Excel-based design tool for the assessment of rubble-mound and caisson breakwaters

Laurens De Smet

Supervisor: Prof. dr. ir. Andreas Kortenhaus
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Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Civil Engineering

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Preface and acknowledgements

This thesis is made as a completion of my master's degree in Civil Engineering at the University of Ghent, Major Dredging and Offshore Engineering. It consists of a manual for two programs: the CE-Cloud and the CE-Cloud_AutoCAD. Both programs assist an engineer in designing a rubble-mound and/or a caisson breakwater, but the latter is also supported in AutoCAD.

I have chosen this thesis for several reasons. First of all, it is a very practical thesis. I truly hope engineers will learn how to use the CE-Cloud and come up with realistic designs. The CE-Cloud is consequently made as user-friendly as possible, in order to be easily understandable. Secondly, the CE-Cloud is programmed in Visual Basic for Applications (VBA). Since I had never worked with VBA before, it was a challenge for me to learn to work with this tool through tutorials. It is also a very clever tool, which I will be able to use later in my professional career. Finally, I have chosen this thesis, since I could work on it very independently: familiarizing myself with VBA, implementing the different design formulas, structuring the CE-Cloud, writing the thesis report, etc. In the first semester of the academic year '15-'16 I mainly prepared the content of the CE-Cloud and defined the sequence of the design steps. The whole program and thesis report were however made in an intensive second semester.

I would sincerely like to thank Prof. Dr. Ir. A. Kortenhaus for his efforts and expertise as a supervisor and introducing me to the world of VBA and coastal engineering. I am also grateful for the advice of D. Gallach Sanchez who reviewed my design steps and practical approaches. I would also like to thank him for proofreading the rubble-mound section of this thesis report. Further I thank Mrs. H. Devos and Mr. V. Peeters for reviewing the whole report.

Finally, I would like to thank my parents, fellow-students and VTK colleagues for supporting me throughout my studies and thesis assessment.

If the reader/user should have any questions considering this thesis and the CE-Cloud, he/she can always contact me on: laurensdesmet93@gmail.com

Laurens De Smet, June 2016

Permission

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Abstract

Nowadays offshore structures, and in extension breakwaters, find more and more maritime applications. Consequently, it is of major importance to calculate a thorough and up-to-date design of these structures. The CE-Cloud is a clear and user-friendly program in which an engineer can design a rubble-mound and/or a caisson breakwater, based on the Coastal Engineering Manual and EurOtop Manual. Both designs can subsequently be compared on a practical and financial basis. Since the hydraulic boundary conditions can change over the breakwater's length, the CE-Cloud can design multiple cross-sections of the same breakwater and automatically import them into AutoCAD or save the coordinates in a textfile. Finally, the CE-Cloud provides a cost breakdown tool which generates clear graphs of the different costs per meter of the generated breakwater trunks in function of the process steps and used materials.

Keywords: CE-Cloud, rubble-mound breakwater, caisson breakwater, design comparison, cost analysis of breakwaters

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Abstract – **Nowadays offshore structures, and in extension breakwaters, find more and more maritime applications. Consequently, it is of major importance to calculate a thorough and up-to-date design of these structures. The CE-Cloud is a clear and user-friendly program in which an engineer can design a rubble-mound and/or a caisson breakwater, based on the Coastal Engineering Manual [1] and EurOtop Manual [2]. Both designs can subsequently be compared on a practical and financial basis. Since the hydraulic boundary conditions can change over the breakwater's length, the CE-Cloud can design multiple cross-sections of the same breakwater and automatically import them into AutoCAD or save the coordinates in a textfile. Finally, the CE-Cloud provides a cost breakdown tool which generates clear graphs of the different costs per meter of the generated breakwater trunks in function of the process steps and used materials.**

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I. INTRODUCTION

Due to the rising sea water level, breakwaters are becoming unavoidable to protect the hinterland. There are plenty of construction types for these structures, but the rubble-mound and caisson breakwater are the most common configurations.

The CE-Cloud is an Excel-based design program which assists the engineer in executing a safe, but economic, design for these two structures. Subsequently, the engineer can make a thought-through decision which of the two breakwater types should be installed, dependent on financial and practical considerations. The design formulas are mainly originating from the Coastal Engineering Manual [1], the EurOtop Manual [2] and the Rock Manual [3].

If the hydraulic boundary conditions change over the length of the breakwater, a configuration transition is favorable. The breakwater subsequently consists of multiple different cross-sections. The user can design up to five different cross-sections in the CE-Cloud and implement them into the final breakwater. Once this is executed, the program generates a clear cost and material overview of the whole breakwater.

Multiple additional tools are implemented in the CE-Cloud to assist the engineer in analyzing and visualizing several design characteristics. The first tool automatically generates an AutoCAD drawing of the designed cross-section. The second tool can save the corresponding coordinates of the generated cross-section in a textfile. The last and third tool visualizes the cost breakdown of the whole breakwater by generating graphs of the trunk expenses per meter in function of the process steps (production, transport and construction), and used materials.

The user does not need to be a coastal engineering expert to use this program, which is made as user-friendly as possible. A certain coastal engineering background and insight is however required to make a safe and realistic design.

II. THE COASTAL ENGINEERING CLOUD

The CE-Cloud consists of three main sections. First, there is the design of the rubble-mound breakwater. Secondly, there is the design of the caisson breakwater. And thirdly the program generates all characteristics of the final breakwater which can consist of multiple cross-sections.

For each of the different designing steps, a design sheet is available in the CE-Cloud which is divided in three main sections: general input, calculations and final output. In the first section, the user needs to insert the necessary inputs. Dependent on the design approaches and formulas, the user subsequently needs to define several specific inputs in the calculation section, after which the different design values are generated. Once this is done, the user can select a certain approach to yield the final output. Subsequently the next design step can be commenced.

A certain color code is implemented in the CE-Cloud to guide the user in the meaning of the corresponding parameters. If the cell is green, it means that the user can insert a certain input value manually. Depending on the parameter, a default value can be available. The orange cells consist of intermediate parameters which are not considered in the final design. The yellow cells represent the final parameters which can be selected as final output for the considered design step. Note that next to every parameter, its unit and description are clearly indicated.

Each of the design sheets is provided with a progress button which generates a clear figure of the considered breakwater cross-section. This is a general sketch of the structure, on which the different designed sections are indicated by use of colors (green: already designed, orange: is being designed in the active design sheet).

III. THE RUBBLE-MOUND BREAKWATER

A rubble-mound breakwater is a coastal structure consisting of a rubble core, protected by several filter layers and an armour layer. If the design steps, explained in this section, are executed in the given sequence, a realistic design will be found. Figure 1, at the end of this document, shows a typical cross-section of a rubble-mound breakwater with all its features.

A. *Hydraulic boundary conditions*

Several hydraulic boundary conditions of the breakwater need to be properly defined in order to characterize the incoming wave energy and geometric restrictions. These conditions can be calculated in four different ways: the manual input, the Pierson-Moskowitz spectrum, the JONSWAP spectrum and the input file. In the first approach, the user simply inserts the necessary parameters manually. The second and third approach both consider standard wave spectra which give a rather theoretical result for the hydraulic parameters, based on the wind velocity at a height of 10 m above the SWL. In the fourth approach, the user can insert measured wave heights with their corresponding periods, generated from a measurement device. Subsequently, the CE-Cloud will automatically generate the necessary parameters according to Goda [4]. Note that the different boundary conditions need to be defined at the sea- and leeside, in order to determine a detailed design.

B. *Armour unit selection*

The armour units are the main protective elements, against erosion, in the breakwater design. Their stability should be of major concern for the designer. These units can either consist of rocks or concrete armour units. Rocks are however economically and practically more interesting. If the necessary rock dimensions are not available, concrete armour units will be installed. These units mainly gain stability due to their selfweight and interlocking properties. All available formulas in the CEM [1] are available in the CE-Cloud to calculate the following armour units: concrete cubes, tetrapods, dolos, accropodes, CORE-LOCs, tribars and Xblocs. Note that the slope of the breakwater is intrinsically defined by selecting a certain armour unit as final output.

C. *Height assessment*

In the next design sheet the crest freeboard R_c is determined, after which the total height of the breakwater is calculated. The crest freeboard is mainly a function of the breakwater slope and the incoming wave height. Several design approaches are implemented in the CE-Cloud, based on the EurOtop Manual [2] (probabilistic and deterministic approach) and the CEM [1].

It is possible to install a submerged berm on the seaside slope of the breakwater. This way the overtopping and/or the amount of armour units can be decreased.

D. *Filter and core materials*

Between the armour units and the core material, two filter layers are applied. These filters need to provide sufficient stability for the armour layer units, but need to prevent smaller materials from washing out.

The appropriate filter and core gradings are automatically generated in the CE-Cloud by use of standard gradings, mathematically expressed by use of the Rosin-Rammler curves [5]. Subsequently the three different filter criteria: retention, permeability and internal stability are checked.

E. *Crest width*

The crest width is a very important parameter in the installation of the breakwater. The construction cost of the breakwater is significantly lower if land-based equipment is used than if sea-based equipment is used. Therefore, it is better to provide sufficient crest width in order to install the necessary equipment on the crest.

Note that this crest width will also decrease the amount of overtopping discharge that reaches the leeside, resulting in a safer design.

F. *Toe stability*

The intersection between the armour layers and the bottom of the sea is very vulnerable for scour and instability. Consequently, an appropriate design for the toe materials, rocks or concrete units, should be executed. If armour units are displaced out of their layer, they will come to rest on this toe, resulting in an increased stability.

G. *Roundhead assessment*

Due to the high cone-overflow velocities at the head-section of the breakwater, a separate design for the armour units of the roundhead should be executed. Another reason for this stability reduction is the reduced support from the neighbouring units at the leeside of the cone. Two different empirical approaches are available in the CE-Cloud for designing these units. The first approach considers rocks and dolos, the second considers tetrapods and tribars.

H. *Cost analysis*

In the CE-Cloud, a full cost breakdown of the structure can be generated and visualized. In order to generate these costs, a cost list is available which can easily be accessed and adjusted to the user's preferences. This list gathers several costs per volume, weight or transported kilometer of the used materials.

This cost breakdown is approached in two different ways. First there is the breakdown in function of the process steps: production, transport and construction. Secondly, the costs are split up in function of the breakwater materials: armour units, filter, core material, etc. As such, a clear cost overview is generated in function of the process steps and corresponding materials.

I. *Final design*

At this stage, the breakwater is fully determined and a final design sheet is generated. This sheet gathers the most important information of the designed cross-section in an easily printable lay-out. It is split up in four different sections: hydraulic boundaries, layer information, dimensioning and the cost breakdown.

In the dimensioning section, the user can easily access the AutoCAD drawing tool. First, a sheet with all the breakwater's coordinates is generated after which the designed cross-section can be automatically drawn in AutoCAD. Note that AutoCAD should be available on the user's computer. If this is not the case, the user can also save the coordinates in a textfile.

Note that the final design sheet for the caisson breakwater will look very similar to this design sheet in order to easily compare both designs.

At the bottom of the final design sheet, the user can select the designed cross-section to be one of the cross-sections of the total breakwater.

IV. THE CAISSON BREAKWATER

A caisson breakwater consists of a concrete caisson, filled with sand, which is installed on a rubble-mound foundation. If the design steps, explained in this section, are executed in the

given sequence, a realistic design will be determined. Figure 2, at the end of this document, shows a typical cross-section of a caisson breakwater with all its features.

A. Hydraulic boundary conditions

The hydraulic boundary conditions are determined in a similar way as in the corresponding design sheet for the rubble-mound breakwater, explained in III.A. There is however no need to define the boundary conditions at the leeside.

B. Design water depth at the toe of the caisson

The CE-Cloud provides the user with a possible range of values for the water depth at the toe of the caisson, based on four different criteria: being able to berth the design ship in low water conditions, no large wave forces acting on the foundation, no impulsive waves are impacting on the caisson and a minimal foundation height to spread the caisson loads. The user can subsequently insert a final value, based on the generated range.

C. Crest freeboard

For the calculation of the height of the breakwater and caisson, the crest freeboard R_c should be determined first. This freeboard is calculated, based on the mean allowable overtopping discharge which needs to be inserted by the user as general input. Several design approaches are implemented in the CE-Cloud, based on the EurOtop Manual [2] and CEM [1]. Note that the program will automatically detect whether the waves are impulsive or not and use the corresponding formulas.

Since the necessary freeboard at the leeside is assumed to be very moderate, the configuration of the top cap can be adjusted, in order to reduce the amount of concrete at the leeside. This can be implemented in the program by use of a top cap concrete reduction factor. This is the ratio of the concrete which can be saved with respect to the total concrete of the caisson's cross section, per meter.

D. Pressures

In order to calculate the different forces and moments, acting on the caisson, the corresponding pressures need to be calculated first. This is done by use of two approaches: Sainflou [6] and Goda [7]. Since the first approach considers standing, regular waves, it is recommended to use Goda's approach.

Note that also here the CE-Cloud will automatically detect whether the waves are impulsive or not and will use the corresponding formulas to calculate the pressure distribution on the caisson.

E. Forces and moments

In order to analyze the safety of the design in a later design stage, the different forces and moments, acting (per meter) on the caisson, need to be calculated. This is automatically done in the CE-Cloud by use of the formulas of Goda [7] and Takahashi [8]. Note that the width of the caisson B is not known at this stage, therefore the different forces and moments are expressed parametric in B. Since there are stochastic variables, signifying the bias and uncertainty of the calculated forces or moments, present in the implemented formulas, the user can manually insert an additional standard deviation for the calculation of the forces and moments. The generated forces and moments will consequently be more conservative.

F. Armour layer units

Since the caisson can be very heavy, it is very important to protect its foundation from erosion. Therefore, armour layer units are installed on the foundation slopes. Note that these units will logically be smaller than the armour layer units of a rubble-mound breakwater since the former are less subject to wave forces. Consequently, only rocks are considered as armour material. For expressing the stability of these units, two approaches are available in the CEM [1]: Madrigal and Valdés [9] and Tanimoto, Yagyu and Goda [10].

G. Foundation details

The filter and core materials of the caisson breakwater foundation are determined in a similar way as in the rubble-mound breakwater approach. The appropriate gradings, defined by the Rosin-Rammler [5] curves are automatically generated in the CE-Cloud. Since the size of the armour layer units is generally moderate, only one filter layer needs to be installed.

Because the flow conditions near the toe of the caisson can be very dangerous, considering erosion of this area, concrete foot protection blocks need to be installed. It is up to the user to insert the amount of blocks that will be installed at the sea- and leeside of the caisson. The CE-Cloud will automatically generate the necessary dimensions of these blocks by use of the Japanese approach, mentioned in the CEM [1].

At last also the bedprotection is characterized by manually inserting the density and thickness of this layer.

H. Width and safety analysis

The width of the caisson B is still parametric at this stage of the design. This parameter will iteratively be determined in function of three safety factors: safety against sliding and overturning of the caisson, and whether the foundation provides sufficient bearing capacity for the caisson.

First, the user needs to insert an estimated value for the caisson width and complete the design sheet by inserting the appropriate parameters in the green cells. This way, the configuration of the caisson, its levelling method and the final forces and moments acting on it are defined. Subsequently the safety factors are automatically generated after which the user can iteratively change the value for the caisson width B in order to define a safe, but economic value.

I. Cost analysis

Once the caisson breakwater is fully designed, a cost breakdown-sheet is generated. The different costs are calculated by use of the same cost list that was already available for the cost analysis of the rubble-mound breakwater. The expenses are expressed in two different approaches: first there is a breakdown in function of the process steps: production, transport and construction. Secondly the costs are split up in function of the materials which are used in the different sections of the breakwater.

Analogous to the cost assessment of the rubble-mound foundation, the user needs to insert the transport distances and porosities of the different materials as general input.

J. Final design

The final design sheet of the caisson breakwater is split up in four main sections: hydraulic boundaries, layer information, dimensioning and the cost breakdown. This sheet is implemented in such a way that it is easily comparable to the

final design sheet of the rubble-mound breakwater. The user can consequently make an appropriate decision on which breakwater to install for a specific project.

This final design sheet also has the possibility to automatically generate the designed cross-section in AutoCAD or to save the coordinates in a textfile.

At last, the user can select the designed cross-section to be one of the final cross-sections of the total breakwater.

V. BREAKWATER SELECTION

Once the final design sheets of both breakwaters are generated, the user can easily compare both designs and make a thought-through decision on which breakwater to install. The CE-Cloud supports the engineer in making this decision, by providing numerical information. It does however not consider any practical considerations for the breakwater design. A ship can for example easily moor to a caisson and not to a rubble-mound breakwater. On the other hand, the caisson breakwater can cause difficult navigation conditions, since the waves are almost fully reflected on the caisson. Subsequently it is up to the user to decide which breakwater will be installed, based on practical engineering insight and the provided design in the CE-Cloud.

Once the user has made a decision, the designed cross-section can be added to the total breakwater by clicking on the corresponding button in the final design sheet. Note that it is not possible to switch to the other type of breakwater once a certain cross-section of the whole breakwater is defined. Consequently, the decision to install a rubble-mound or caisson breakwater is made based on one cross-section, and not based on the whole breakwater design.

VI. TOTAL COST ASSESSMENT

For certain projects it is possible that the cross-section of the breakwater differs over its length due to changing boundary conditions. This is for example the case if the water depth changes significantly. The transition between two different cross-sections will generally be installed over a short distance. The breakwater can for example consist of two constant cross-sections with a transition of 1 to 5 meters in between. The user can insert a maximum of five different cross-sections in the final breakwater design.

Once all cross-sections are defined, the different spacings between these sections need to be inserted as general input. If this is done, the CE-Cloud will generate a full cost breakdown in function of two approaches: the first approach considers the different costs per meter of the cross-sections in function of the process steps and used materials. The second approach calculates the different costs of these process steps and materials for the trunk sections between the inserted cross-sections. Note that the costs for the second approach are calculated by use of linear interpolation between the costs of the materials for the adjacent cross-sections of the considered trunk.

The CE-Cloud contains a tool which automatically generates the expenses per meter for the different breakwater trunks in function of the process steps and used materials. If the user, for example, selects the transport costs, the tool will subsequently render the transport costs per meter for each of the breakwater trunk-sections in a clear graph.

At the end of the final design sheet, the amount and type of materials which are installed in the different sections of the breakwater are generated.

VII. CONCLUSIONS

The CE-Cloud is a user-friendly, Excel-based design program which assists an engineer in calculating a proper design for a rubble-mound and/or a caisson breakwater. It is up to the user to make a proper decision between both breakwaters, based on the generated data from the CE-Cloud and practical engineering insight. Subsequently, the user can design a breakwater which consists of multiple designed cross-sections due to the changing boundary conditions. In order to easily analyze the provided data in the CE-Cloud, several additional tools are available: a tool which generates the design in AutoCAD, a tool which saves the generated coordinates in a textfile and a last tool which can visualize the different costs of the final breakwater trunk-sections in several graphs.

