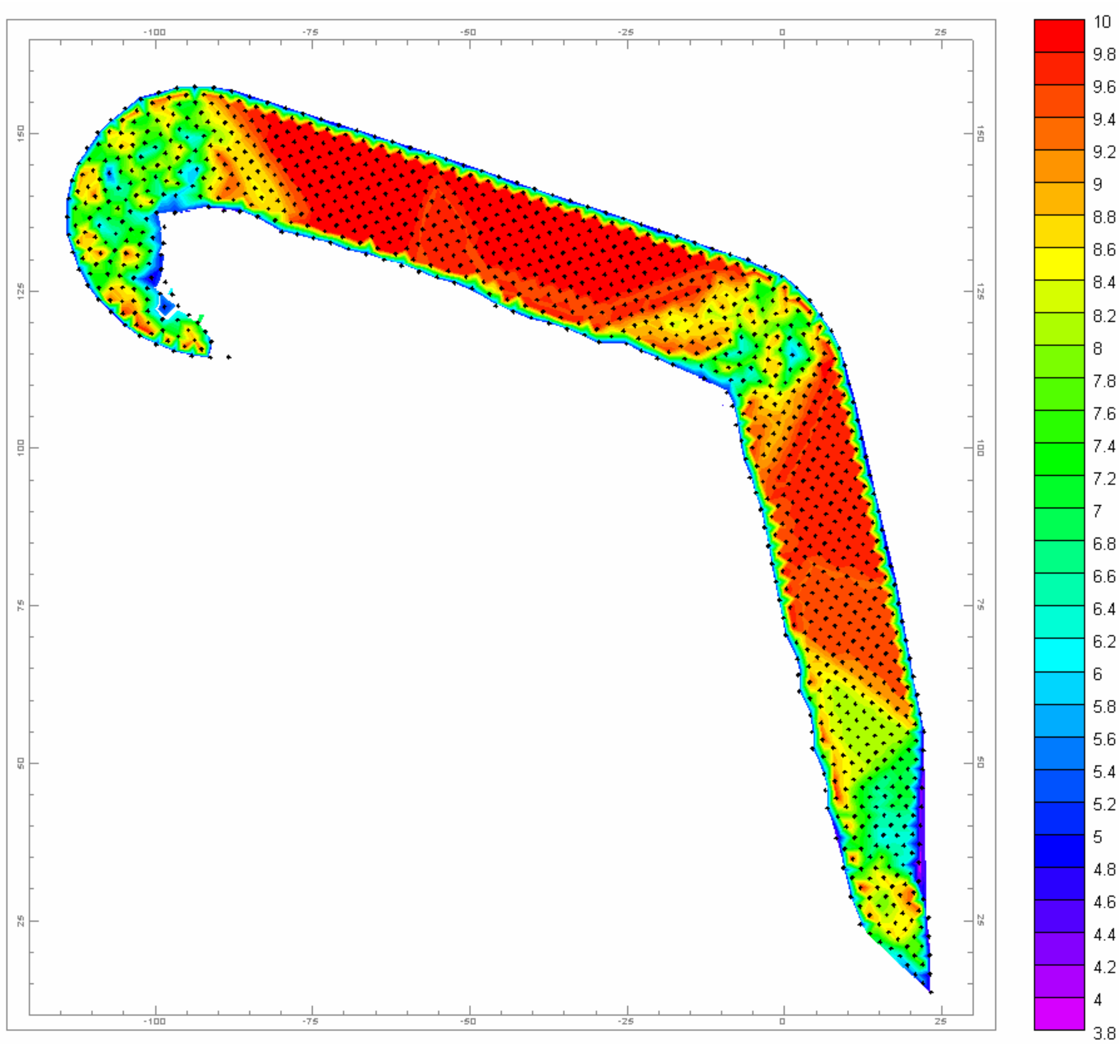


Fig. 7.6 potential interlocking coefficient

The designed placement grid looks so promising that the result of this calculation is used as actual placement guide in Port Oriel.

8 The Conclusions and Recommendations

In this section conclusions and recommendation are presented. The conclusions drawn are in chronological order throughout the report.