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1: SWL (seaside)   7: Second filter layer
2: SWL+H_s/2 (seaside)   8: Core
3: SWL (leeside)   9: Geotextile + bedprotection
4: SWL+H_s/2 (leeside)   10: Toe (seaside)
5: Armour layer   11: Toe (leeside)
6: First filter layer   12: Berm (optional)

Figure 1: Rubble-mound breakwater configuration

1: SWL (seaside)   6: Core
2: SWL+H_s/2 (seaside)   7: Geotextile+bedprotection
3: SWL (leeside)   8: Foot protection blocks
4: Armour layer   9: Bedding layer
5: First filter layer   10: Caisson

Figure 2: Caisson breakwater configuration

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Symbol	Unit	Description
A_e	m²	Eroded area
α	°	Sea bottom slope (hydraulic boundaries)
α	°	Slope of the breakwater
α_{rhead}	°	Slope of the roundhead
α_{I0}	[-]	Goda parameter (Goda, 1974)
α_{I1}	[-]	Goda parameter (Goda, 1974)
α_1	[-]	Goda parameter (Goda, 1974)
α_2	[-]	Goda parameter (Goda, 1974)
α_3	[-]	Goda parameter (Goda, 1974)
α_*	[-]	Goda parameter (Goda, 1974)
b	m	Width of the foot protection blocks
B	m	Crest width (RM)
$B_{m,lee}$	m	Berm width of the foundation at the leeside (CB)
$B_{m(,sea)}$	m	Berm width of the foundation at the seaside (CB)
β	°	Angle of wave incidence
C_r	[-]	Overtopping reduction factor due to the crest width
d	m	Water depth (RM)
d	m	Water depth at the toe of the caisson (CB)
d_b	m	Vertical distance from the berm to the SWL
d_B	m	Vertical distance from the top of a toe to the SWL
d_x	m	Diameter of which x% of the material is smaller
d_*	[-]	Impulsiveness parameter
D	%	Damage parameter
D_n	m	Diameter of the equivalent cube

D_{n50}	m	Equivalent cube length of the median rock
δ_{red}	%	Top cap concrete reduction factor
δ_0	m	Vertical shift in the wave crest and trough
ξ_m	[-]	Surf-similarity index, based on s_m
ξ_{mc}	[-]	Critical surf-similarity index, based on s_m
$\xi_{m-1,0}$	[-]	Surf-similarity index, based on $s_{m-1,0}$
ξ_{0p}	[-]	Surf-similarity index, based on s_{p0}
Δ	[-]	$\frac{\rho_s}{\rho_w} - 1$; Parameter expressing how much larger the density of the armour units is then the density of the seawater, expressed in percentage.
Δt	s	Duration of the design storm
f	1/s	Wave frequency
f_i	[-]	Correction factor for the stability of rocks (Van der Meer, 1991)
F	m	Length of fetch
F_G	kN/m	Reduced weight per meter caisson
F_H	kN/m	Horizontal force per meter caisson
F_U	kN/m	Uplifting force per meter caisson
g	N/kg	Gravity constant
γ	[-]	Enhancement factor JONSWAP spectrum
γ_b	[-]	Breaker index
γ_b	[-]	Berm reduction factor
γ_β	[-]	Oblique waves reduction factor
γ_f	[-]	Surface roughness reduction factor (EurOtop)
γ_h	[-]	Shallow water run-up reduction factor
γ_r	[-]	Surface roughness reduction factor (CEM)
γ_s	[-]	Front geometry reduction factor
γ_v	[-]	Vertical wall reduction factor

h_b	m	Water depth at the top of the toe berm (RM)
h_c	m	Crest freeboard (Goda, 1974)
h_s	m	Water depth at the toe of the structure (CB)
h_w	m	Total caisson height
h'	m	Submerged height of the caisson
h_*	[-]	Impulsiveness parameter
H	m	Significant wave height
H_{m0}	m	Significant wave height in the spectral domain
H_s	m	Significant wave height
$H_{1/3}$	m	Design wave height (Goda, 1974)
$H_{1/10}$	m	Design wave height (SPM, 1984)
$H_{2\%}$	m	Wave height of which 2% are bigger
k	1/m	Wave number
k_Δ	[-]	Layer coefficient
K_D	[-]	Stability coefficient
κ	[-]	Tanimoto, Yagyu and Goda (1982) parameter
$κ_1$	[-]	Tanimoto, Yagyu and Goda (1982) parameter
$κ_2$	[-]	Tanimoto, Yagyu and Goda (1982) parameter
l	m	Length of the foot protection blocks
L_m	m	Local wave length, based on T_m
L_{m-1}	m	Local wave length, based on $T_{m-1,0}$
L_{m0}	m	Wave length in deep water, based on T_m
$L_{m-1,0}$	m	Wave length in deep water, based on $T_{m-1,0}$
L_p	m	Local wave length, based on T_p
L_{p0}	m	Deep water wave length, based on T_p
$λ_1$	[-]	Modification factor (Goda, 1974)
$λ_2$	[-]	Modification factor (Goda, 1974)

λ_3	[-]	Modification factor (Goda, 1974)
m_0	m²	Total spectral wave energy
M_y	kg or t	Weight for which y% of the grading is lighter
M_G	kN/m	Moment due to the reduced weight per meter caisson, around the heel
M_H	kN/m	Moment due to the horizontal force per meter caisson, around the heel
M_U	kN/m	Moment due to the uplifting force per meter caisson, around the heel
M_{50}	kg or t	Median mass of the rocks
η	[-]	Friction factor
η^*	m	Goda parameter (Goda, 1974)
n	[-]	Number of layers
n_{RRM}	[-]	Uniformity index (Rosin-Rammler 1993)
N_{od}	[-]	Numbers of units displaced within a strip width D_n
N_s	[-]	Stability number
N_z	[-]	Number of incoming waves during the design storm
ω	1/s	Angular velocity
ω_p	1/s	Peak angular velocity
p_e	kN/m²	Pressure exerted on the foundation by the caisson
p_{max}	kN/m²	Maximum bearing pressure of the foundation
p_1	kN/m²	Pressure, as indicated on Figure 52
p_2	kN/m²	Pressure, as indicated on Figure 52
p_3	kN/m²	Pressure, as indicated on Figure 52
p_u	kN/m²	Pressure, as indicated on Figure 52
P	[-]	Notional permeability

$\varphi_{n=2}$	[-]	Packing density of dolos
q	m³/s/m	Mean overtopping discharge per meter
Q_*	[-]	Relative overtopping discharge
r	m	Dolos waist ratio
r	m	Thickness of a layer (armour, filter, …)
r_B	[-]	Intermediate parameter for the calculation of γ_b
r_{db}	[-]	Intermediate parameter for the calculation of γ_b
R_c	m	Crest freeboard
$R_{u2\%}$	m	2% mean wave run-up height
R_*	[-]	Relative freeboard height
$\rho_{c,\,dry}$	t/m³	Density of dry concrete
$\rho_{c,wet}$	t/m³	Density of wet concrete
ρ_s	t/m³	Density of concrete or rocks (RM)
$\rho_{s,\,dry}$	t/m³	Density of dry sand
$\rho_{s,wet}$	t/m³	Density of wet sand
ρ_w	t/m³	Density of the water
s_m	[-]	Local wave steepness, based on T_m
s_{m-1}	[-]	Local wave steepness, based on $T_{m-1,0}$
s_{m0}	[-]	Deep water wave steepness, based on T_m
$s_{m-1,0}$	[-]	Deep water wave steepness, based on $T_{m-1,0}$
s_p	[-]	Local wave steepness, based on T_p
s_{p0}	[-]	Deep water wave steepness, based on T_p
S	cm	Settlement of the caisson (CB)
S	[-]	Relative eroded area (RM)
S_{PM}	m²s	Spectral density of the Pierson-Moskowitz spectrum
S_{JON}	m²s	Spectral density of the JONSWAP spectrum

SF_1	[-]	Safety factor for sliding of the caisson
SF_2	[-]	Safety factor for overturning of the caisson
SF_3	[-]	Safety factor for the bearing capacity of the foundation
t'	m	Thickness of the foot protection blocks
t_{bottom}	m	Thickness of the bottom slab of the caisson
t_{outer}	m	Thickness of the outer walls of the caisson
t_{part}	m	Thickness of the partition walls in the caisson
t_{slab}	m	Thickness of the top cap of the caisson
T	m	Draught of the design ship
T_m	s	Mean wave period
$T_{m-1,0}$	s	Spectral wave period
T_p	s	Peak wave period
$T_{1/3}$	s	Design wave period (Goda, 1974)
U_{FH}	[-]	Stochastic variable signifying the bias and uncertainty related to the horizontal force
U_{FU}	[-]	Stochastic variable signifying the bias and uncertainty related to the uplift force
U_{MH}	[-]	Stochastic variable signifying the bias and uncertainty related to the horizontal moment
U_{MU}	[-]	Stochastic variable signifying the bias and uncertainty related to the uplift moment
U_{10}	m/s	Wind velocity at 10 m above the SWL
$U_{19,5}$	m/s	Wind velocity at 19,5 m above the SWL
w_a	kN/m³	Specific weight
W	kN	Unit weight of the layer unit
W_{armour}	kg or t	Unit weight of the armour units
W_{core}	kg or t	Unit weight of the core material
$W_{filter1}$	kg or t	Unit weight of the first filter material

W$_{filter2}$	kg or t	Unit weight of the second filter material
y	%	Fraction of a grading
y$_{NLL}$	%	Fraction corresponding to NLL
y$_{NUL}$	%	Fraction corresponding to NUL
#$_{part}$	[-]	Number of partition walls in the caisson

List of abbreviations

CB: Caisson breakwater

CE: Coastal engineering

CE-Cloud: Coastal Engineering Cloud

CEM: Coastal engineering Manual

HB: Hydraulic boundaries

JONSWAP: Joint North Sea Wave Observation Project

NLL: Nominal lower limit (10%)

NUL: Nominal upper limit (70%)

PM: Pierson-Moskowitz

RM: Rubble-mound

SPM: Shore protection manual

SWL: Sea water level

VBA: Visual Basic for Applications

1. Introduction

Nowadays offshore structures, and in extension breakwaters, find more and more applications. Breakwaters are maritime defense structures which have multiple functions:

- Preventing shoreline erosion
- Preventing flooding of the hinterland
- Sheltering of a harbour basin or entrance
- Protection of water intakes and outfalls
- …

There are plenty of breakwater types, but the rubble-mound and caisson breakwater are the most common structures. They find more and more applications in the construction and expansion of harbours due to the globalization of the transport sector. As a result of the rising sea water level (SWL), these structures are also used more and more to protect the shoreline. Furthermore, these structures are inevitable for the construction of energy and luxury islands.

Breakwaters are able to dissipate significant wave and current energy. Therefore, their design should be sufficiently conservative, to guarantee a stable and economic protection against the most averse weather and hydrodynamic conditions. Failure of these defensive structures could have major consequences. The two main documents which are available to calculate a realistic and safe design for these breakwaters are the Coastal Engineering Manual and the EurOtop Manual.

The rubble-mound and caisson breakwater mainly have the same function, but differ significantly in their design. The rubble-mound breakwater consists of a rubble core, protected by several filter layers and an armour layer. The caisson breakwater consists of a caisson, filled with sand, which is installed on a stable, rubble-mound foundation.

The Coastal Engineering Cloud (CE-Cloud), of which the logo is shown in Figure 1, is an Excel-based design program which helps the engineer in designing these two breakwaters. By finishing the available design sheets, the user can come up with two design cross-sections: one for the rubble-mound and one for the caisson breakwater. Subsequently it is up to the user to select one of the generated cross-sections as final result, based on the provided data in the CE-Cloud and practical engineering insight.

Figure 1: The CE-Cloud logo

Since the boundary conditions of a breakwater can change over its length, the breakwater can consist of multiple different cross-sections. Therefore, it is possible in the CE-Cloud to design five different cross-sections for the same breakwater. Subsequently a final cost sheet is generated which gathers all expenses and materials of the different trunk-sections of the total breakwater.

This report introduces the user to the possibilities and the different design approaches/methods that are implemented in the CE-Cloud. First, a general introduction to the application and implementation

of the CE-Cloud is given. Secondly and thirdly, the different design steps for the assessment of the rubble-mound and caisson breakwater are thoroughly explained. In a forth part, the calculation of the total breakwater, consisting of multiple cross-sections, is discussed. Finally, a conclusion is included which recapitulates the application of the CE-Cloud with its different features. It is recommended to open the CE-Cloud while reading this thesis report in order to understand the discussed design steps more easily.

2. The CE-Cloud

2.1. Introduction

The Coastal Engineering Cloud (CE-Cloud) is an Excel-based design program for the assessment of coastal structures. This tool was developed at the Technical University of Braunchweig and is further updated at the University of Ghent. The initial program consisted of three major windows:

- Waves
- Dikes
- Probability and risk

Two additional windows are implemented in which the following two coastal structures can be designed:

- The rubble-mound breakwater
- The caisson breakwater

The main menu of the CE-Cloud is shown in Figure 2. In which the new windows are indicated in the red rectangle.
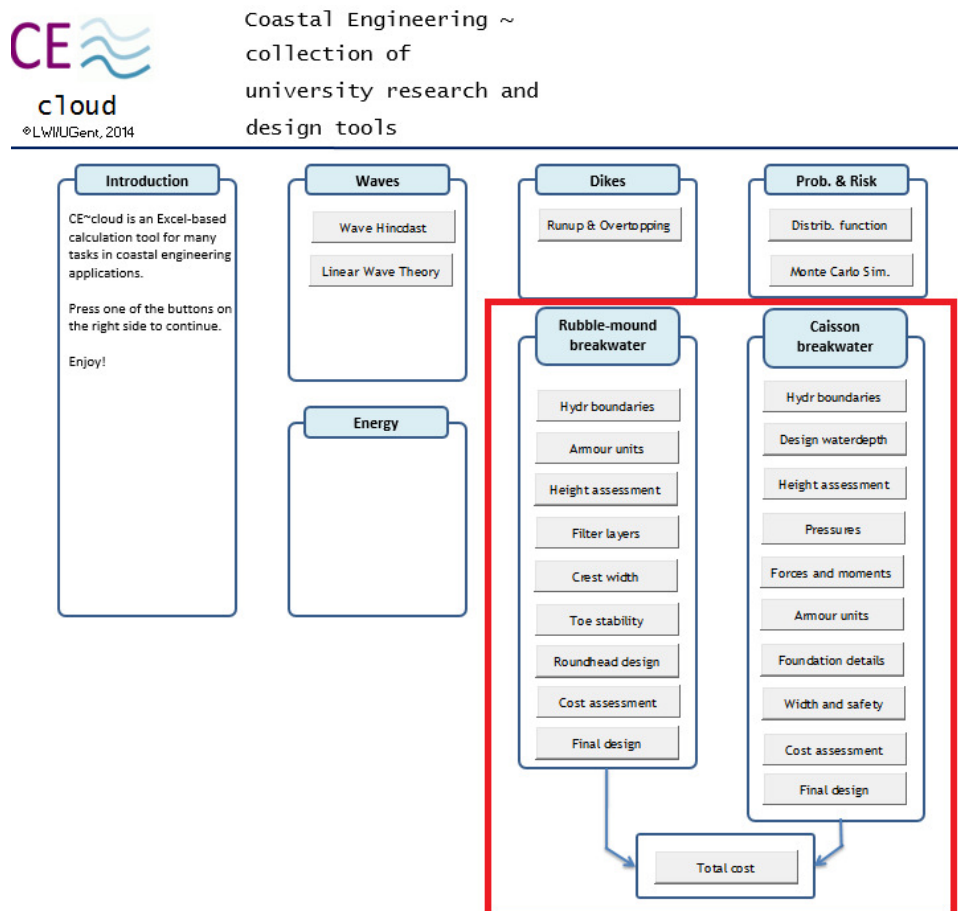
Figure 2: The main menu of the CE-Cloud

For each of the two breakwaters, the CE-Cloud guides the engineer to determine a safe, but economic, design for a particular cross-section. Subsequently a cost assessment for both breakwaters is

generated to provide a clear cost breakdown. At this point, the user can make a thought-through decision whether to install a rubble-mound or a caisson breakwater. The program will also assist the user in comparing both designs.

Since the boundary conditions of a breakwater can differ over its length, it is possible to design multiple cross-sections of the same breakwater. Up to five different cross-sections can be implemented in the CE-Cloud. Subsequently the program generates a final sheet which gathers all the expenses and used materials for the whole breakwater.

2.2. Getting started with the CE-Cloud

There are two versions of the Coastal Engineering Cloud available: CE-Cloud and CE-Cloud_AutoCAD. The complete version will only run on computers which have AutoCAD installed. If this is not the case, the program will constantly generate error messages. Please read section 3.10.3. carefully before starting to design in this version. The other version will run on every computer and will not give these error messages. It is however not possible to generate an AutoCAD drawing. When opening both versions, a message will pop-up in which the user needs to switch on the macro's by clicking on the corresponding button.

During designing, it is possible that the CE-Cloud generates an error message due to circular references in the sheet. This can however be ignored without any influence on the final design.

It is the intention of the CE-Cloud to be as user-friendly and as clear as possible. Consequently, the user can design the breakwater by simply finishing a sequence of design sheets. Once a certain breakwater detail or sheet is finished, it will not be changed in a later design step. This is however a rough simplification, since designing is generally an iterative process. An experienced user could design in an iterative way with this program, but it is not recommended.

To start designing, the user needs to click on the "Hydr. boundaries"-button of one of the breakwaters in the main menu. The user will then be redirected to a new sheet where the different hydraulic boundary conditions can be defined. Note that this sheet was made visible by clicking on the button and will become invisible when navigating to the next design step. The view scale of each design sheet is automatically set to 80%. The user can always go back to the main menu by clicking on the "Main menu"-button at the top of every sheet or go to the next phase of the design by clicking on the "Go to the next design step"-button at the bottom of every design sheet.

At the top of each sheet, some general information is given as is shown in Figure 3.
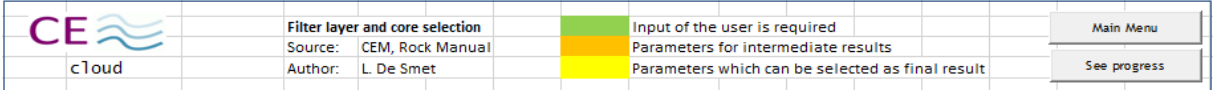
Figure 3: Head of the "Filter layer and core selection"- sheet (CE-Cloud)

First of all, the title of the sheet indicates the part of the breakwater that is designed in this particular section. Additionally, the used sources and the author of the sheet are mentioned. At the right, the "Main Menu"-button and the "See progress"-button are shown. The latter button opens a window which indicates the completed (green) and non-completed (red) design steps. A figure is also provided to indicate the finished parts in green and the parts which are being designed, in the active sheet, in

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orange. An example for the filter and core material progress window can be found in Figure 4. The different progress figures of all design sheets are gathered in Annex B.
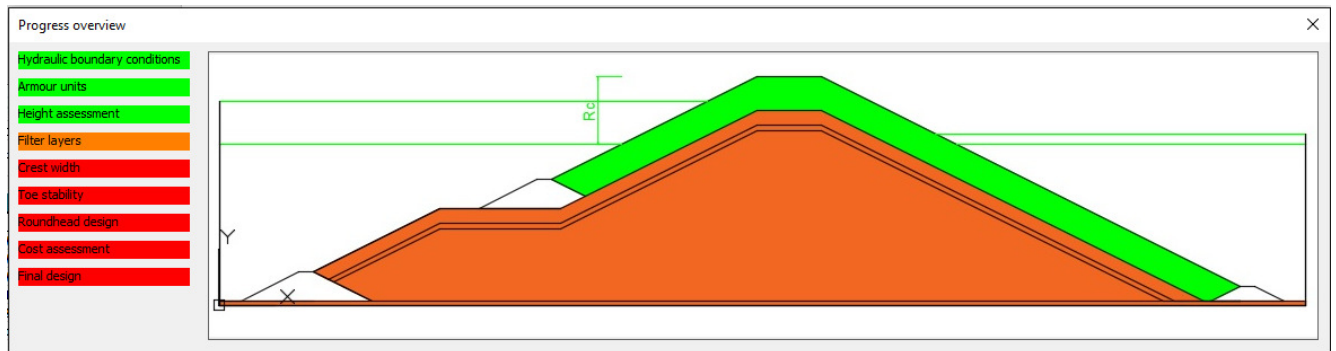
Figure 4: Progress window for the filter and core material assessment (CE-Cloud)

The different sheets in the CE-Cloud also work with a color code of which the legend is present at the top of every sheet (see Figure 3):

- Green: The user needs to insert a realistic value for the considered parameter. Note that it is assumed that the user has a coastal engineering background.
- Orange: Orange cells represent intermediate parameters which are automatically generated in the CE-Cloud for further design.
- Yellow: In comparison to orange cells, the yellow cells yield results which can be selected by the user as final output.

The user simply needs to insert the correct values in the green cells of each design sheet and select the results of a certain approach within this sheet as final output. Subsequently the user will be redirected to the next sheet, etc. Once the final design of one breakwater type is finished, the CE-Cloud will generate a total cost breakdown (based on a cost list) and a final design sheet. By clicking on the "Main menu"-button, the user can start designing the other type of breakwater by selecting the "Hydr boundaries"-button of the corresponding breakwater and following similar design steps. Once both breakwaters have been designed, the user can easily compare both final design sheets and make a motivated choice to install a rubble-mound or a caisson breakwater.

If the breakwater consists of multiple different cross-sections, the user can also design multiple cross sections and make a cost assessment of the total breakwater. This sheet can be accessed by clicking on the "Total cost"- button in the Main menu. More information for designing multiple cross-sections of the same breakwater is given in section 5.1.

2.3. Visual Basic for Applications Editor

It is not the intention of this thesis report to explain the CE-Cloud from a programming point of view but from an engineering point of view. A short description of the use and configuration of the Visual Basic Editor is however given in this paragraph. This editor consists of three main sections:

- Microsoft Excel Objects: Each of the design sheets is an object. Within this object, the different buttons and their use are defined.
- Forms: The forms consist of the windows which will pop-up if the user selects one of the "See progress"-buttons.