8.1 Conclusions

- The quality of the placement pattern has a major influence on the hydraulic stability. The hydraulic stability is largely generated by interlocking. Interlocking is the mechanism that units hook into each other, this is best achieved by a diamond-shaped placement pattern. [3.1]

- Packing density is a first indication of the quality of the armour layer. If the packing density is low the distance between the units is large, reducing interlocking. [3.3.3]

- The packing density is constant for a range of horizontal placement distances. This is cause by a flexible diamond-shaped pattern, when the horizontal distance increases the upslope decreases. [3.3.5]

- Off centre placement of a unit will result in a larger upslope distance. This is caused by the fact that the unit can not sink entirely in between the two base units. [3.3.9]

- Irregular horizontal placement distances will be automatically corrected. The diamond-shaped pattern has the positive property that the error in horizontal placement distance is cut in half each row higher up. [3.3.10]

- All Xbloc units can be placed by only two sling methods, one sling method for units in the first row and one sling method for all other units. [4.1]

- The recommended sling length is three times the characteristic diameter [D] of the unit. This sling length makes it possible to rotate the unit from storage orientation to placement orientation and gives a stable and save position during placement [4.1]

- Oscillating water motion due to waves can cause significantly unit response. When the wave period is close to the eigen period of the unit hanging in a crane, the response amplitude is in the order of the characteristic unit diameter [D]. [4.2]

- The unit response can be predicted by a forced pendulum. The forces action on the pendulum are calculated by the Morison equation for a stationary object in a oscillating flow. [4.2]

- It is possible to place Xbloc units on a predefined position. Each unit has a small deviation on its designed position but on average the units are placed on the designed positions. [5]

- The packing densities found by realistic placement tests have the same packing density as grids tested in hydraulic model tests. So it is likely that these densities will also be achievable in prototype. [5.4]

- The accuracy with guided placement is in the order of 0.2 D which is small enough to prevent cumulative errors. With unguided placement the accuracy is in the order of 0.5 D which results in cumulative errors and is thus not useable. [5.5]

- Off centre placement of units is possible, but units with a off centre distance smaller than 0.2 D tend to roll back to the centre. To make the placement predictable the units are designed in the middle or more than 0.2 D off centre. [5.7]
- Off centre placed units do not only shift towards the left or right but also upslope. The angle in which the units shifts is found in the experiment to be 45 degrees. [5.8.2]
- The automated grid design tool works properly for all breakwater layouts and the designed placement grid includes all theory described in chapter three. [7]

8.2 Recommendations

The recommendations are divided in three categories, further model placement tests, hydraulic testing of placement variables and monitoring of prototype placements.

8.2.1 Further model placement tests

The off centre placement is implemented in the design of a placement grid to solve the problem with small horizontal placement distances. These small horizontal distances will only occur on a curved section of breakwater, for example a head. In order to test placement behaviour of units placed off centre it is recommended that this is tested on a curved test section.

From section 4.2 it is clear that units are vulnerable to waves during placement. Therefore it is recommended to study the accuracy of placement for different wave climates. From these tests guidelines for acceptable sea conditions can be made to prevent placement failure in prototype.

8.2.2 Hydraulic testing of placement variables

Because a significant part of the hydraulic strength is generated by interlocking is important to test the influences of placement variables on hydraulic strength.
To design a placement grid a range of horizontal placement distances is used. To make sure this has no negative influence of hydraulic stability the influence of different horizontal placement distances with the normal packing densities should tested.
Another parameter to test is the influence of packing density. It is possible that by lower packing densities units are pulled out of the armour layer. But it is also possible that the whole slope settles and strengthens itself.

8.2.3 Monitoring of prototype placements

The model placement test have been performed as realistic as possible but to make sure the there are no scale effects it is recommended to monitor prototype placements. The parameters of interest are accuracy of unit positioning, packing density and settlement after the first moderate storm. The settlement is especially interesting when a reduced packing density is used due to large units, see section 3.3.7.

Appendix on CD-ROM:

Placement tests

- Experiment analysis
- Pictures

Swing tests

- Experiments
- Software

Software Design Tool

- Software Design Tool (executable)
- Source code placement software
- Manual Placement software
- Test cases used in chapter 7 (input and output files)

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