- Modules: Each design sheet is connected to a module in which all the formulas which are used in this particular sheet have been implemented. The definition of a design formula is generally defined in the same way. An example is shown in Figure 5 below:

```
'****************************************************************!
Function cubesvdm(h_s As Double, delta As Double, N_od As Double, N_z As Double, s_m As Double) As Variant
'****************************************************************!
' cubesvdm calculates the equivalent cube length of a median rock for the armour layers of a RM-breakwater
' Input:
'    H_s = the design wave height
'    delta = rho_s/rho_w-1
'    N_od = Number of units displaced out of the armor layer within a strip width of one cube length D_n
'    N_z = Number of waves in the design storm
'    s_m= Deep water wave steepness
' Output:
'    cubesvdm = the equivalent cube length of median rock, Van der Meer (1991)
' Other modules needed:
'    NONE
' Written by:
'    lds, 23.2.2016
' Revised by:
'****************************************************************!
'Internal variables
Dim tanalpha As Double
Dim xi_m As Double

tanalpha = 1 / 1.5
xi_m = tanalpha / Sqr(s_m)

If (xi_m <= 3) Or (xi_m >= 6) Then
    cubesvdm = "N/A"
Else
    cubesvdm = h_s / (delta * (6.7 * N_od ^ 0.4 / (N_z ^ 0.3) + 1) * s_m ^ (0.1))
End If
End Function
```

Figure 5: Implemented design formula for cubes in VBA (Van der Meer, 1988b)

2.4. Program lay-out

The lay-out of the CE-Cloud is designed in such a way that it can guide a new user through the program. As already explained, the color codes (green, orange and yellow) indicate whether input of the user is required or not. Each sheet also has a fixed width. This makes the sheet easier to read and print.

3. Design and analysis of a rubble-mound breakwater with the CE-Cloud

3.1. Introduction

Due to heavy weather conditions and the resulting sea state, coastal structures, harbours, dikes, etc., could be severely damaged. To prevent this, breakwaters are constructed. There is no need to emphasize that it is very important to make a conservative, but economic design for these breakwaters. A rubble-mound breakwater is a structure consisting of a rubble core, protected by several filter layers and an armour layer. It provides protection to the hinterland by dissipating the incoming energy of currents and waves. This energy conversion is affected by four different processes: wave reflection, wave breaking, porous flow and energy transmission by overtopping.

There will always be some reflection of the incoming waves at the seaside of a breakwater. This reflection is however moderate for a rubble-mound breakwater due to its gentle slope and the porous behavior of the outer armour layer units. This is a very important feature of the structure since the superposition of incoming and reflected waves could create difficult and dangerous navigation conditions near a breakwater.

A lot of energy is dissipated in a short period of time if a wave breaks on the breakwater. Therefore, the structure needs to be properly designed for these occasional, high impact loads. This breaking phenomenon is mainly governed by the slope of the breakwater and the steepness of the waves.

Since the structure consists of rocky core material, filter layers and armour units, a significant part of the incoming energy can be dissipated within the voids of the breakwater. Due to this porous flow, the energy is partly dissipated from within the structure.

Finally, a very small part of the energy could be transmitted by the wave overtopping process. The breakwater is designed for a certain mean overtopping discharge q, so it is possible that a part of the incoming wave energy reaches the leeside of the breakwater. Note that it is not economical to design the breakwater for zero overtopping since this would yield a significantly high crest freeboard for which a lot of materials are needed. Most of the design formulas are also not valid for zero overtopping.
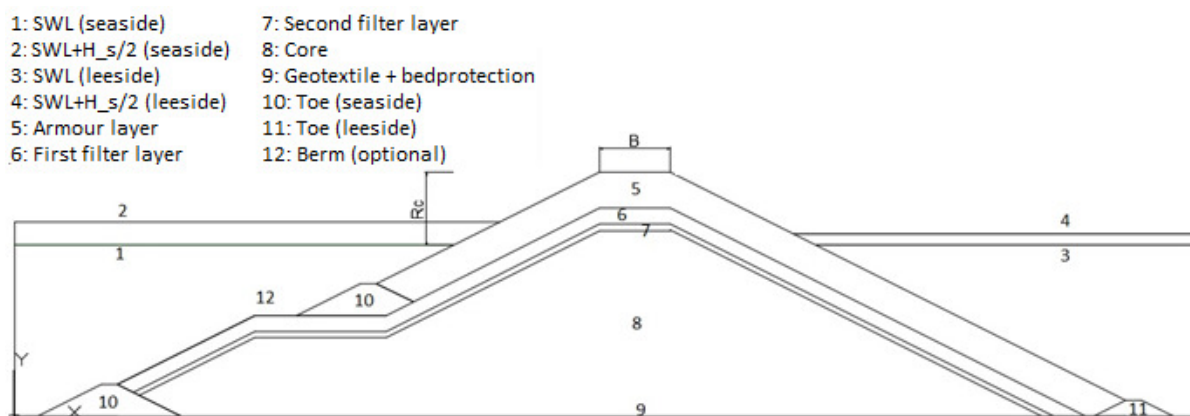
Figure 6: Rubble-mound breakwater configuration (CE-Cloud)

The rubble-mound breakwater consists of several different components which are designed in the CE-Cloud, as is indicated in Figure 6. The different design steps which are implemented in the program can be found in Figure 7. To start designing, the hydraulic boundary conditions are defined to get a clear overview of the energy flows in the area. In practice these data are measured by measurement devices, so an amplitude, energy and energy density spectrum is provided to characterize the incoming waves. Depending on the situation, the measurements and calculations should not only be executed on the seaside, but also on the leeside. The incoming wave energy at this latter side will of course be much lower than at the seaside.

In the next step, the armour layer units are designed. These units can either consist of rocks or concrete armour units. The placement of rocks is a simple and cheap solution. By use of the formulas of Van der Meer (1988, 1991) and Hudson (1974), an estimation of the required weight of the unit rock can be established in order to provide sufficient stability. Depending on the hydraulic boundary conditions, it could be clear that the required dimensions and weights for the rocks to provide sufficient stability, are too large. This is of course inconvenient for construction operations and availability. Therefore, concrete armour units can be installed. They provide a higher stability for lower unit weights due to their interlocking capacity. No need to mention that this will yield higher construction and material costs.

In the next step the height of the breakwater is determined by calculating the necessary crest freeboard R_c. This freeboard is mainly a function of the significant wave height H_s and the mean overtopping discharge q, which needs to be defined by the user. Note that it is up to the engineer to insert a safe, but economic value for the mean overtopping discharge q.

Since the core and soil materials are much smaller than the armour layer units, two filter layers need to be installed between the armour layer units and the core material. These filters mainly have three functions: they need to be sufficiently large and strong to provide the necessary bearing capacity for the armour units. Secondly, they have to be sufficiently small in order to block smaller materials from escaping through the voids of the larger layer on top of it. Thirdly, they need to have sufficient internal stability. Since the first two functions contradict each other, it is up to the engineer to design a filter which meets both requirements as well as possible. The core material is designed in a similar way as the filter material.

Next, the width of the crest is designed. This parameter plays an important role during construction. Since it is preferable to use the cheaper land-based equipment instead of the more expensive sea-based equipment, sufficient crest width should be provided. This allows the construction of the breakwater to be executed from the crest as soon as the breakwater emerges.

At this stage of the design, the general lay-out and contours of the breakwater are known and more detailed parts of the structure can be designed. First of all, the toes of the structure are determined. These breakwater elements provide stability at the interface between the armour layers and the sea bottom and prevent erosion of these vulnerable areas. They are mostly made out of the same material as the filter or armour layer for economic considerations.

At the ends of a breakwater, a roundhead can be installed which needs to be properly designed. This area generally sustains more extensive and frequent damage than the trunk, mainly due to the high cone-overflow velocities and the reduced support from the neighbouring units at the leeside.

At this point, the design is finished and a financial analysis of the different aspects of the breakwater is executed. This analysis is mainly split up in the different process steps (production, transport and construction) and the used materials.

Finally, a final design sheet is generated in the CE-Cloud which gathers all the most important characteristics of the design. Furthermore, two features are implemented in the program to automatically draw the designed cross-section in AutoCAD or generate its coordinates in a textfile.

Figure 7: Design steps for the rubble-mound breakwater

3.2. Hydraulic boundary conditions

3.2.1. Introduction

Since a breakwater is always constructed in a maritime environment, it is very important to properly define its hydraulic boundary conditions. The structure must be able to mitigate the incoming wave forces and significantly reduce the overtopping discharges to protect the hinterland. Subsequently the significant wave height and water levels need to be defined in order to provide a safe design. Once these parameters are known, the different design phases can be executed. Note that current forces are not taken into account since these are generally negligible with respect to the high wave forces.

The "Hydraulic boundary"-sheet is split up in two main sections: the sea- and the leeside, because their corresponding hydraulic parameters differ. In the following design steps, it is assumed that the seaside is at the left of the breakwater's cross section.

Each of these two sections (sea- and leeside) is split up in three categories: general input, further input and final output. The general input defines important characteristics which need to be inserted by the user, independent of the design method, to calculate the final hydraulic boundary parameters. By use of the further input, these final parameters can be calculated in four different ways:

- The manual input
- The Pierson-Moskowitz spectrum
- The JONSWAP spectrum (Joint North Sea Wave Observation Project)
- The input file

The user can execute one or more of the four above-mentioned methods and select one set of values as final output by clicking on the "Set as parameters"-button. The CE-Cloud will then gather all the hydraulic boundary information in the "Final output"-section at the bottom of the sheet. Note that this procedure is the same for the sea- as well as for the leeside.

3.2.2. General input

In this subsection, the user needs to insert the general information considering the hydraulic boundaries of the breakwater:

- ρ_w [t/m³]: The density of the seawater, default value: 1,025 t/m³
- d [m]: The water depth. Note that an absolute value needs to be inserted, independent of any reference level. It is up to the user to consider a certain (storm) surge level or high tide, it all depends on the conditions in which the breakwater is designed.
- α [°]: The mean sea bottom slope near the breakwater.
- β [°]: The angle of wave incidence. Note that an angle of 0° corresponds to perpendicular wave attack.
- $T_p\big/T_m$ [-]: Ratio between the peak and mean wave period. A default value of 1,25 is proposed.
- $T_p\big/T_{m-1,0}$ [-]: Ratio between the peak and spectral wave period. A default value of 1,1 is proposed which corresponds to Rayleigh distributed waves.

3.2.3. Further input

Once the general input is defined, the method-specific inputs are required. Therefore, the user needs to fill in the green cells corresponding to the chosen method. It is also possible to execute multiple methods and make a final selection of the output parameters afterwards by clicking on the "Set as parameters"-button.

Manual input

The manual input approach is the most straightforward method. The user only needs to insert the significant wave height H_s and the peak wave period T_p. The CE-Cloud will subsequently generate the necessary hydraulic parameters which are given below:

- H_{m0} [m]: The significant wave height in the spectral domain. This parameter is assumed to be equal to the inserted significant wave height H_s. Note that it is up to the user to define a good estimate for H_s (H_{m0}). A corresponding return period of 1000 years at the seaside is proposed, which is the design return period for the Belgian coast.
- T_m [s]: The mean wave period, which is calculated as:

$$T_m = \frac{T_p}{T_p / T_m} \tag{1}$$

- $T_{m-1,0}$ [s]: The spectral wave period defined as m_{-1}/m_0, which is calculated as:

$$T_{m-1,0} = \frac{T_p}{T_p / T_{m-1,0}} \tag{2}$$

- $L_{p,0}/L_{m,0}/L_{m-1,0}$ [m]: The deep water wave length, corresponding to the peak, mean and spectral wave period respectively. These parameters are calculated as:

$$L_{x,0} = \frac{g \cdot T_x^2}{2\pi} \tag{3}$$

- $L_p/L_m/L_{m-1}$ [m]: The local wave length, corresponding to the peak, mean and spectral wave period respectively. These parameters are calculated iteratively by use of the linear wave theory:

$$L_x = \frac{g \cdot T_x^2}{2\pi} \cdot \tanh\left(\frac{2\pi \cdot d}{L_x}\right) \begin{cases} if \ \dfrac{d}{L_x} < \dfrac{1}{25}, Shallow \ water \\ if \ \dfrac{1}{25} < \dfrac{d}{L_x} < \dfrac{1}{2}, Transitional \ water \\ if \ \dfrac{d}{L_x} > \dfrac{1}{2}, Deep \ water \end{cases} \tag{4}$$

- Water classification: Determines whether the water is shallow, intermediate or deep, by use of equation (4). This classification is based on the local wave length L_m.
- $s_{p0}/s_{m0}/s_{m-1,0}$ [-]: The deep water wave steepness corresponding to the peak, mean and spectral deep water wave length respectively:

$$s_{x0} = \frac{H_{m0}}{L_{x0}} \tag{5}$$

- $s_p/s_m/s_{m-1}$ [-]: The local wave steepness corresponding to the peak, mean and spectral water wave length respectively:

$$s_x = \frac{H_{m0}}{L_x} \tag{6}$$

The CE-Cloud automatically generates all above-mentioned parameters once the significant wave height H_s and the peak wave period T_p have been inserted. In the three following approaches, these two parameters are generated, after which the remnant hydraulic parameters are calculated in an

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analogous way. The user can select the generated values as final output by clicking on the "Set as parameters"-button.

The Pierson-Moskowitz spectrum

Ocean waves are generated by wind blowing over the sea surface. Depending on the extent and speed of this wind, the waves are smaller or larger. Several spectra are proposed to describe the wave spectrum corresponding to this phenomenon. One of these spectra is the Pierson-Moskowitz spectrum which is an idealized and very straightforward approach. This spectrum describes a fully developed sea, which corresponds to wind blowing over a very large area (roughly 5.000 wavelengths) for a long time (roughly 10.000 wave periods). It is assumed that the waves are in equilibrium with the wind. Consequently, the only parameter to characterize this spectrum is the wind velocity at a height of 10 m above the sea surface U_{10}. The density of this spectrum S_{PM} is defined as:

$$S_{PM}(\omega) = \frac{\alpha \cdot g^2}{\omega^5} \cdot exp\left(-\beta \cdot \left(\frac{\omega_0^4}{\omega}\right)\right)$$

(7)

In which:

- $\alpha = 8{,}1 \cdot 10^{-3}$
- $\beta = 0{,}74$
- $\omega = 2\pi \cdot f$ [Hz], with f the wave frequency [Hz]
- ω_p [Hz]: The peak angular velocity, given by:

$$\omega_p = 0{,}877 \cdot \frac{g}{U_{19{,}5}}$$

(8)

In order to calculate the significant wave height $H_{1/3} = H_s$, the total area m_0 beneath the spectral curve is calculated. This area represents the total wave energy and can be approximately formulated as:

$$m_0 = \int_0^\infty S_{PM}(\omega) \cdot d\omega = 2{,}74 \cdot 10^{-3} \cdot \frac{U_{19{,}5}^4}{g^2}$$

(9)

The wind velocity at a height of 19,5 m $U_{19{,}5}$ is assumed to be 2,6% larger than U_{10}:

$$U_{19.5} \approx 1{,}026 \cdot U_{10}$$

(10)

Subsequently the significant wave height H_s can be derived as:

$$H_s = H_{1/3} = 4 \cdot \sqrt{m_0}$$

(11)

In a next step, the peak wave period T_p is calculated by rewriting equation (8) for the peak wave frequency ω_p as:

$$T_p = 2\pi \cdot \frac{U_{19.5}}{0{,}877 \cdot g}$$

(12)

Once the design wave height H_s and the peak wave period T_p are calculated with equations (11) and (12), the remnant hydraulic parameters are calculated analogous to the manual input. The CE-Cloud also provides a plot of the frequency spectrum. An example of such a plot is given in Figure 8 below:
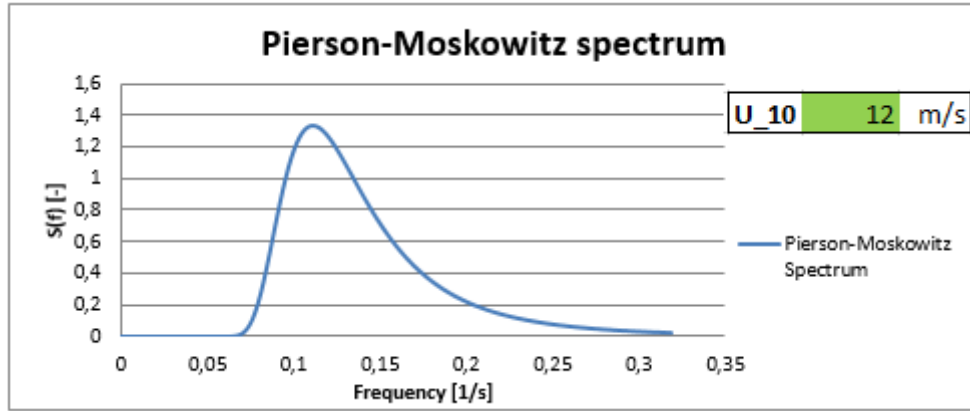
Figure 8: Pierson-Moskowitz frequency spectrum (CE-Cloud)

Since this is a very theoretical approach, it is not recommended to use this method in real-life calculations. It gives however a good estimation in case of a fully developed sea, which can be compared to the results found in the other approaches.

The JONSWAP spectrum

Based on data of the Joint North Sea Wave Observation Project (JONSWAP), Hasselman et al. (1973) concluded that real-life wave spectra are never fully developed. Consequently, the Pierson-Moskowitz spectrum does not yield very realistic results. In order to obtain a better fit, the latter spectrum is mutliplied by a peak enhancement factor γ. Therefore, three parameters need to be inserted by the user:

- U_{10} [m/s]: The wind velocity at a height of 10 m above the sea surface.
- F [m]: The length of fetch
- γ [-]: The peak enhancement factor

The JONSWAP spectral density S_{JON} is expressed as:

$$S_{JON}(\omega) = S_{PM}(\omega) \cdot \gamma^r = \frac{\alpha \cdot g^2}{\omega^5} \cdot exp\left(-\beta \cdot \left(\frac{\omega_0^4}{\omega}\right)\right) \cdot \gamma^r \qquad (13)$$

With:

$$r = exp\left(-\frac{(\omega - \omega_p)^2}{2 \cdot \sigma^2 \cdot \omega_p^2}\right) \text{ and } \sigma = \begin{cases} 0,07 & if \ \omega \leq \omega_p \\ 0,08 & if \ \omega > \omega_p \end{cases} \qquad (14)$$

With the peak wave frequency ω_p, given by:

$$\omega_p = 22 \cdot \left(\frac{g^2}{U_{10} \cdot F}\right)^{1/3} \qquad (15)$$

Note that the parameters α and β are defined differently than for the Pierson-Moskowitz approach:

$$\alpha = \begin{cases} 0{,}076 \cdot \left(\dfrac{U_{10}^2}{F \cdot g} \right)^{0.22} & if \ 0{,}0081 < \alpha < 0{,}01 \\ 0{,}0081 & if \ \alpha < 0{,}0081 \ or \ 0{,}01 < \alpha \end{cases}$$ (16)

$$\beta = \frac{5}{4}$$ (17)

If α does not fit in the range between 0,0081 and 0,01; the values for α and ω_p are set equal to 0,0081 and 0,5 respectively. The latter values are representative values for the North Sea.

Similar to the previous spectrum, the total wave energy m_0 of the JONSWAP spectrum is calculated to derive the significant wave height $H_{1/3}$. The energy m_0 can be formulated as:

$$m_0 = \int_0^\infty S_{JON}(\omega) \cdot d\omega = 1{,}67 \cdot 10^{-7} \cdot \frac{U_{10}^2 \cdot F}{g}$$ (18)

After which the significant wave height is expressed as:

$$H_s = H_{1/3} = 4 \cdot \sqrt{m_0}$$ (19)

Rewriting equation (15) for ω_p yields an expression for the peak wave period T_p:

$$T_p = \frac{2\pi}{22} \cdot \left(\frac{U_{10} \cdot F}{g^2} \right)^{\frac{1}{3}}$$ (20)

As the two major parameters (H_s and T_p) have been defined, the remaining hydraulic parameters can be calculated analogous to the manual input calculations. Similar to the Pierson-Moskowitz approach, the JONSWAP spectrum is plotted in the CE-Cloud. Figure 9 below clearly shows the peak enhancement of the JONSWAP spectrum.
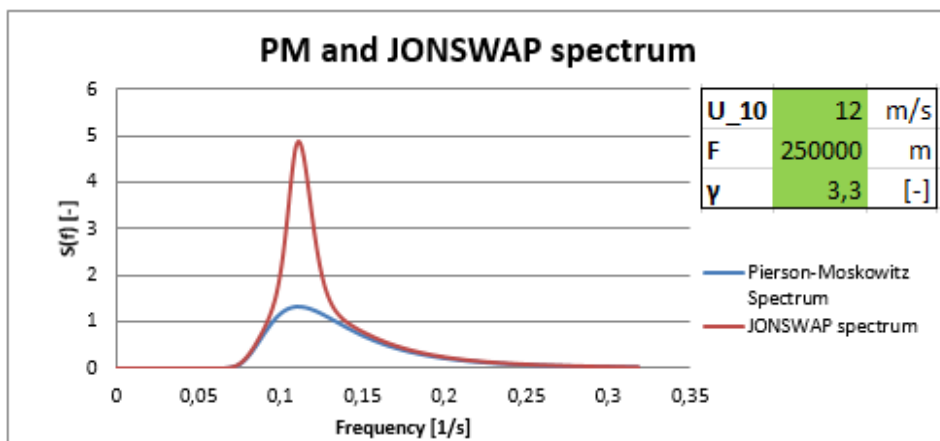
Figure 9: PM and JONSWAP frequency spectrum (CE-Cloud)

The same remark as for the Pierson-Moskowitz approach can be made for the JONSWAP spectrum as well. The latter gives a good approximation for the spectrum of the North Sea. It is however not

common practice to define hydraulic boundary conditions for real-life applications by use of standard spectra.

Imported file

Both above-mentioned approaches are attempts to describe the sea state for a very special condition: wind blowing continuously over the sea surface with a constant velocity. This yields only one peak in both wave spectra. In more realistic situations, another peak could be present due to either swell or local wind actions. Therefore, a fourth input method is provided in the CE-Cloud: the imported file. In this case, the user can insert data of measured wave heights with their corresponding wave periods. The program will subsequently calculate all necessary hydraulic parameters.

To use this feature, the CE-cloud automatically detects whether data are available or not. The program will indicate this next to the blue arrow shown in Figure 10.
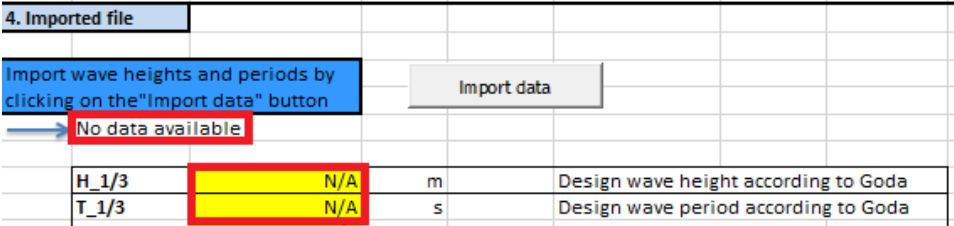
Figure 10: Import data feature (CE-Cloud)

To insert or alter the dataset, the user can click on the "Import data"-button after which a new spreadsheet, shown in Figure 11, will open.
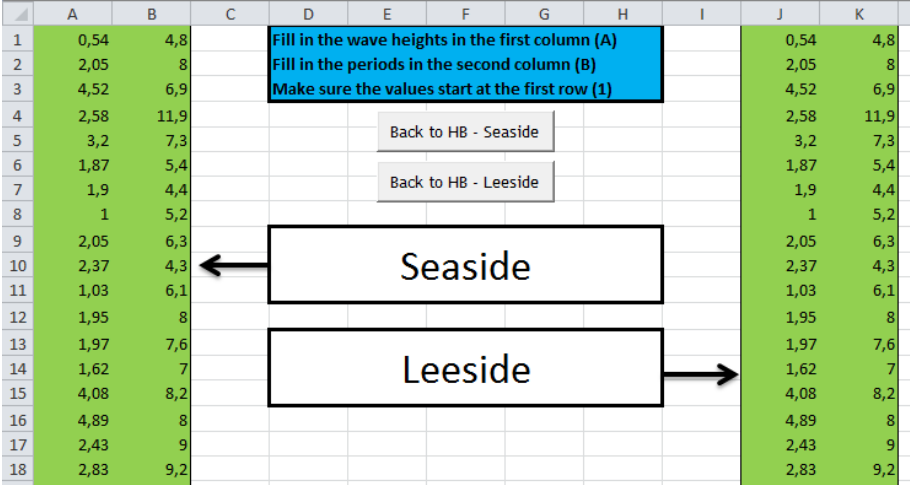
Figure 11: Import data sheet (CE-Cloud)

As is indicated on Figure 11, the user can insert the measured wave heights in the first column (A) and the corresponding wave periods in the second column (B). Note that columns A and B contain the wave data at the seaside. It is however possible to insert data for the leeside waves in columns J and K in a similar way. This can for example be the case if data of an existing breakwater are used. When all the values are inserted, the user can easily go back by clicking on the "Back to HB – Seaside/Leeside"-button. The CE-Cloud will automatically process the data and generate the design wave height $H_{1/3}$ and the corresponding mean wave period $T_{1/3}$ according to Y. Goda (1985).

The design wave height $H_{1/3}$ is the mean wave height of the highest 1/3rd waves. The corresponding design wave period $T_{1/3}$ is defined as the mean value of the corresponding periods of the 1/3rd highest waves. Once these two parameters are calculated, the remnant hydraulic parameters are determined analogous to the manual input approach.

If the user has inserted or changed the dataset, it is possible that the CE-Cloud does not automatically generate the design wave height $H_{1/3}$ and corresponding $T_{1/3}$. Therefore it is advised to click on the cells (B132, C134 and C135), indicated in Figure 10, and press enter. The selected cells will subsequently be recalculated and yield the correct parameters corresponding to the inserted dataset.

3.2.4. Final output

By clicking on the "Set as parameters"-button, the CE-Cloud will save the final output of a certain approach. Note that the user does not need to execute all four approaches. It is however recommended to execute more than one approach in order to compare the results and make a thought-through decision. The CE-Cloud also provides an option to delete all final values and select the values of another method.

During the lifetime of the breakwater or during construction, the structure could be prone to wave forces on the leeside. Therefore, the user also needs to define the hydraulic boundary conditions on this side. This section is completely analogous to the calculation of the seaside boundary conditions, except for the inserted values by the user.

3.3. Armour unit selection

3.3.1. Introduction

After the hydraulic parameters have been determined, the first design phase can be commenced: the selection of the armour layer units. Since the design wave forces on the armour layer can be significantly high, it is very important to check the hydraulic stability of these units. The structural integrity of these components will however not be checked. Due to the irregular flow conditions near the breakwater and random positioning of the armour units, a theoretical approach is not possible. Therefore all design formulas, available in the CE-Cloud, are empirical and based on hydraulic model test results. The stability of an armour unit N_s is expressed as the ratio of the drag F_D and lift force F_L compared to the gravity force F_G, acting on the unit. The latter can be rewritten as:

$$N_s = \frac{F_D + F_L}{F_G} = \frac{H}{\Delta \cdot D_n}$$

(21)

With:

- H [m]: The design wave height.
- $\Delta = \frac{\rho_S}{\rho_w} - 1$ [-]: Parameter expressing how much larger the density of the armour units is then the density of the seawater, expressed in percentage.
- ρ_S [t/m³]: Density of the armour units. This can be the density of rocks or concrete.
- ρ_w [t/m³]: Density of the seawater. This was already inserted in the "Hydraulic boundaries"-section.
- D_n [m]: Diameter of the equivalent cube.

The armour units can either consist of natural rocks or concrete armour units. It is generally advised to install natural rocks since they result in the cheapest design in most cases. There is also no need for skilled and precise placement work, which significantly saves construction time. Since the interlocking properties of rocks are negligible, their stability is mainly based on their selfweight. This means that the necessary rock weight and dimensions for specific hydraulic boundary conditions could be very large. Depending on the site, these rocks could be unavailable.

If this is the case, the user can also design and install concrete armour units. These concrete units are cast in different shapes to provide additional stability due to their interlocking properties. They can generally be subdivided in three categories, as is shown on Figure 12:

- Massive: Similar to the natural rocks, these units only acquire stability due to their selfweight.
- Slender: The stability is mainly provided due to interlocking effects between neighbouring units.
- Bulky: This is a hybrid solution which combines the advantages of both massive and slender units.
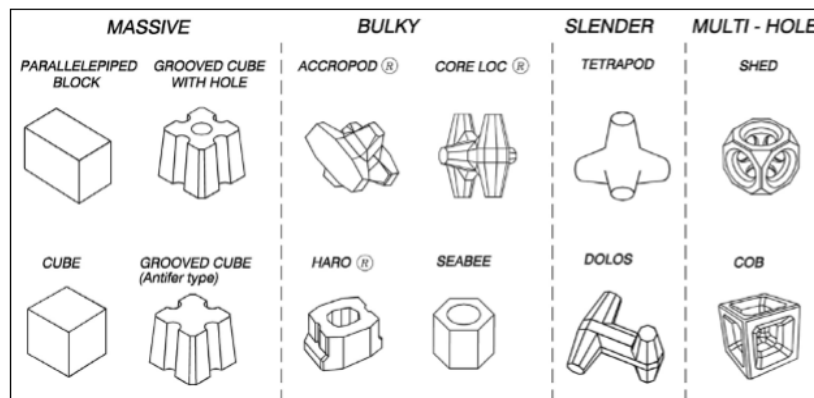
Figure 12: Types of armour layer units (CEM)

All available formulas in the Coastal Engineering Manual, which are applicable for rubble-mound breakwaters are implemented in the CE-Cloud. The user can consequently design one or more of the following armour units:

- Rocks: Hudson (1974), Van der Meer (1988), Van der Meer (1991)
- Concrete cubes: Van der Meer (1988b); Brorsen, Burcharth and Larsen (1974), Hudson (1974)
- Tetrapods: Van der Meer (1988b), Hudson (1974)
- Dolos: Burcharth and Liu (1992)
- Accropode: Van der Meer (1988b), Burcharth et al. (1988), Hudson (1974)
- CORE-LOC: Melby and Turk (1994/1997)
- Tribar: Hudson (1974)
- Xbloc: Hudson (1974)

Most armour unit designs are determined in function of six predefined standard breakwater slopes: 1:1, 1:1,33; 1:1,5; 1:2, 1:3 and 1:4. Several design approaches are however only applicable for one particular slope. The CE-Cloud will subsequently consider the corresponding slope. Therefore, the user implicitly selects the breakwater slope α by selecting a certain armour layer unit.

Once the seaside armour layer units have been designed, the user can start designing the leeside units. The CE-Cloud provides two option: the user can either select the same units as at the seaside or design rocks in an analogous way as for the seaside. Since the waves at the leeside are assumed to be moderate, it is generally not necessary to install very heavy or interlocking armour layer units on the leeside slope. If this is the case, installing different armour units at the lee- and seaside is not cost efficient. Therefore, the same concrete armour units are installed at both sides of the breakwater if concrete units are required at the leeside. Note that on the breakwater's crest, the same armour units as on the seaside slope are installed.

3.3.2. General input

Similar as for the hydraulic parameter sheet, the user needs to insert several general input parameters:

- ρ_s [t/m³]: The density of the armour units. Note that this can either be the density of rock or concrete. It is up to the user to insert the corresponding value for the installed unit.
- $\triangle t$ [s]: The duration of the design storm. A default value of 12 hours (43200 s) is assumed.

3.3.3. Rock

Hudson (1974)

Hudson formulated a stability expression for a two-layered, rock armoured slope which is not overtopped. Note that the latter requirement is not always met, but in most cases the overtopping will be kept to a minimum (see section 3.4.2). The equation states:

$$\frac{H}{\Delta \cdot D_{n50}} = (K_D \cdot \cot(\alpha))^{\frac{1}{3}}$$

(22)

The equivalent cube length of the median rock D_{n50} can subsequently be written as:

$$D_{n50} = \frac{H}{\Delta \cdot (K_D \cdot \cot(\alpha))^{\frac{1}{3}}}$$

(23)

In which:

- H [m]: The design wave height, which is equal to H_s or $H_{1/10,}$ dependent on the Shore Protection Manual (1977 or 1984) which is used. In the CE-Cloud only the version of 1984 is used since the one of 1977 is based on regular wave tests, which do not result in realistic results. The value of $H_{1/10}$ is subsequently calculated as:

$$H_{1/10} = 1{,}27 \cdot H_s$$

(24)

Equation (24) is only valid for Rayleigh distributed wave heights, which are non-depth-limited. For the case of depth-limited waves, this formula will also be used, resulting in a conservative design.

- $\Delta = \frac{\rho_s}{\rho_w} - 1$ [-]: Parameter expressing how much larger the density of the armour units is then the density of the seawater, expressed in percentage.

- α [°]: Slope angle of the breakwater. As already mentioned, the equivalent cube length of the median rock D_{n50} is calculated for multiple standard slope angles. It is up to the user to select a certain design value for D_{n50} with the corresponding slope for α.
- K_D [-]: Stability coefficient, which can be found in Table 1. This parameter is a function of the stone shape, placement configuration of the stones and whether the waves are breaking or not. The stone shape can be smooth rounded or rough angular. The placement configuration can either be random or special. In the latter configuration, the stones are placed with their longest axis perpendicular to the slope face. Note that this will significantly increase the construction time and costs, which were the main advantages of using rocks.

To define whether the waves are depth-limited or not, the breaker index γ_b is introduced:

$$\gamma_b = \frac{H_s}{d}$$

(25)

If the breaker index γ_b is smaller than 0,55; the waves are non-depth-limited or non-breaking. If the index is however larger than (or equal to) 0,55; the waves are depth-limited or breaking.

Table 1: Stability coefficients for rocks (SPM, 1984)

K_D-values by SPM 1984, $H = H_{1/10}$.

Stone shape	Placement	Damage, D^4 = 0-5%	
		Breaking waves [1]	Nonbreaking waves [2]
Smooth rounded	Random	1.2	2.4
Rough angular	Random	2.0	4.0
Rough angular	Special [3]	5.8	7.0

It is assumed that the value of the damage D lies between 0 to 5%, as can be seen in Table 1. Meaning that maximum 5% of the armour units from the active zone are displaced. The active zone extends from the middle of the crest to the depth at the seaside where the waves cause zero damage (roughly 1,5 times the design wave height H_s beneath the SWL).

Now the equivalent cube length D_{n50} has been determined, the median mass of the rocks M_{50} can be calculated by use of the following formula:

$$M_{50} = \rho_s \cdot D_{n50}^3$$

(26)

At this point D_{n50} and M_{50} are determined for each of the standard slope angles. The user can subsequently select a particular rock with corresponding dimensions, weight and breakwater slope angle as final output. This can be done by clicking on the accompanying "Select"-button.

Note that equation (22) will also be used to design the following types of armour units: concrete cubes, tetrapods, accropodes, tribars and Xblocs. The stability coefficient K_D will be the only parameter which will vary in the different design approaches.

Van der Meer (1988)
Van der Meer derived a formula for a two-layered, rock armoured slope which is not overtopped. Similar to the Hudson approach, the overtopping discharges are assumed to be rather moderate. Van der Meer considers two types of incoming waves: plunging ($\xi_m \leq \xi_{mc}$) or surging waves ($\xi_m > \xi_{mc}$). Therefore the surf-similarity index ξ_m and critical surf-similarity index ξ_{mc} are determined:

$$\xi_m = \frac{\tan(\alpha)}{\sqrt{s_m}} \; and \; \xi_{mc} = (6{,}2 \cdot P^{0,31} \cdot \tan(\alpha)^{0.5})^{\frac{1}{P+0,5}}$$

$$(27)$$

With:

- P [-]: The notional permeability, shown in Figure 13, which needs to be inserted by the user as specific input. A default value of 0,4 is assumed.
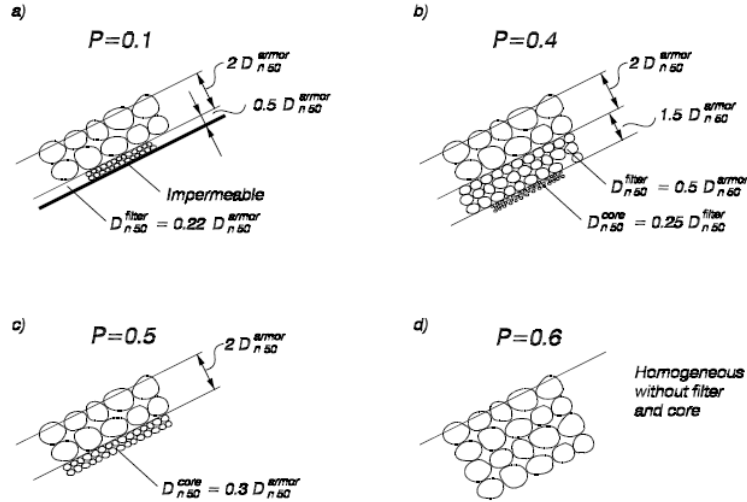
Figure 13: Notional permeability (CEM)

Once it is determined whether the incoming waves are plunging or surging, the stability equation of Van der Meer can be applied:

$$\frac{H_s}{\Delta \cdot D_{n50}} = \begin{cases} 6{,}2 \cdot S^{0.2} \cdot P^{0,18} \cdot N_z^{-0.1} \cdot \xi_m^{-0,5} \; ; Plunging \; waves \\ 1{,}0 \cdot S^{0,2} \cdot P^{-0,13} \cdot N_z^{-0,1} \cdot \cot(\alpha)^{0,5} \cdot \xi_m^{P} \; ; Surging \; waves \end{cases}$$

$$(28)$$

Equation (28) can be rewritten in function of the equivalent cube length of median rock D_{n50} as:

$$D_{n50} = \begin{cases} \dfrac{H_s}{\Delta \cdot 6{,}2 \cdot S^{0,2} \cdot P^{0,18} \cdot N_z^{-0,1} \cdot \xi_m^{-0,5}} \; ; Plunging \; waves \\ \dfrac{H_s}{\Delta \cdot 1{.}0 \cdot S^{0,2} \cdot P^{-0,13} \cdot N_z^{-0,1} \cdot \cot(\alpha)^{0,5} \cdot \xi_m^{P}} \; ; Surging \; waves \end{cases}$$

$$(29)$$

With:

- H_s [m]: The design wave height. For depth-limited waves this value should be replaced by $H_{2\%}/1{,}4$. The value of $H_{2\%}$ is however not known. Therefore, the value of H_s will also be used for depth-limited waves. This assumption implicitly assumes that the waves are Rayleigh distributed, which is not the case for depth-limited waves, resulting in a more conservative design.
- S [-]: The relative eroded area, which is indicated in Figure 14. Broderick (1983) defined S as the number of squares with length D_{n50} which fit into the eroded area A_e. The formula states:

$$S = \frac{A_e}{D_{n50}^2} \tag{30}$$
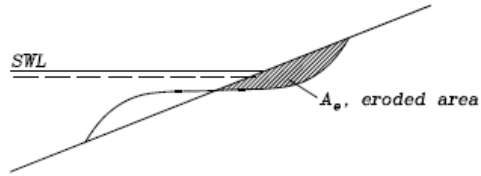
Figure 14: Eroded area (Broderick, 1983)

- N_z [-]: Number of incoming waves during the design storm. This value is calculated by dividing the duration of the design storm $\triangle t$ by the mean wave period T_m.

Equation (28) is only valid for the following ranges of parameters N_z, P, s_m and ρ_s:

$$N_z \leq 7500$$

$$0{,}1 \leq P \leq 0{,}6$$

$$0{,}005 \leq s_m \leq 0{,}06$$

$$2 \; ^t/_{m^3} \leq \rho_s \leq 3{,}1 \; ^t/_{m^3}$$

If the above-mentioned parameters are not within their defined range, the CE-Cloud will yield a "N/A"-value.

Similar to the Hudson approach, the median mass of the rocks M_{50} is automatically determined by use of equation (26). By clicking on the "Select"-button, the user can select a certain type of rock as final armour layer unit.

Van der Meer (1991)
Van der Meer defined a correction factor f_i for the equivalent cube length of the median rock D_{n50} calculated with equation (29):

$$f_i = \left(1{,}25 - 4{,}8 \cdot \frac{R_c}{H_s} \cdot \sqrt{\frac{s_{0p}}{2\pi}} \right)^{-1} \tag{31}$$

With:

- R_c [m]: The crest freeboard, which is defined as the height of the breakwater above the SWL. The value of R_c will be determined in the next design step. The user can however insert an estimated value at this stage.

Equation (31) is only valid for the following range:

$$0 < \frac{R_c}{H_s} \cdot \sqrt{\frac{s_{0p}}{2\pi}} < 0{,}052$$

If this requirement is not met, the CE-Cloud will yield a "N/A"-value. Once the diameter of the equivalent cube is calculated as $f_i \cdot D_{n50}$, the median mass of rocks M_{50} is automatically generated and the corresponding units can be selected.

3.3.4. Concrete cube

Concrete cubes are the cheapest concrete armour units which can be installed. This is mainly due to their regular shape for which less complicated formwork is required.

Figure 15: Concrete cubes

Van der Meer (1988b)

Van der Meer defined the following formula for the stability of concrete cubes on a two-layered non-overtopped slope:

$$\frac{H_s}{\Delta \cdot D_n} = \left(6.7 \cdot \frac{N_{od}^{0.4}}{N_z^{0.3}} + 1 \right) \cdot s_m^{-0.1} \qquad (32)$$

In which:

- N_{od} [-]: The number of units displaced out of the armour layer within a strip width of one cube length D_{n50}. This parameter needs to be inserted by the user as specific input and generally lies between the range of 0 and 2.

Equation (32) is only valid if the following three requirements are met:

1: The incoming waves are non-depth-limited ($\gamma_b < 0{,}55$). They are also assumed to be irregular with a wave front parallel to the breakwater.

2: The cubes are applied in two layers on a 1:1,5 slope. Therefore, it is not possible to define another slope.

3: The surf-similarity index ξ_m needs to be in the range of 3 to 6.

If one of the upper requirements is not met, the program will yield a "N/A"-value.

Brorsen, Burcharth and Larsen (1974)

Another expression for the stability of concrete cubes on a rubble-mound slope was developed by Brorsen, Burcharth and Larsen (1974). They defined the average stability N_s as a function of the damage level D, which needs to be inserted by the user as specific input. Table 2 below shows the corresponding stability N_s:

Table 2: Stability of cubes (Brorsen, Burcharth and Larsen, 1974)

Damage level	$N_s = \frac{H_s}{\Delta D_n}$
Onset, $D = 0\%$	1.8 - 2.0
Moderate, $D = 4\%$	2.3 - 2.6

As can be seen on Table 2, the damage level is split up in two sections: onset (0 %) and moderate (4 %) damage. In the CE-Cloud a range of 0 to 2 % is assumed for an onset damage level and 2 to 5 % for a moderate damage level. If the damage exceeds the upper limit of 5%, the CE-Cloud will return a "N/A"-value. There are two additional requirements which need to be met:

1: This approach is only valid for the following range of slope angles: $1,5 \leq \cot(\alpha) \leq 2$. Since the CE-Cloud works with six standard slopes, the user can only insert slope angles: 1:1,5 and 1:2, as is clearly indicated in the CE-Cloud sheet. If another value is inserted, the program will return an error message. Note that this angle does not have any influence on the stability of the cubes as can be seen in Table 2.

2: The incoming waves are irregular and non-depth-limited ($\gamma_b < 0,55$).

Table 2 shows a certain range for the stability values N_s for each of the two damage levels (onset and moderate). The lowest value of each of these ranges is implemented in the CE-Cloud, yielding a more conservative design.

The stability formula can subsequently be rewritten in function of the median cube length D_{n50}:

$$D_{n50} = \frac{H_s}{\Delta \cdot N_s}$$

(33)

Hudson (1974)

As has already been mentioned in the Hudson approach for the design of rocks (section 3.3.3), this approach can also be applied to define the stability of concrete cubes. The only parameter which will change is the stability coefficient K_D of which the corresponding values are gathered in Table 3 below:

Table 3: Stability coefficients for cubes, tetrapods and tribars (Rock Manual)

Armour unit	Country	Year	K_D values in Hudson stability formula				Slope
			Trunk		Head		
			Breaking waves	Non-breaking	Breaking waves	Non-breaking	
Cube (double)	–	–	6.5	7.5		5	1:1.5 – 1:3
Tetrapod	France	1950	7	8	4.5	5.5	1:2
Tribar	USA	1958	9	10	7.8	8.5	1:2

As can be seen on Table 3, a value of 6,5 or 7,5 is used in case of breaking and non-breaking waves respectively. Note that this is only valid for a range of slopes between 1:1,5 and 1:3. Since the CE-Cloud works with a general set of standard slopes, the user can only insert three slopes: 1:1,5; 1:2 and 1:3. If another slope is inserted, a warning window will pop-up. Once the stability coefficient K_D is determined, the equivalent cube length D_{n50} can be calculated by use of the Hudson equation (23).

3.3.5. Tetrapod

The tetrapod is one of the slender concrete armour units which can be designed in the CE-Cloud. Two design approaches are implemented in the CE-Cloud: Van der Meer (1988b) and Hudson (1974).

Figure 16: Tetrapod

Van der Meer (1988b)

Van der Meer defined the following formula for a two-layered, tetrapod armoured, non-overtopped slope:

$$\frac{H_s}{\Delta \cdot D_n} = \left(3{,}75 \cdot \frac{N_{od}^{0.5}}{N_z^{0.25}} + 0{,}85\right) \cdot s_{0m}^{-0.2} \tag{34}$$

Equation (34) is only valid if the following three requirements are met:

1: The waves are non-depth-limited ($\gamma_b < 0{,}55$), irregular and their wave front is parallel to the breakwater.

2: The units are installed in two layers on a 1:1,5 slope. Note that the user is subsequently not able to select another slope if this method is used. The CE-Cloud automatically generates a 1:1,5 slope.

3: The surf similarity index ξ_m, calculated with equation (27), needs to be in the range between 3,5 and 6.

If one of the upper requirements is not met, the CE-Cloud will return a "N/A"-value, except for the first requirement. In this case the formula of d'Angremond, Van der Meer and van Nes (1994) is used, which expresses the stability of tetrapods in case of depth-limited waves:

$$\frac{H_s}{\Delta \cdot D_n} = 1{,}4 \cdot \left(3{,}75 \cdot \frac{N_{od}^{0.5}}{N_z^{0.25}} + 0{,}85\right) \cdot s_{0m}^{-0.2} \tag{35}$$

Note that equation (35) is the same as equation (34) for non-depth-limited waves, but multiplied by a factor 1,4.

Hudson (1974)

The same Hudson equation (23) for the design of rocks and concrete cubes can be used to express the stability of tetrapods. The corresponding stability coefficient K_D can be found in Table 3. A value of 7 or 8 is considered for breaking and non-breaking waves respectively. Note that the breakwater slope has a fixed value of 1:2. The user is consequently not able to define a particular slope angle.

3.3.6. Dolos

The second slender armour unit which is implemented in the CE-Cloud is the dolos. Analogous to the tetrapod, the latter unit mainly acquires stability due to interlocking effects with its neighbouring units. Only one approach is available in the CE-Cloud to design this type of armour unit: Burcharth and Liu, 1992.

Figure 17: Dolos

Burcharth and Liu (1992)

Burcharth and Liu defined the following formula for the stability of dolos units:

$$\frac{H_s}{\Delta \cdot D_n} = (47 - 72 \cdot r) \cdot \varphi_{n=2}^{2/3} \cdot N_{od}^{1/3} \cdot N_z^{-0.1} \tag{36}$$

In which:

- r [-]: The dolos's waist ratio (insertable by the user) which normally lies in the range between 0,32 and 0,42.
- $\varphi_{n=2}$ [-]: The packing density (insertable by the user), ranging between 0,61 and 1.

Equation (36) is valid for breaking and non-breaking waves which are irregular and head-on. For the construction of the armour layer, the dolos are randomly installed in two layers on a 1:1,5 slope. Note that this is a fixed value, so the user is not able to define a particular slope angle. In order to use equation (36) there are three requirements which should be met:

$$0,32 < r < 0,42$$

$$0,61 < \varphi < 1$$

$$2,49 < \xi_{0m} < 11,7$$

If one of the upper requirements is not met, the CE-Cloud will yield a "N/A"-value.

3.3.7. Accropode

Accropodes are bulky armour layer units which acquire their stability due to their selfweight and interlocking effect. Three different design approaches are available in the CE-Cloud: Van der Meer (1988b), Burcharth et al. (1998) and Hudson (1974).
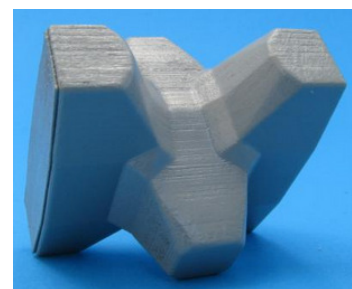
Figure 18: Accropode

Van der Meer (1988b)

Van der Meer defined a stability expression for accropodes which are installed in one layer (in accordance with the SOGREAH recommendations) on a fixed 1:1,33 slope:

$$\frac{H_s}{\Delta \cdot D_n} = \begin{cases} 3{,}7 - No\ damage \\ 4{,}1 - faillure \end{cases} \tag{37}$$

The CE-Cloud will only consider the value of 3,7 corresponding to "no damage". The only requirement for the use of equation (37) is that the waves are non-breaking ($\gamma_b < 0{,}55$). If this is not the case, the CE-Cloud will return a "N/A"-value. The waves are also assumed to be irregular and head-on.

Note that there is no influence of the number of waves N_z in this approach in comparison to the other Van der Meer approaches.

Burcharth et al. (1998)

Burcharth et al. defined another stability expression for accropodes on a one layered slope, constructed according to the SOGREAH recommendations, with a fixed gradient of 1:1,33:

$$\frac{H_s}{\Delta \cdot D_{n50}} = A \cdot (D^{0.2} + 7{,}70) \tag{38}$$

With:

- A [-]: Coefficient with a mean value of 0,46
- D [-]: Relative number of units displaced over more than a distance D_{n50}. This parameter needs to be inserted by the user.

Equation (38) is valid for both breaking and non-breaking wave conditions. The incoming waves are also assumed to be irregular and head-on. Furthermore, the following requirement considering the surf-similarity index ξ_m, given in equation (27), needs to be met:

$$3{,}5 < \xi_m < 4{,}5$$

If this is not the case, the CE-Cloud will yield a "N/A"-value.

Hudson (1974)

The third design approach for accropodes considers the Hudson equation (23). Sogreah (2000) recommends the following values for the stability coefficients K_D:

$$K_D = \begin{cases} 15, Non-breaking\ waves \\ 12, Breaking\ waves \end{cases}$$

Since it is assumed that the accropodes are placed considering the SOGREAH requirements, a breakwater slope of 1:1,33 is automatically considered.

3.3.8. CORE-LOC

Another type of bulky armour layer units are the CORE-LOC's. They provide stability due to their selfweight and partly due to interlocking effects. Only one design approach is available in the CE-Cloud: Melby and Turk (1994).

Figure 19: CORE-LOC

Melby and Turk (1994)

Melby and Turk used the general Hudson equation (23) to define the stability of CORE-LOC units. They found that the stability coefficient K_D equals 16 for trunk sections, independent on whether the waves are depth-limited or non-depth-limited. It is however assumed that the units are placed randomly in one single layer. Additionally, it can be noted that these units can interlock properly with dolos units. Therefore, they are specifically suited for repairing existing dolos slopes.

The CE-Cloud calculates the equivalent cube length D_{n50} for a general set of breakwater slopes. It is up to the user to compare each of the results, and select a final slope by clicking on the "Select"-button.

3.3.9. Tribar

Only one approach is available in the CE-Cloud to design tribars: Hudson (1974).

Figure 20: Tribars

Hudson (1974)

For the use of tribars, only the Hudson equation (23) is available. Similar to the design of concrete cubes or accropodes, the stability coefficient K_D will have a specific value for tribars, defined by the SPM (1984). This value is a function of both the type of placement (random or pattern-placed) and whether the waves are breaking or non-breaking. The corresponding values for K_D can be found in Table 4 below:

Table 4: Stability coefficients for tribars (SPM, 1984)

Placement	Layers	Breaking waves[1]	Nonbreaking waves[2]	Slope angle cot α
Random	2	9.0	10.0	$1.5 - 3.0$
Pattern-placed	1	12.0	15.0	(not given)
[1] Depth-limited breaking with waves breaking in front of and on the armor slope. [2] No depth-limited breaking occurs in front of the armor slope.				

It is up to the user to select whether the units are randomly or pattern-placed by selecting the corresponding checkboxes in the CE-Cloud. Also the slope of the breakwater needs to be selected in these checkboxes (for randomly placed units). For the pattern-placed units, a slope of 1:2 is automatically assumed, according to the Rock Manual.

3.3.10. Xbloc

FInally, the user can also design Xblocs as final armour layer units by use of the approach of DMC (2003).

Figure 21: Xbloc

Hudson (1974)

For the design of Xblocs, the general equation (33) for the stability of units can be used and rewritten in function of the equivalent cube length D_{n50}. The Rock Manual provides Table 5 considering the stability N_s of Xblocs:

Table 5: Stability of Xblocs (Rock Manual)

Armour type	Damage level	Stability number $H_s/\Delta D_n$				References / remarks
		Trunk		Head		
		Non-breaking waves	Breaking waves	Non-breaking waves	Breaking waves	
Xbloc	0% (N_{od} = 0)	2.8 (16.0)		2.6 (13.0)		DMC (2003) [7,8]

It is clear that there is no difference in stability for non-breaking or breaking waves, according to DMC (2003). The value of the stability N_s is set equal to 2,8; which corresponds to a stability coefficient K_D of 16 in the Hudson equation (23).

Furthermore, it is given that this approach is only valid for a fixed 1:1,33 slope. Consequently, it is not possible for the user to select another slope.

3.3.11. Final output

Once the user has finished one or more of the design approaches, the final armour unit with its corresponding slope angle can be selected by clicking on the accompanying "Select"-button. Subsequently the armour layer characteristics are generated and saved as final output. Figure 22 shows an example of such an output.

Type of armour unit	Rocks	[-]	Type of armour layer unit
Stone shape	Smooth & rounded	[-]	Shape of the unit
Placement	Randomly	[-]	How are the units placed?
Theory	Hudson	[-]	Which theory was used
ρ_s	2,6	t/m³	Density of the rocks/units
tan(α)	1:4	[-]	Tangens of the breakwater slope
D_n50	1,53	m	Diameter of the median rock size
M_50	9,31	t	Median rock/unit weight
Amount of layers	2	[-]	Number of ALU layers

Figure 22: Final output example of the armour layer selection sheet (CE-Cloud)

3.4. Overtopping-based height assessment

3.4.1. Introduction

If the maximal wave run-up level R_{max} exceeds the freeboard R_c of a breakwater, overtopping will occur. Therefore, the overtopping performance is thoroughly investigated in order to determine an economic value for the breakwater's height h_{tot}. The overtopping discharge is mainly a function of the hydraulic boundary conditions and the slope configuration of the breakwater. It is not possible to characterize this overtopping process by use of theoretical expressions due to the stochastic nature of the wave run-up and the various influencing factors in the overtopping process. Therefore, all approaches in the CE-Cloud consist of empirical formulas which are derived from experimental investigations in which reduction factors are implemented to take into account the different configurations of the breakwater such as roughness elements, berms, etc.

As soon as the user has defined the estimated, mean overtopping discharge (per meter breakwater) q as general input, several crest freeboards are generated corresponding to the different overtopping approaches. These formulas are split up in two sections according to their source: the EurOtop Manual or the CEM. The different design approaches are gathered below:

- EurOtop Manual:
    - Deterministic design
    - Probabilistic design
- CEM:
    - Owen (1980, 1982)
    - Bradbury and Allsop (1988)
    - Aminti and Franco (1988)
    - Pederson and Burcharth (1992)
    - Van der Meer and Janssen (1995)

3.4.2. General input

The general input consists of defining the mean overtopping discharge per meter q for the breakwater. The user can subsequently implement the safety against overtopping for vehicles, pedestrians, buildings, etc. for this specific project, according to Figure 23. A default value of $0,001 \frac{m^3}{s \cdot m}$ is implemented in the CE-Cloud which is a moderately safe, but economic design value. Note that it is not possible to insert zero overtopping since this parameter can be found in the denominator for several design formulas in the CE-Cloud.
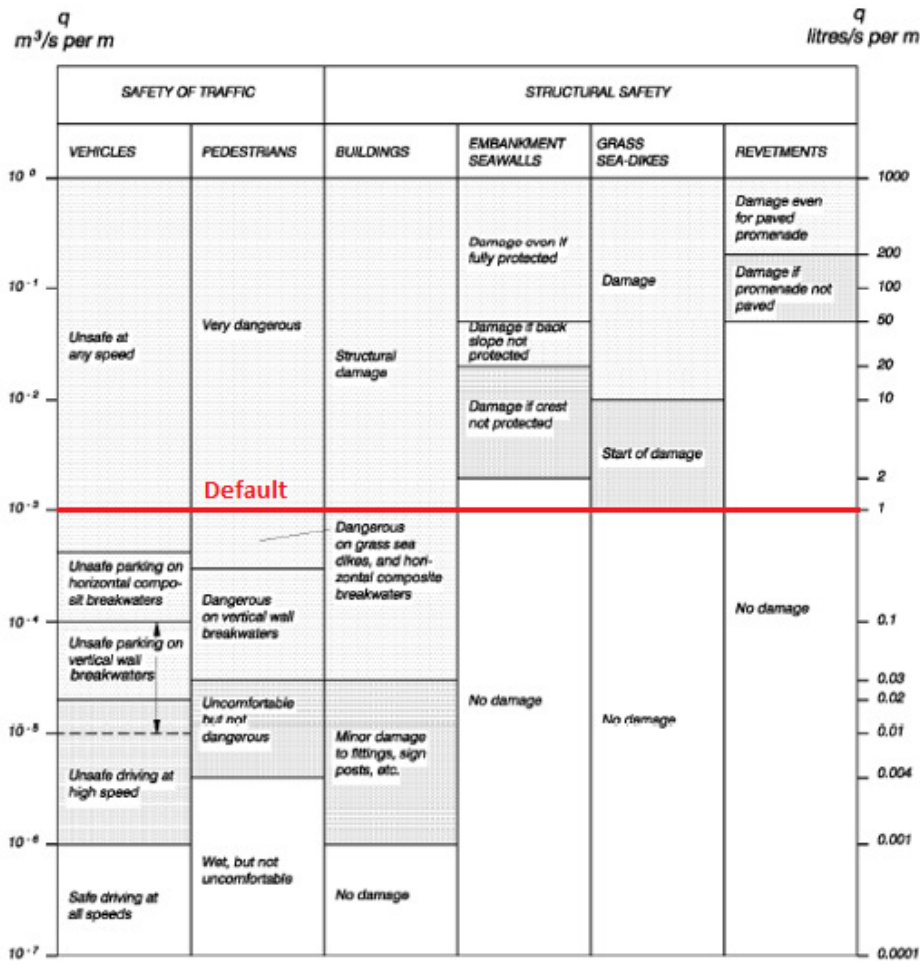
Figure 23: Safety in function of the mean overtopping discharge (EurOtop)

Since the crest width of the breakwater is not yet designed at this stage, the overtopping reduction factor C_r due to the crest width, can not yet be determined. The experienced user, however, can insert an estimated value for this parameter in the general input. If the user has no experience with this reduction factor, a default value of 1 is considered.

The last parameter which is required in the general input consists of the depth of the water bottom with respect to a standard reference level. As such, the breakwater design is vertically positioned with respect to this standard level. The CE-Cloud mentions TAW (Tweede Algemene Waterpassing) in its description, which is mainly used in Belgium. It is however possible for the user to consider another reference level such as NAP (Normaal Amsterdams Peil) by inserting the corresponding input value and ignoring the CE-Cloud description.

3.4.3. EurOtop Manual

Since the overtopping discharges are easily measurable, there is a large database of overtopping discharges available to define several empirical formulas. In both design approaches from the EurOtop Manual, the probabilistic and deterministic approach, these data are plotted in function of the relative freeboard height R_* and the relative overtopping rate Q_*. The fitted, empirical formulas for these data all obey to the following standard expression:

$$Q_* = a \cdot \exp(-b \cdot R_*) \qquad (39)$$

It is assumed that the results of R_* and Q_* are normally distributed. The probabilistic approach considers the mean values of these parameters. For the deterministic design, the discharge Q_* is increased by one standard deviation by decreasing the value of b. This subsequently results in a safer design.

Deterministic design

The deterministic approach for the calculation of the necessary crest freeboard R_c depends on whether a berm is installed on the rubble-mound breakwater or not. This section is subsequently split up in two sections: a section considering a rubble-mound slope without a berm, and a section which considers the slope with a berm. The user can insert this berm and its characteristics by clicking on the corresponding checkbox in the design sheet. If there is no need to install a berm, the CE-Cloud will automatically generate the necessary crest freeboard R_c by use of the deterministic equation (40) for armoured rubble slopes. Since there is no specific research available for the case in which a berm is installed on the rubble-mound slope, the EurOtop Manual recommends the deterministic equation (43) for sloping, impermeable structures such as dikes and seawalls. Note that it is rather uncommon practice to install a berm on a rubble-mound breakwater. Installing a berm can reduce the overtopping discharge or the amount of (expensive) armour units, as can be seen on Figure 6.

For a rubble slope without a berm, the following deterministic equation is considered:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0,2 \cdot exp\left(-2,3 \cdot \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right)$$

(40)

Equation (40) can subsequently be rewritten in function of the crest freeboard R_c:

$$R_c = ln\left(\frac{q}{0,2 \cdot \sqrt{g \cdot H_{m0}^3}}\right) \cdot \left(\frac{-H_{m0} \cdot \gamma_f \cdot \gamma_\beta}{2,3}\right)$$

(41)

With:

-   γ_f [-]: The roughness reduction factor. This parameter is automatically calculated in the CE-Cloud since the armour layer units are already determined. Values for γ_f can be found in Table 6 below:

Table 6: Roughness reduction factors for the armour layer units (EurOtop)

Type of armour layer	γ_f
Smooth impermeable surface	1.00
Rocks (1 layer, impermeable core)	0.60
Rocks (1 layer, permeable core)	0.45
Rocks (2 layers, impermeable core)	0.55
Rocks (2 layers, permeable core)	0.40
Cubes (1 layer, random positioning)	0.50
Cubes (2 layers, random positioning)	0.47
Antifers	0.47
HARO's	0.47
Accropode™, ,	0.46
Xbloc®	0.45
CORE-LOC®	0.44
Tetrapods	0.38
Dolosse	*0.43*

A value of 0,5 is assumed for tribars. Note that the roughness reduction factor has a major influence on the amount of overtopping.

- γ_β [-]: Oblique waves reduction factor, given by equation (42) below. Note that the angle of wave incidence β has already been defined in the previous section considering the hydraulic boundary conditions.

$$\gamma_\beta = \begin{cases} 1 - 0{,}0063 \cdot |\beta|\,; 0° \leq |\beta| \leq 80° \\ \qquad 0{,}496\,; |\beta| > 80° \end{cases} \tag{42}$$

All the above-mentioned parameters are generated in the CE-Cloud or have already been defined earlier by the user. Therefore no specific input is required and the program automatically calculates the necessary crest freeboard R_c.

For the other case in which a berm is installed on the breakwater, the approach for an impermeable, composite slope of a dike is used. Therefore two parameters need to be inserted by the user: the width of the berm B and the vertical distance from the SWL to the berm d_b, indicated in Figure 24. Note that the CE-Cloud only considers berms beneath the SWL, so only positive values are expected for d_b.

Since there are no armour units installed on the slope beneath the berm and on the berm itself, as can be seen on Figure 6, the outer layer on these parts of the breakwater needs to be sufficiently stable. Therefore, a blue window in the CE-Cloud warns the user to locate the berm sufficiently low to avoid instability of the berm units due to wave forces. As a general rule of thumb d_b should be larger than 1,5 times the design wave height H_s (proposed in the EurOtop Manual.) Note that if the berm is placed sufficiently low, its influence on the overtopping discharge is negligible. This will however yield a more economical design since less armour layer units need to be installed, which are in most cases the most expensive features of the rubble-mound breakwater. It is up to the user to keep this in mind while implementing the berm configuration. Note that the installation of a berm on a rubble-mound slope is uncommon practice.

Once these two parameters d_b and B have been defined, the following formula can be applied:

$$\frac{q}{\sqrt{gH_{m0}^3}} = \frac{0,067}{\sqrt{\tan(\alpha)}} \cdot \gamma_b \cdot \xi_{m-1,0} \cdot exp\left(-4,3 \cdot \frac{R_c}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right) \qquad (43)$$

With a maximum of:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0,2 \cdot exp\left(-2,3 \cdot \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right) \qquad (44)$$

Equation (44) perfectly corresponds to the overtopping equation (40) for a simple rubble slope without a berm.

Despite the fact that the surface roughness reduction factor γ_f and oblique waves reduction factor γ_β are defined differently in this approach, their values are set equal to the corresponding values from the previous approach of the rubble slope without a berm. This is assumed to compensate that this approach considers an impermeable slope, which is not realistic for a rubble-mound breakwater. The remaining parameters are:

- α [°]: The slope of the breakwater. Note that the same angle is assumed for the slope above as beneath the berm.
- $\xi_{m-1,0}$ [-]: Deep water surf-similarity index, based on the spectral deep water wave steepness $s_{m-1,0}$, calculated as:

$$\xi_{m-1,0} = \frac{\tan(\alpha)}{\sqrt{s_{m-1,0}}} \qquad (45)$$

Note that the value of $\xi_{m-1,0}$ may not exceed the upper limit of 5 in this approach. If this is the case, the CE-Cloud will automatically return a "N/A"-value.

- γ_v [-]: Vertical wall reduction factor. Since the maximum slope steepness in the CE-Cloud is 1:1, there is no need for a correction. Consequently, γ_v equals unity. There is no possibility for the user to implement vertical walls in the rubble-mound breakwater design.
γ_b [-]: Berm reduction factor, given by equation (46) below:

$$\gamma_b = 1 - r_B \cdot (1 - r_{db}) \qquad (46)$$

The first parameter r_B can be determined in function of B, H_s and α, as is shown in equation (47) and Figure 24. Note that in the latter figure, the berm is located above the SWL, which is not possible to design in the CE-Cloud. The configuration of the submerged berm is however the same.

$$r_B = \frac{B}{L_{berm}} = \frac{B}{B + 2 \cdot \frac{H_s}{\tan(\alpha)}} \qquad (47)$$
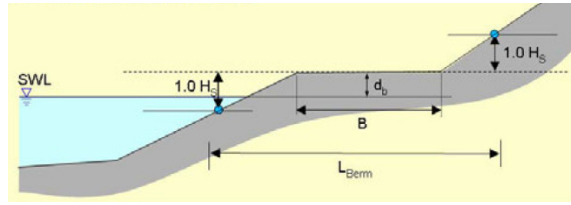
Figure 24: Berm configuration (EurOtop)

The second parameter r_{db} can be calculated in function of d_b (indicated on Figure 24) and the 2% mean wave run-up height $R_{u2\%}$:

$$r_{db} = \begin{cases} 0{,}5 - 0{,}5 \cdot cos\left(\pi \cdot \dfrac{d_b}{R_{u2\%}}\right); berm\ above\ SWL \\[4mm] 0{,}5 - 0{,}5 \cdot cos\left(\pi \cdot \dfrac{d_b}{2H_{m0}}\right); berm\ below\ SWL \end{cases} \tag{48}$$

With:

- $R_{u2\%}$ [m]: The 2% mean wave run-up height of which the deterministic expression is given as:

$$\frac{R_{u2\%}}{H_{m0}} = 1{,}75 \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \xi_{m-1,0} \tag{49}$$

With a maximum of:

$$\frac{R_{u2\%}}{H_{m0}} = \gamma_b \cdot \gamma_\beta \cdot \left[4{,}3 - \frac{1{,}6}{\sqrt{\xi_{m-1,0}}}\right] \tag{50}$$

The calculation for $R_{u2\%}$ is implemented in the CE-Cloud but is not used for the design of the rubble-mound breakwater since it is assumed that the berm is always beneath the SWL. The formula is however available for further extensions of the CE-Cloud.

Note that there is a lower limit for the product of the four reduction factors:

$$\gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v \geq 0.4$$

If the above-mentioned criterion is not met, mainly due to the low value of γ_f, the product will automatically be set equal to 0,4 in the CE-Cloud.

Probabilistic design
The probabilistic approach for the calculation of the crest freeboard R_c is executed analogously to the deterministic approach. This part is also split up in two sections: a section considering a rubble-mound slope without a berm, and a section which considers the slope with a berm. The first section calculates the necessary freeboard by use of the probabilistic approach of a simple rubble slope. The second section calculates the crest freeboard by use of the probabilistic approach for a composite slope of an impermeable, bermed dike.

For the first section, it is not necessary to insert additional parameters. The crest freeboard R_c is automatically generated. For the second section, the same parameters as for the deterministic approach need to be inserted: B and d_b. Consequently, the CE-Cloud is able to calculate the crest freeboard R_c for the deterministic and probabilistic approach with the same parameters. Therefore these parameters are not explicitly explained again in this section.

For a rubble slope without a berm, the following probabilistic equation is considered:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0,2 \cdot exp\left(-2,6 \cdot \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right)$$

(51)

Equation (51) can subsequently be rewritten in function of the crest freeboard R_c:

$$R_c = ln\left(\frac{q}{0,2 \cdot \sqrt{g \cdot H_{m0}^3}}\right) \cdot \left(\frac{-H_{m0} \cdot \gamma_f \cdot \gamma_\beta}{2,6}\right)$$

(52)

When a berm is installed on the seaside slope, the probabilistic approach for the slope of an impermeable, composite dike is used:

$$\frac{q}{\sqrt{gH_{m0}^3}} = \frac{0,067}{\sqrt{\tan(\alpha)}} \cdot \gamma_b \cdot \xi_{m-1,0} \cdot exp\left(-4,75 \cdot \frac{R_c}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right)$$

(53)

With a maximum of:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0,2 \cdot exp\left(-2,6 \cdot \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right)$$

(54)

Note that for the calculation of the berm reduction factor γ_b for a berm above SWL, the 2% mean wave run-up height is expressed in a probabilistic approach:

$$\frac{R_{u2\%}}{H_{m0}} = 1,65 \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \xi_{m-1,0}$$

(55)

With a maximum of:

$$\frac{R_{u2\%}}{H_{m0}} = \gamma_b \cdot \gamma_\beta \cdot \left[4 - \frac{1,5}{\sqrt{\xi_{m-1,0}}}\right]$$

(56)

Note that it is assumed that the berm is submerged. The formula for $R_{u2\%}$ is consequently not used, but it is implemented in case of further extensions in the CE-Cloud. Analogous to the deterministic approach, a lower limit of 0,4 is imposed on the product of the different reduction factors.

3.4.4. The Coastal Engineering Manual

In the Coastal Engineering Manual, there are two general expressions available to fit the empirical results:

$$Q_* = a \cdot R_*^{-b} \qquad (57)$$
$$Q_* = a \cdot \exp(-b \cdot R_*) \qquad (58)$$

In which:

- a and b [-]: Approach-specific fitting parameters

Note that equation (58) is the same as equation (39) from the EurOtop Manual. In the CE-cloud five different design formulas are implemented:

- Owen (1980, 1982)
- Bradbury and Allsop (1988)
- Aminti and Franco (1988)
- Pedersen and Burcharth (1992)
- Van der Meer and Janssen (1995)

The approaches of Bradbury and Allsop (1988), Aminti and Franco (1988) and Pedersen and Burcharth (1992) consider a specific slope configuration with a crown wall. The CE-Cloud can determine the corresponding crest freeboard, but is not able to take this specific configuration into account in later design steps. The cost assessment and drawing tool are only based on a simple rubble-slope (with or without a berm), without crown walls. The user should keep this in mind when selecting one of these methods.

Owen (1980, 1982)
Owen derived an overtopping expression for the case of a straight or bermed impermeable slope. This formula is valid for irregular, head-on waves which are non-depth-limited. If the waves are depth-limited, the CE-Cloud will return a "N/A"-value. The expression of Owen is given below:

$$\frac{q}{g \cdot H_s \cdot T_{0m}} = a \cdot exp\left(-b \cdot \frac{R_c}{H_s} \cdot \sqrt{\frac{s_{0m}}{2\pi}} \cdot \frac{1}{\gamma_r}\right) \qquad (59)$$

And can subsequently be rewritten as:

$$R_c = ln\left(\frac{q}{g \cdot H_s \cdot T_{0m} \cdot a}\right) \cdot \left(-\frac{H_s}{b} \cdot \sqrt{\frac{2\pi}{s_{0m}}} \cdot \gamma_r\right) \qquad (60)$$

With:

- γ_r [-]: The surface roughness reduction factor which needs to be inserted by the user. Table 7 gathers several representative values. Note however that Owen's approach considers an impermeable slope, which is not the case for a rubble-mound breakwater. Therefore it is recommended to insert the roughness reduction factors γ_r corresponding to the selected armour layer units as is indicated in Table 6.

Table 7: Surface roughness reduction factors (Owen, 1980/1982)

Surface roughness reduction factor γ_r. Updated γ_r-values are given in Table VI-5-3.

Smooth impermeable (including smooth concrete and asphalt)	1.0
One layer of stone rubble on impermeable base	0.8
Gravel, gabion mattresses	0.7
Rock riprap with thickness greater than $2 D_{n50}$	0.5 - 0.6

- a,b [-]: Fitted coefficients which were empirically determined. At this point the user needs to decide whether a berm will be installed or not by clicking on the corresponding checkboxes in the CE-Cloud sheet. If a straight slope is to be installed, the coefficients a and b will only be a function of the slope angle, as can be seen on Table 8. If a berm is to be installed, the CE-cloud needs two additional inputs: the width of the berm B and the vertical distance between the berm and the SWL d_b, both parameters are indicated in Figure 23. The coefficients a and b are only defined for specific combinations of B, d_b and the slope α as can be seen on Table 9. If the user inserts an invalid combination, the CE-Cloud will generate a "N/A"-value. Note that the notation of d_b is the same as h_B in Table 9.

Table 8: Parameters a and b for a straight slope (Owen, 1980/1982)

Coefficients in Eq VI-5-22
Straight smooth slopes.
Non-depth limited waves.

Slope	a	b
1 : 1	0.008	20
1 : 1.5	0.010	20
1 : 2	0.013	22
1 : 3	0.016	32
1 : 4	0.019	47

Table 9: Parameters a and b for a bermed slope (Owen, 1980/1982)

Coefficients in Eq VI-5-22
Bermed smooth slopes.
Non-depth limited waves.

Slope	h_B (m)	B (m)	$a \cdot 10^4$	b
1 : 1	−4.0	10	64	20
1 : 2			91	22
1 : 4			145	41
1 : 1	−2.0	5	34	17
1 : 2			98	24
1 : 4			159	47
1 : 1	−2.0	10	48	19
1 : 2			68	24
1 : 4			86	46
1 : 1	−2.0	20	8.8	15
1 : 2			20	25
1 : 4			85	50
1 : 1	−2.0	40	3.8	23
1 : 2			5.0	26
1 : 4			47	51
1 : 1	−1.0	5	155	33
1 : 2			190	37
1 : 4			500	70
1 : 1	−1.0	10	93	39
1 : 2			340	53
1 : 4			300	80
1 : 1	−1.0	20	75	46
1 : 2			34	50
1 : 4			39	62
1 : 1	−1.0	40	12	49
1 : 2			24	56
1 : 4			1.5	63
1 : 1	0	10	97	42
1 : 2			290	57
1 : 4			300	80

Bradburry and Allsop (1988)

Bradburry and Allsop defined an overtopping formula for a straight rock armoured slope 1:2 with a berm in front of a crown wall for non-depth-limited waves. Consequently this approach is only valid if rocks on a 1:2 slope have been selected in the previous design stage. Figure 25 shows the five possible configurations of the breakwater. It is up to the user to select a specific configuration by clicking on the corresponding checkbox. Note that the width of the berm G is equal to three armour units D_{n50} next to each other.
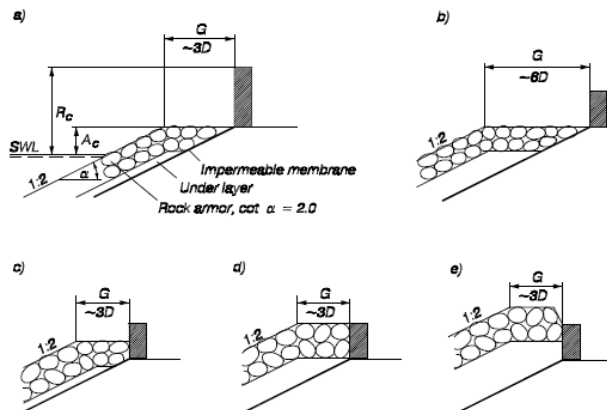
Figure 25: Slope configurations (Bradburry and Allsop, 1988)

All these configurations make use of the same equation (61), proposed by Bradbury and Allsop:

$$\frac{q}{g \cdot H_s \cdot T_{0m}} = a \cdot \left(\left(\frac{R_c}{H_s} \right)^2 \cdot \sqrt{\frac{s_{0m}}{2\pi}} \right)^{-b} \qquad (61)$$

Which can be rewritten as:

$$R_c = \sqrt{\left(\frac{q}{g \cdot H_s \cdot T_{0m} \cdot a} \right)^b \cdot \sqrt{\frac{2\pi}{s_{0m}}} \cdot H_s} \qquad (62)$$

With:

- a, b [-]: Fitted parameters which can be found in Table 10 below:

Table 10: Fitted parameters a and b (Bradburry and Allsop, 1988)

Section	G/H_s	G/R_c	A/R_c	$a \cdot 10^9$	b
a	0.79 - 1.7	0.75	0.28	6.7	3.5
		0.58	0.21	3.6	4.4
		1.07	0.39	5.3	3.5
		0.88	0.32	1.8	3.6
b	1.6 - 3.3	2.14	0.39	1.0	2.8
c	0.79 - 1.7	1.07	0.71	1.6	3.2
d	0.79 - 1.7	1.07	1.00	0.37	2.9
e	0.79 - 1.7	0.83	1.00	1.30	3.8

In a first step, it is checked whether the ratio G/H_s lies within the defined range of the selected configuration. For configurations b to e, the coefficients a and b can be generated directly. For configuration a, R_c is calculated with $a = 6,7 \cdot 10^{-9}$ and $b = 3,5$ in a first iteration. Consequently, the ratio G/R_c is determined and a final value for R_c is calculated in a second iteration.

Note that in a lot of tested cases the value of G/H_s lies not within the defined range. If this is the case, the CE-Cloud returns a "N/A"-value.

Aminti and Franco (1988)
Aminti and Franco derived new fitting coefficients a and b for equation (62) of Bradburry and Allsop (1988) to determine the overtopping of a straight slope with a berm in front of a crown wall. The slope can either consist of rocks, cubes or tetrapods with a gradient of 1:2 or 1:1,33. If the selected gradient and armour units from the previous design stage do not correspond to one of these combinations, the CE-Cloud will yield a "N/A"-value. This approach considers irregular, head-on waves which are non-depth-limited.

The user can insert the width G of the berm in function of the ratio between G and the equivalent cube length D_{n50}. The only valid values for G/D_{n50} are 3, 5 and 7, corresponding to G/H_s equal to 1,1; 1,85 and 2,6. Note that this is a very rough assumption.

Once the value of the berm width G is determined, the CE-Cloud automatically generates the corresponding crest freeboard by use of equation (62). The coefficients a and b are defined in Table 11 below:

ARMOR	cot	G/H_s	$a \cdot 10^8$	b
ROCK	2.00	1.10	17	2.41
		1.85	19	2.30
		2.60	2.3	2.68
	1.33	1.10	5.0	3.10
		1.85	6.8	2.65
		2.60	3.1	2.69
CUBES	2.00	1.10	8.3	2.64
		1.85	15	2.43
		2.60	84	2.38
	1.33	1.10	62	2.20
		1.85	17	2.42
		2.60	1.9	2.82
TETRAPODS	2.00	1.10	1.9	3.08
		1.85	1.3	3.80
		2.60	1.1	2.86
	1.33	1.10	5.6	2.81
		1.85	1.7	3.02
		2.60	0.92	2.98

Pedersen and Burcharth (1992)

Pedersen and Burcharth expressed a formula for the overtopping of a rock armoured permeable slope (P=0,4) with a berm in front of a crown wall:

$$\frac{q \cdot T_{0m}}{L_{0m}^2} = 3{,}2 \cdot 10^{-5} \cdot \left(\frac{H_s}{R_c}\right)^3 \cdot \frac{H_s^2}{A_c \cdot B \cdot \cot(\alpha)} \tag{63}$$

This can be rewritten as:

$$R_c = \sqrt[3]{3{,}2 \cdot 10^{-5} \cdot \frac{H_s^5}{A_c \cdot B \cdot \cot(\alpha)} \cdot \frac{L_{0m}^2}{q \cdot T_{0m}}} \tag{64}$$

With:

- A_c [m]: The height of the berm with respect to the SWL, as is indicated in Figure 26
- B [m]: The width of the berm, as is indicated in Figure 26
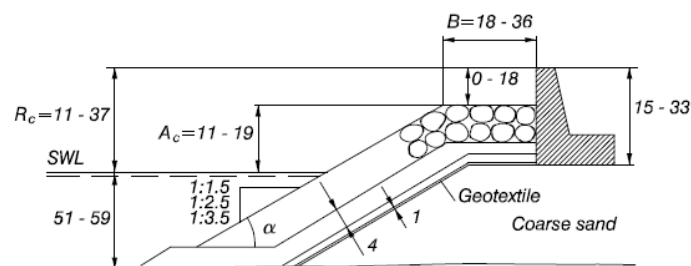
Figure 26: Berm configuration (Pedersen and Burcharth, 1992)

The user needs to insert the latter two parameters A_c and B after which the CE-Cloud will automatically generate the corresponding value for the crest freeboard R_c.

Van der Meer and Janssen (1995)

For a straight or bermed impermeable slope, Van der Meer and Janssen formulated two expressions in function of the deep water surf-similarity index ξ_{0p} [-], given by:

$$\xi_{0p} = \frac{\tan(\alpha)}{\sqrt{s_{p0}}} \tag{65}$$

For $\xi_{0p} < 2$:

$$\frac{q}{\sqrt{gH_s}} \cdot \sqrt{\frac{s_{0p}}{\tan(\alpha)}} = 0{,}06 \cdot exp\left(-5{,}2 \cdot \frac{R_c}{H_s} \cdot \frac{\sqrt{s_{0p}}}{\tan(\alpha)} \cdot \frac{1}{\gamma_r \cdot \gamma_b \cdot \gamma_h \cdot \gamma_\beta}\right) \tag{66}$$

With:
$$0{,}3 < \frac{R_c}{H_s} \cdot \frac{\sqrt{s_{0p}}}{\tan(\alpha)} \cdot \frac{1}{\gamma_r \cdot \gamma_b \cdot \gamma_h \cdot \gamma_\beta} < 2$$

For $\xi_{0p} > 2$:

$$\frac{q}{\sqrt{gH_s}} = 0{,}2 \cdot exp\left(-2{,}6 \cdot \frac{R_c}{H_s} \cdot \frac{1}{\gamma_r \cdot \gamma_b \cdot \gamma_h \cdot \gamma_\beta}\right) \tag{67}$$

With:

- γ_r [-]: The surface roughness reduction factor of which the values can be found in Table 12 below. This parameter needs to be inserted by the user. Note that it is recommended to insert the roughness reduction factors of the installed armour units, given in Table 6 to compensate for the fact that the rubble-slope is permeable.

Table 12: Surface roughness reduction factor (Van der Meer and Janssen, 1995)

Surface Roughness Reduction Factor γ_r in Equation VI-5-3, Valid for $1 < \xi_{op} < 3\text{-}4$	
Type of Slope Surface	γ_r
Smooth, concrete, asphalt	1.0
Smooth block revetment	1.0
Grass (3 cm length)	0.90 - 1.0
1 layer of rock, diameter D, ($H_s /D = 1.5 - 3.0$)	0.55 - 0.6
2 or more layers of rock, ($H_s /D = 1.5 - 6.0$)	0.50 - 0.55
Roughness elements on smooth surface (length parallel to waterline = P, width = b, height = h)	

- γ_β [-]: Oblique waves reduction factor. It is assumed that the incoming waves are long-crested such that this reduction factor is expressed as:

$$\gamma_\beta = \begin{cases} 1{,}0 \; ; for \; 0° \leq \beta \leq 10° \\ cos^2(\beta - 10°) \; ; for \; 10° \leq \beta \leq 50° \\ 0{,}6 \; ; \; for \; \beta > 50° \end{cases} \tag{68}$$

- γ_b [-]: Berm reduction factor. As was the case for the calculations of the EurOtop Manual (section 3.4.3), the user can install a berm on the seaside slope by selecting the corresponding checkbox in the CE-Cloud. If this is done, the user needs to insert values for the parameters B and d_b which are shown on Figure 27. Note that the berm is assumed to be horizontal.
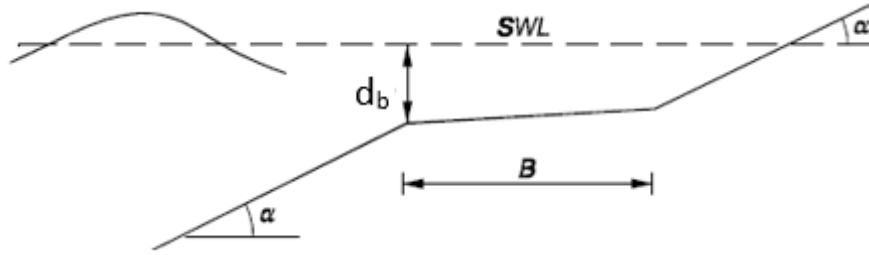
Figure 27: Berm configuration (CEM)

The formula for the berm reduction factor is given by:

$$\gamma_b = 1 - r_B \cdot (1 - r_{dB})$$

(69)

With:

$$r_B = 1 - \frac{\tan(\alpha_{eq})}{\tan(\alpha)} = \frac{B \cdot \tan(\alpha)}{B \cdot \tan(\alpha) + 2 \cdot H_s} \quad \text{(see Figure 28)}$$

(70)

$$r_{dB} = 0,5 \cdot \left(\frac{d_b}{H_s}\right)^2, 0 \le r_{dB} \le 1$$

(71)
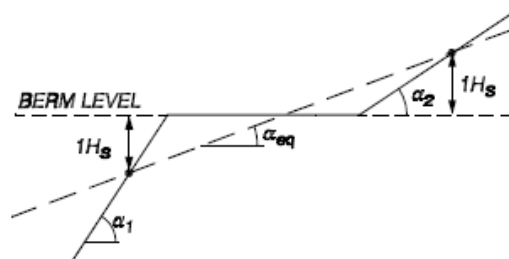
Figure 28: α_{eq} definition sketch (CEM)

Note that in the CE-Cloud it is assumed that α_1 is equal to α_2.

- γ_h [-]: Shallow water run-up reduction factor. Since the incoming waves are no longer Rayleigh distributed in shallow waters, a correction factor γ_h is provided:

$$\gamma_h = \frac{H_{2\%}}{1,4 \cdot H_s}$$

(72)

The value of $H_{2\%}$ is however not known, so there is no possibility to calculate a precise value for γ_h. Therefore, the value of γ_h is set equal to unity which implicitly assumes that the incoming waves are Rayleigh distributed, even for shallow waters. This is however a conservative assumption.

Analogous to the deterministic and probabilistic approach in the EurOtop manual, a lower limit of 0,4 is imposed on the product of the different reduction factors.

3.4.5. Final output

Once the user has determined one or more values for the crest freeboard R_c, a final output value can be selected by clicking on the corresponding "Select"-button. By adding the water depth d to this crest freeboard R_c, the total height of the breakwater h_{tot} is calculated. If the depth of the sea bottom in TAW (or another reference level) is subsequently added to h_{tot}, the highest point of the breakwater in TAW (or another reference level) is determined.

Note that the approaches of Bradbury and Allsop (1988), Aminti and Franco (1988), and Pedersen and Burcharth (1992) are valid for slopes with a berm in front of a crown wall. The CE-Cloud is able to determine the required crest freeboard, but does not support a detailed design for the crown wall. The generated crest freeboards can subsequently be used as an indicator, or to compare results. The user should however be aware that the cost assessment and drawing tool do not recognize this crown wall.

3.5. Filter layer and core material selection

3.5.1. Introduction

Two layers of granular filters are installed between the armour layer and the core material. These filter layers protect the underlying material from erosion resulting from wave impacts and currents, but should prevent excessive pore pressure buildup within this underlying material. They subsequently need to provide sufficient stability for the armour layer units, but need to be small enough to avoid washing out of the base material through their voids. Two filter layers are generated in the CE-Cloud to determine an economic, but durable design which meets the different filter criteria (explained in section 3.5.3). Granular filters also have a lot of advantages: they are generally very durable and provide a good contact surface between the core and the armour layer units. Due to their porosity, they also contribute to the damping of the incoming wave energy. This, together with the fact that they are mostly inexpensive and widely available, makes the granular filters appropriate materials to install in the breakwater.

3.5.2. General input

For the selection of the filter layer units, there is no method-specific input required. The user only needs to define the general input parameters and the CE-Cloud will automatically generate the best-fitting filter material.

The general input firstly consists of the weight ratios between the unit weight of the armour units W_{armour} (or W) and the median weight of the units of the other layers (filter 1, 2 and core) W_x. The default values in case of a rock armoured slope are given below, as can be seen on Figure 29.

$$\frac{W_{armour}}{W_{filter1}} = 10 \ \& \ \frac{W_{armour}}{W_{filter2}} = 200 \ \& \ \frac{W_{armour}}{W_{core}} = 4000$$
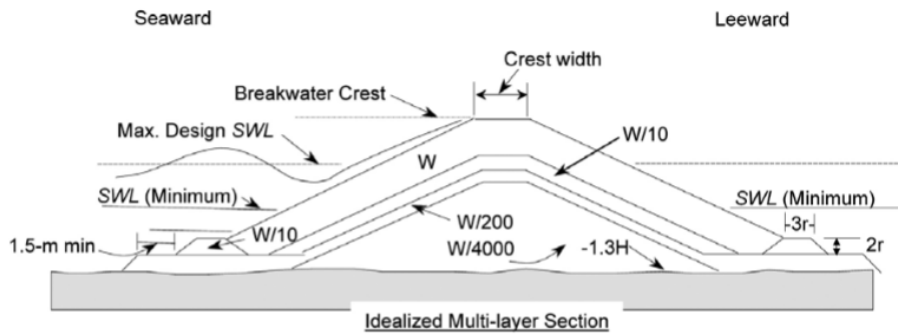
Figure 29: Weight distribution of the RM breakwater (CEM)

Secondly, the user needs to insert the densities of the layer materials. Since the unit weights and densities of the different materials are subsequently known, the design dimensions of the different materials can be generated and the three filter criteria (explained in section 3.5.3) can be checked.

Thirdly, the user can insert the amount of units n which are placed on top of each other within the same layer, together with the layer coefficient k_Δ to calculate the thicknesses of each of the layers. Table 13 shows several values for the layer coefficient k_Δ.

Table 13: Layer coefficients for the filter/core materials (CEM)

Layer Coefficient and Porosity for Various Armor Units				
Armor Unit	**n**	**Placement**	**Layer Coefficient** k_Δ	**Porosity P (percent)**
Quarrystone (smooth)[1]	2	Random	1.02	38
Quarrystone (rough)[2]	2	Random	1.00	37
Quarrystone (rough)[2]	∃3	Random	1.00	40
Quarrystone (parallepiped)[3]	2	Special	--	27
Quarrystone[4]	Graded	Random	--	37
Cube (modified)[1]	2	Random	1.10	47
Tetrapod[1]	2	Random	1.04	50
Tribar[1]	2	Random	1.02	54
Tribar[1]	1	Uniform	1.13	47
dolos[5]	2	Random	0.94	56
Vol. < 5 m³ Core-Loc[6] 5 < Vol. < 12 m³ 12 < Vol. < 22m³	1	Random	1.51	60 63 64
Vol. < 5 m³ Accropod[7] 5 < Vol. < 12 m³ 12 < Vol. < 22m³	1	Random	1.51	57 59 62

[1]   Hudson (1974)
[2]   Carver and Davidson (1983)
[3]   Layer thickness is twice the average long dimension of the parallelepiped stones. Porosity is estimated from tests on one layer of uniformly placed modified cubes (Hudson 1974).
[4]   The minimum layer thickness should be twice the cubic dimension of the W_{50} riprap. Check to determine that the graded layer thickness is ∃1.25 the cubic dimension of the W_{max} riprap (see Equations VI-5-119 and VI-5-120).
[5]   Carver and Davidson (1977)
[6]   Turk and Melby (1997)
[7]   Accropod informational brochure

3.5.3. Filter and core material selection

In the first step, the median weight of the different layer units W_x is calculated by dividing the median weight of the armour layer units W_{armour} by the corresponding weight ratios W_{armour}/W_x which were

defined in the general input. Considering the different filter criteria (explained later) and the operational feasibility, it is not possible to install filter units which all have the same size and weight. Therefore standard gradings are defined and installed. The Rock Manual provides several of these standard gradings which are mathematically described by use of the Rosin-Rammler (1993) curves.

These curves give the relation between the fraction of grading y which is lighter than the units with a corresponding weight M_y. The Rosin-Rammler curves are expressed as:

$$M_y = M_{50} \cdot \left(\frac{-\ln(1-y)}{0,693} \right)^{\frac{1}{n_{RRM}}}$$
(73)

In which:

$$M_{50} = \frac{NLL \cdot \left(\frac{\ln(1-y_{NNL})}{-0,693} \right)^{\frac{-1}{n_{RRM}}} + NUL \cdot \left(\frac{\ln(1-y_{NUL})}{-0,693} \right)^{\frac{-1}{n_{RRM}}}}{2}$$
(74)

$$n_{RRM} = \frac{log \left(\frac{\ln(1-y_{NUL})}{\ln(1-y_{NLL)}} \right)}{log \left(\frac{NUL}{NLL} \right)}$$
(75)

With:

- y [-]: The fraction passing value.
- M_y [kg]: The mass corresponding to the fraction y.
- n_{RRM} [-]: The uniformity index.
- NLL/NUL [-]: Nominal lower (<10%)/upper (>70%) limit mass of a grading.
- $y_{NLL/NUL}$ [-]: Fraction corresponding to NLL/NUL.

The different values for M_y corresponding to NUL/NLL can be found in Table 14 below. The gradings are split up in three classes: heavy, light and coarse. Note that the coarse gradings are not expressed in kg, but in mm. The Rosin-Rammler equation (73) is still valid for these coarse gradings, but M_y is replaced by D_y, which is the diameter corresponding to the fraction y.

Table 14: M_y values for the different standard gradings (Rock Manual)

Class designation		ELL	NLL	NUL	EUL	M_{em}	
Passing requirements		< 5%	< 10%	> 70%	> 97%	lower limit	upper limit
Heavy	kg	kg	kg	kg	kg	kg	kg
	10000-15000	6500	10000	15000	22500	12000	13000
	6000-10000	4000	6000	10000	15000	7500	8500
	3000-6000	2000	3000	6000	9000	4200	4800
	1000-3000	700	1000	3000	4500	1700	2100
	300-1000	200	300	1000	1500	540	690

		ELL	NLL	NUL	EUL	M_{em}	
		< 2%	< 10%	> 70%	> 97%	lower limit	upper limit
Light	kg	kg	kg	kg	kg	kg	kg
	60-300	30	60	300	450	130	190
	10-60	2	10	60	120	20	35
	40-200	15	40	200	300	80	120
	5-40	1.5	5	40	80	10	20
	15-300 *)	3	15	300	450	45	135

		ELL	NLL	NUL	EUL		
		< 5%	< 15%	> 90%	> 98%	< 50%	
Coarse	mm	mm	mm	mm	mm	mm	
	45/125	22.4	45	125	180	63	
	63/180	31.5	63	180	250	90	
	90/250	45	90	250	360	125	
	45/180 **)	22.4	45	180	250	63	
	90/180 ***)	45	90 ***)	180 ***)	250	n.a.	

*) wide light grading, **) wide coarse grading, ***) gabion grading, NLL = 20% and NUL = 80%

The curves corresponding to the different standard gradings can be found in Figure 30, Figure 31 and Figure 32. Note that the calculated median weights M_{50} or diameter D_{50} (in case of a coarse grading) of the different gradings is given in the legends, expressed in kg or mm (in case of a coarse grading).
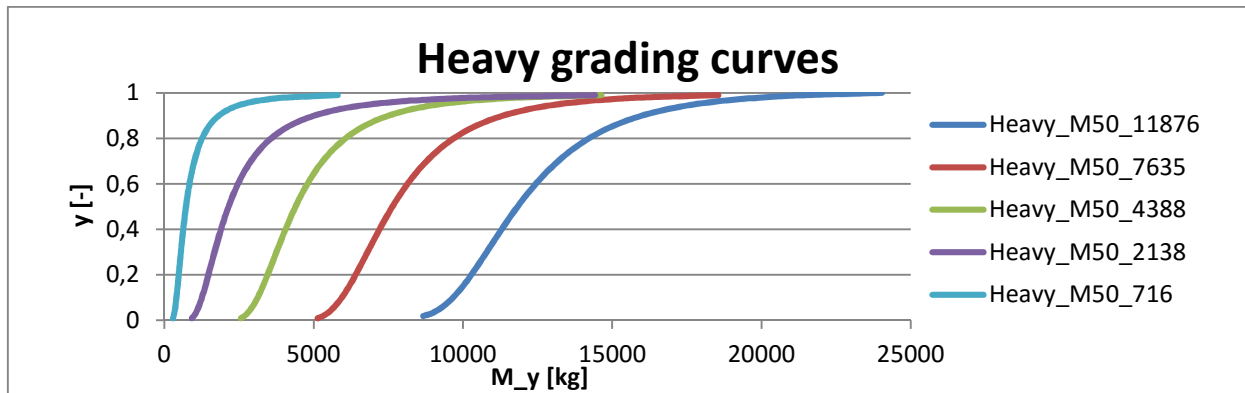
Figure 30: Heavy grading curves (Rosin-Rammler, 1993)
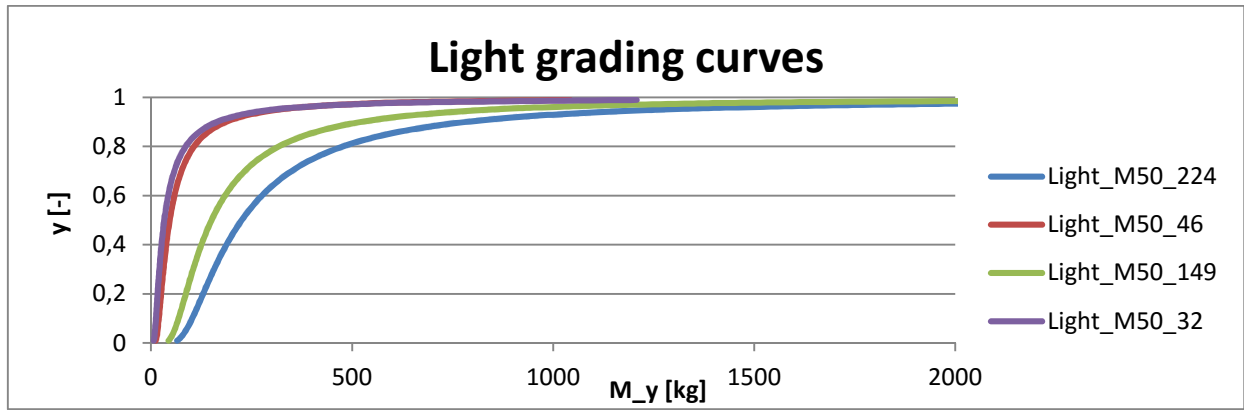
Figure 31: Light grading curves (Rosin-Rammler, 1993)
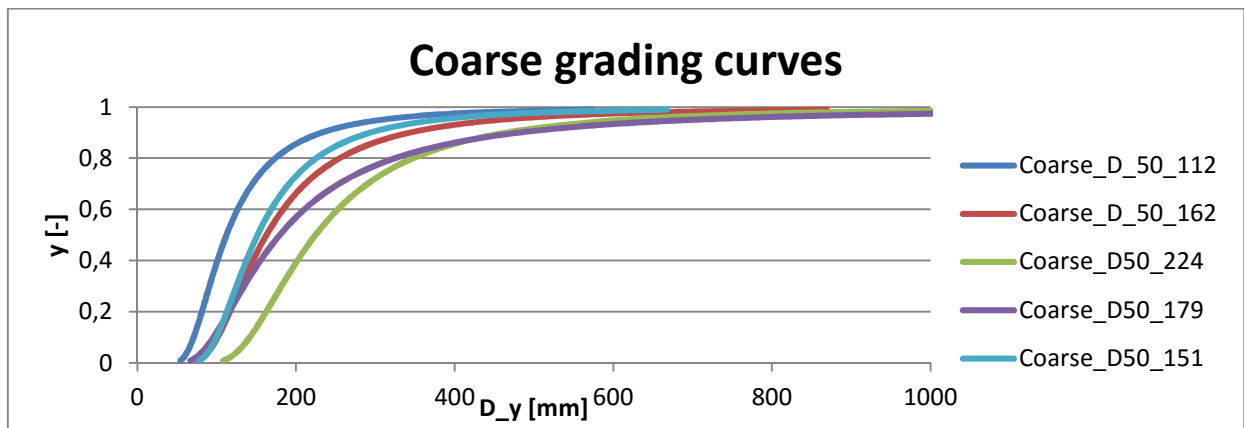
Figure 32: Coarse grading curves (Rosin-Rammler, 1993)

Since the median unit weight W_x of each of the layers is known, the best fitting standard grading can be generated in the CE-Cloud. This selection is based on the grading with a median weight value M_{50} closest to W_x.

In a first window, the CE-Cloud generates the rock size (heavy, light or coarse), the standard filter grading and the corresponding median weight M_{50}. As is shown in Figure 33 below:

W_filter1	0,533	t	Unit weight of the filter layer 1 material
Rock size	Heavy	[-]	Rock size of filter 1
Filter grading	300 - 1000	kg	Standard grading of the filter 1
M_50	716	kg	Median rock weight

Figure 33: Filter information window (CE-Cloud)

The CE-Cloud subsequently determines the different diameter fractions d_{10}, d_{15}, d_{50}, d_{60} and d_{85} in a second window. These fractions are calculated by use of the following expression:

$$d_y = \sqrt[3]{\frac{M_y}{\rho}}$$
(76)

Note that equation (76) is only used for heavy and light gradings. For a coarse grading, the Rosin-Rammler equation (73) can be used directly to calculate d_y.

At this point, the most appropriate grading is generated in the CE-Cloud. Subsequently it is checked If the proposed grading meets the different filter criteria:

- Retention criterion: In order to prevent loss of foundation materials due to migration through the filter voids, the following requirement should be met:

$$\frac{d_{15,filter}}{d_{85,foundation}} < 5$$

In case of a filter overlying coarse foundation materials, the retention criterion can also be defined as:

$$\frac{W_{50,filter}}{W_{50,foundation}} < 20$$

- Permeability criterion: To prevent excessive pore pressures buildup, the hydraulic gradient across the different layers should be limited by providing sufficient permeability. This criterion can be expressed as:

$$\frac{d_{15,filter}}{d_{15,foundation}} > 5$$

- Internal stability criterion: loss of fine particles within the same grading should be prevented in order to retain its internal stability. This criterion is expressed as:

$$\frac{d_{60,filter}}{d_{10,filter}} < 10$$

The CE-Cloud determines whether the proposed standard grading meets the above-mentioned criteria. If this is not the case, the user can select a wider grading or change the general input. Note that the former will only be possible for light and coarse filter gradings as is indicated in Table 14. The user can also select gabions to be installed. This is however uncommon practice for the construction of a rubble-mound breakwater.

Note that it is not possible to change the general input values once a wider grading or gabions have been selected. This is because the formula to generate a certain grading is overwritten by clicking on the "Use wider grading"- or "Use gabions"-button. The original value is saved, so the user can still recall this result by clicking on the "Undo"-button. But the original formula itself is lost.

Since the different layer materials are known at this stage, the thickness of the two filter layers can be determined by use of the following formula:

$$r = n \cdot k_\Delta \cdot \left(\frac{W}{w_a}\right)^{\frac{1}{3}} \tag{77}$$

With:

- n [-]: Number of units (vertically) in the layer, defined in the general input.
- k_Δ [-]: Layer coefficient, defined in the general input.
- W [kN]: Unit weight of the layer unit.
- w_a [kN/m³]: Specific weight of the considered layer material.

3.5.4. Final output

In contrast to previous sections, the user does not need to select a certain approach to define the final output. In a first part, the four main layer characteristics of the armour, filter and core materials are gathered:

- Type of material [-]
- Median rock weight M_{50} [kg]
- Equivalent cube length of the median rock D_{50} [m]
- The thickness of the layer r [m]

The CE-Cloud subsequently generates two plots: one to visualize the two filter layer gradings, and one to plot the core material grading. Note that the axes of the latter are not defined since this material could be light (expressed in kg) or coarse (expressed in mm). By clicking on the "Show values"-button beneath these graphs, the different values which are plotted, are shown.

For economic reasons, the filter layer materials at the leeside are assumed to be the same as at the seaside. It is however possible that the armour units at both sides of the breakwater differ, as has already been discussed in the design of the armour units. The thickness of the leeside armour layer is automatically generated in this section by use of equation (77).

Finally, the bedprotection characteristics can be defined. A geotextile will first be applied on the sea bottom after which a granular bedprotection layer is installed. The latter provides a uniform construction base for the breakwater by filling up the bottom irregularities. It is however not possible to design and generate the filter properties of the geotextile and bedding layer in the CE-Cloud. The user can only insert the density of the bedding material and a value for the mean height of this bedding layer.

Note that the available filter materials are very site- and supplier-specific. The Rosin-Rammler curves, that are used in the CE-Cloud, describe standard gradings which can give a good indication for the necessary filter materials. The user, however, has to keep in mind that the filter material selection is not an exact science. Consequently, a good understanding of the different filter criteria is necessary to select an available grading for the real design.

3.6. Crest width assessment

3.6.1. Introduction

For the determination of the crest width, the CE-Cloud provides two options. The first option consists of manually inserting an engineering-judged value, based on several construction considerations. The second option is based on a general design formula, proposed in the Coastal Engineering Manual. Since several breakwater characteristics are already defined in prior design stages, there is no general input required in this design sheet.

3.6.2. Width calculation

For the first design option, the user can manually insert an appropriate value for the crest width, based on engineering insight. A general rule of thumb states that the crest width should be larger than three times the median cube length D_{n50} of the armour units. This is also clearly indicated in the blue window in the CE-Cloud, shown on Figure 34, where the value of $3 \cdot D_{n50}$ is automatically calculated.

Figure 34: Crest width warning window (CE-Cloud)

The crest width is also an important parameter for the construction method. The breakwater can either be constructed with land- or sea-based equipment. Generally, it is much cheaper and easier to construct a breakwater with land-based equipment. Sufficient crest width should however be provided in order to safely install the necessary crane(s) and import the construction materials by truck. In most cases, it is beneficial to invest in a wider crest width in order to use land-based equipment, since constructing from a pontoon (sea-based equipment) is much more expensive and difficult. Figure 35 shows some characteristic widths for the different equipment.
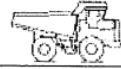
type		capacity (m³)	weight (ton)	wheel load (ton) ground pressure	width (m)
(off higway) dump truck		20 - 90	empty: 30 - 110 loaded: 60 - 270	front/rear (ton) empty: 15/15 - 50/60 loaded: 20/40 - 90/180	wheel base 3.7 - 5.7
articulated dump truck		12 - 27	empty: 20 - 40 loaded: 40 - 90	front/rear (ton) empty: 10/10 - 20/20 loaded: 14/26 - 30/60	wheel base 5.7 - 6.8
wheel loader		2.5 - 9	15 - 86		bucket width 2.7 - 4.7
track loader		2.5 - 3	25	60 - 90 kPa	bucket width 2.7
backhoe crane		0.5 - 15	15 - 200	40 - 150 kPa	track gauge 2 - 5
front shovel		2 - 15	40 - 200	70 - 190 kPa	track gauge 2 - 5
bulldozer		blade width 2.5 - 5 m	10 - 80	50 - 100 kPa	track gauge 2 - 3

Figure 35: Characteristics of the different equipment (Rock Manual)

In the second design option, the crest width is calculated in the same way as the thickness of the armour and filter layers by use of a similar expression as equation (77):

$$B_{crest} = n \cdot k_\Delta \cdot \left(\frac{W}{w_a}\right)^{\frac{1}{3}}$$

(78)

With:

- n [-]: Number of units in the width direction. This value can be inserted by the user, but should be at least equal to 3.
- k_Δ [-]: Layer coefficient for the armour units on the crest, which is automatically generated by the CE-Cloud.

3.6.3. Final output

It is up to the user to select the resulting crest width of one of the two above-mentioned methods as final output by clicking on the corresponding "Select"-button. Once a final value is selected, the CE-Cloud will calculate the crest width reduction factor for overtopping C_r. This reduction factor is expressed in the EurOtop Manual as:

$$C_r = 3{,}06 \cdot exp\left(-1{,}5 \cdot \frac{B}{H_{m0}}\right) \; with \; C_r \le 1$$

<div align="right">(79)</div>

Since the overtopping-based height assessment is already executed, this parameter only gives an indication of the safety against overtopping. It is not recommended to go back in the program and reimplement this value in the "Overtopping"-sheet. It is however possible for the experienced user. Note that in this "Overtopping"-sheet, the user could insert an estimation for this reduction factor.

3.7. Toe stability check

3.7.1. Introduction

Since the intersection of the armour layers with the bottom of the sea is very vulnerable for scour and instability, an appropriate design for the toe materials and configuration is executed. If armour units are displaced out of their layer, they will come to rest on this toe, resulting in an increased stability. The toe generally consists of rocks or armour layer units.

The design of the toes at the sea- and leeside is executed separately in the CE-Cloud, since their corresponding configurations can differ. Note that if a berm is installed, there is also a toe installed on this berm, as can be seen on Figure 6. This toe has the same configuration as the toe near the sea bottom.

The applied toe materials are mainly a function of the water depth d and the design wave height H_s. For very shallow water ($d \le 1{,}5 \cdot H_s$), it is recommended to use the armour units as toe material as can be seen on Figure 36. For the other water conditions, the user can design rocks, concrete cubes or the armour units.
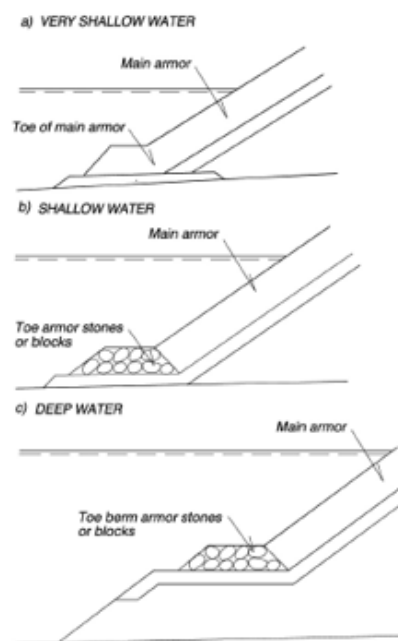
Figure 36: Toe configurations (CEM)

Note that it is assumed that the slope of the sides of the toe are the same as the slope of the armour layer. In case of a berm, two toes are installed at the seaside: one at the sea bottom and one on the berm.

3.7.2. General input

In order to execute an appropriate design for the different toes, two parameters need to be inserted as general input. The first parameter expresses the allowable damage N_{od} of the armour layer. This is defined as the number of units which are displaced out of the armour within a strip width of D_{n50}. General values for N_{od} are:

$$N_{od} = \begin{cases} 0,5 - No\ damage \\ 2 - Acceptable\ damage \\ 4 - Severe\ damage \end{cases}$$ (80)

The second parameter describes the width of the toe in amount of units b_{toe}. A recommended value for this parameter is 3 to 5. For the assessment of the height of the toe, two layers of materials are assumed.

In the general input, the CE-Cloud determines whether the water is very shallow, shallow, intermediate or deep. If the water is very shallow, the user is guided to click on the "Select armour units"-button. Automatically the CE-cloud will generate an appropriate toe design consisting of armour layer units.

If the water is not very shallow, the user can proceed with the assessment of rocks or concrete cubes as toe material by use of the design formulas provided in the Coastal Engineering Manual.

The general input is of course also available for the design of the toe at the leeside. The user can however directly select the same toe as at the seaside by clicking on the "Select same toe"-button.

3.7.3. Calculation of toe materials

The Coastal Engineering Manual provides two different approaches for the design of toes: Van der Meer, d'Angremond and Gerding (1995) for rocks and Burcharth et al. (1995a) for rocks or concrete cubes. It is also possible in the CE-cloud to select the first or second filter layer material as toe material.

Van der Meer, d'Angremond and Gerding (1995)

Van der Meer, d'Angremond and Gerding formulated an expression for the stability of a toe berm consisting of two layers of rocks with a density $\rho_s = 2,68 \frac{t}{m^3}$. The expression is valid for irregular, head-on waves:

$$\frac{H_s}{\Delta \cdot D_{n50}} = \left(0,24 \cdot \frac{h_b}{D_{n50}} + 1,6\right) \cdot N_{od}^{0,15}$$ (81)

With:

- h_b [m]: Water depth at the top of the toe berm. Since the height of the toe is not yet determined, this parameter can be substituted by:

$$h_b = \begin{cases} d - 2 \cdot D_{n50}; No\ berm \\ d_B - 2 \cdot D_{n50}; With\ a\ berm \end{cases}$$ (82)

- d_B [-]: The distance from the berm to the SWL, in case a berm is installed on the breakwater.

In equation (82) D_{n50} can be found at both sides of the expression. This formula can subsequently be rewritten in function of D_{n50}:

$$D_{n50} = \begin{cases} \dfrac{\dfrac{H_s}{\Delta} - 0{,}24 \cdot d \cdot N_{od}^{0,15}}{1{,}12 \cdot N_{od}^{0,15}} \; ; No \; berm \\[4ex] \dfrac{\dfrac{H_s}{\Delta} - 0{,}24 \cdot d_B \cdot N_{od}^{0,15}}{1{,}12 \cdot N_{od}^{0,15}} \; ; With \; a \; berm \end{cases} \tag{83}$$

Equation (83) is only valid for the following ranges:

$$0{,}4 < \frac{h_b}{d \; or \; d_B} < 0{,}9$$

$$0{,}28 < \frac{H_s}{d \; or \; d_B} < 0{,}8$$

$$3 < \frac{h_b}{D_{n50}} < 25$$

If the toe design does not meet all three above-mentioned requirements, the CE-Cloud will return a "N/A"-value.

Once the value of D_{n50} is determined, M_{50} can easily be calculated by use of equation (26). Since equation (83) considers rocks, the CE-Cloud automatically generates the appropriate rock grading by use of the standard Rosin-Rammler (1993) curves which were previously used to define the filter layers and core material in section 3.5.3. The CE-Cloud will also automatically detect if the proposed grading has already been used in the previously designed layers, resulting in an economic design.

Once the value for D_{n50} have been determined, the user can select this value as final output by clicking on the "Select rocks"-button.

Burcharth et al. (1995a)
Burcharth et al. formulated a stability formula for two layers of rocks or parallelepiped concrete blocks as toe material. The formula states:

$$\frac{H_s}{\Delta \cdot D_{n50}} = \left(0{,}4 \cdot \frac{h_b}{\Delta \cdot D_{n50}} + 1{,}6 \right) \cdot N_{od}^{0,15} \tag{84}$$

Equation (84) can subsequently be rewritten in function of D_{n50}, taking into account equation (82):

$$D_{n50} = \begin{cases} \dfrac{H_s - 0{,}4 \cdot d \cdot N_{od}^{0,15}}{N_{od}^{0.15} \cdot (1{,}6 \cdot \Delta - 0{,}8)} \; ; No \; berm \\[4ex] \dfrac{H_s - 0{,}4 \cdot d_B \cdot N_{od}^{0,15}}{N_{od}^{0.15} \cdot (1{,}6 \cdot \Delta - 0{,}8)} \; ; With \; a \; berm \end{cases} \tag{85}$$

For the upper formula, the density of the rocks or concrete ρ_s needs to be defined by the user as specific input. There are no restrictions mentioned for applying equation (85), but in certain cases the result becomes negative which yields a "N/A"-value in the CE-Cloud. Once D_{n50} has been calculated, M_{50} and the corresponding rock grading are subsequently generated in the CE-Cloud. Note that the above-mentioned equation (85) is valid for rocks and concrete blocks. The user can select which material needs to be installed, by clicking on the corresponding "Select"-button.

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Manual selection

It is of course more profitable to use materials which are already used in other parts of the breakwater as toe material. Therefore the CE-Cloud detects whether the proposed gradings from equation (83) and (85) have already been used. If this is not the case, the user can manually select one of the previously designed filter materials to be installed in the toe by clicking on the corresponding "Select as toe material"-button.

3.7.4. Final output

The final output simply gathers all the characteristics of the toe material and its geometrics. An example of such an output is given in Figure 37 below:

Material	Rocks	[-]	Type of unit
Grading	300 - 1000	kg	Grading of the units
D_n50	0,68	m	Equivalent cube length of median rock
M_50	716	kg	Median rock weight
ρ_s	2,3	t/m³	Density of the units
H	1,36	m	Height of the toe
B	2,04	m	Width of the toe
Slope	1:1,5	[-]	Slope of the toe (same as for the armour layer)

Figure 37: Final output of the toe design (CE-Cloud)

Note that the design is done at the sea- and at the leeside. It is also possible to select the same toe at both sides by clicking on the "Select same toe"-button.

3.8. Roundhead assessment

3.8.1. Introduction

The stability of units on a head-section is significantly smaller than on a trunk section, if the same units are considered. This is mainly due to the high cone-overflow velocities at the head which could be enhanced by wave refraction. Another reason for this stability reduction is the reduced support from neighbouring units in the direction of wave overflow on the leeside of the cone. Since the flow conditions are very complex near the roundhead, only empirical approaches, resulting from hydraulic model tests, are available to express the stability of the roundhead units. Two formulas are known for either rocks/dolos and tetrapods/tribars. It is up to the user to design and select one of these four units. By selecting one of these units, the CE-Cloud will automatically generate the design characteristics.

Note that these heavier armour units are only installed on a specific section of the roundhead which is indicated in Figure 38.
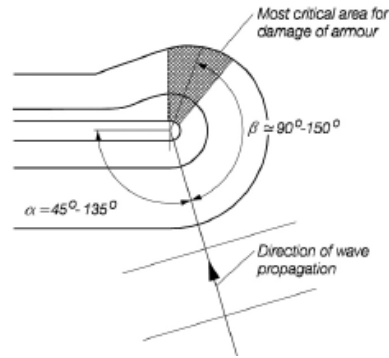
Figure 38: Roundhead armour configuration (CEM)

3.8.2. General input

Since a lot of variables are already defined, only one parameter needs to be inserted by the user: the roundhead slope α_{rhead}. In a lot of cases the same armour units are used in the roundhead as for the trunk sections, but applied in a milder slope to increase stability. The default value for α_{rhead} is set equal to the slope angle of the trunk section at the leeside. The user is however free to change this value.

3.8.3. Roundhead stability calculation

Two design methods are mentioned in the CEM and are implemented in the CE-Cloud: Carver and Heimbagh (1989) and Hudson (1974). The first approach considers dolos and rocks, the second considers tetrapods and tribars.

Dolos and rocks

Carver and Heimbaugh (1989) formulated an expression for the rock or dolos stability at a head-section. This formula is however only applicable for monochromatic waves, which is not a realistic representation of the real incoming waves. It is up to the user to keep this in mind when installing dolos or rocks. The formula is given by equation (86) below:

$$\frac{H}{\Delta \cdot D_{n50}} = A \cdot \xi^2 + B \cdot \xi + C_c$$

(86)

With A, B and C_c dimensionless coefficients which are a function of the slope angle and the surf-similarity index ξ_m, calculated with equation (27). The coefficients A, B and C_c can be found in Table 15 below:

Table 15: Coefficients A, B and C_c (Carver and Heimbaugh, 1989)

Armor Type	A	B	C_c	Slope	Range of ξ
Stone	0.272	-1.749	4.179	1V to 1.5H	2.1 – 4.1
Stone	0.198	-1.234	3.289	1V to 2.0H	1.8 – 3.4
Dolos	0.406	-2.800	6.881	1V to 1.5H	2.2 – 4.4
Dolos	0.840	-4.466	8.244	1V to 2.0H	1.7 – 3.2

Equation (86) is only valid for a certain range of slopes and surf-similarity indices as can be seen on Table 15. As a simplification, there is no restriction implemented considering the used slope. If the slope is closest to 1:1,5; the first and third row of Table 15 are considered for stones and dolos respectively. The second and fourth row are considered if the slope is closest to 1:2. If the surf-

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similarity index ξ_m is however not within the defined range, the CE-Cloud will yield a "N/A"-value as result.

Tetrapods and tribars

For the stability of tetrapods and tribars on a roundhead slope, the CEM provides the general Hudson equation (23). The values of the stability coefficient K_D are depending on whether the waves are breaking or not and the slope angle of the roundhead α_{rhead}. The different values for K_D can be found in Table 16 below:

Table 16: Stability coefficients for tetrapods and tribars on the roundhead (CEM)

Armor Unit	Placement	Layers	Breaking Waves[1]	Nonbreaking Waves[2]	Slope Angle cot α
Tetrapod	Ramdom	2	5.0[3]	6.0	1.5
			4.5	5.5	2.0
			3.5	4.0	3.0
Tribar	Random	2	8.3	9.0	1.5
			7.8	8.5	2.0
			6.0	6.5	3.0
Tribar	Pattern	1	7.5	9.5	(not given)

[1] Depth-limited breaking with waves breaking in front of and on the armor slope.
[2] No depth-limited breaking occurs in front of the armor slope.
[3] K_D values shown in italics are unsupported by tests results and are provided only for preliminary design purposes.

If the considered slope of the roundhead is not present in Table 16, the value of K_D for the closest slope is selected. Consequently, this approach will always yield a result. Note that only random placement is considered, which implicitly means that the roundhead consists of two layers.

3.8.4. Final output

As already mentioned, the CE-Cloud can generate the full roundhead design once the slope angle α_{rhead} is defined. By selecting one of the four armour units (rocks, dolos, tetrapods or tribars), the final roundhead characteristics are generated in a final table. The thickness of the roundhead armour layer is automatically calculated by use of equation (77). An example of such a final output is shown in Figure 39 below:

Armour units	Tribar	[-]	Type of armour units
D_n50	1	m	Diameter of median rock size
M_50	2,6	t	Median unit weight
r	2,04	m	Thickness of the armour layer

Figure 39: Roundhead output example (CE-Cloud)

3.9. Cost analysis

3.9.1. Introduction

In the CE-Cloud, a thorough cost breakdown of the breakwater can be generated and visualized. In order to determine these costs, a cost list is available which can easily be accessed and adjusted to the user's preferences by clicking on the "Cost list"-button. This list gathers the different costs per volume/weight or kilometer of several materials. This cost list, and subsequently the cost breakdown, is approached in two different ways. First, there is the breakdown in function of the production, transport and construction costs, which are called the process steps. Secondly, the costs are split up in

function of the breakwater materials: armour units, filter and core material, etc. Consequently, a clear cost overview is generated in the CE-Cloud in function of the process steps and used materials.

Note that the cost calculation is very site-specific. It is up to the user to insert realistic values for the different costs of the used materials in function of the process steps. The default values in the cost list are adopted from Tutuarima and d' Angremond (1998). The same cost list will be used for the cost analysis of the caisson breakwater, which is discussed in section 4.10.

3.9.2. Generating the cost breakdown

For the calculation of the different costs in function of the process steps and used materials, the user needs to insert two types of general input parameters. The first type consists of the distances over which the different breakwater materials are transported. This will consequently be used to calculate the transport costs. The second type of input consists of the porosity of the different materials. This needs to be taken into account for the calculation of the total amount of materials which are needed to construct the breakwater. See Table 13 for several standard porosity values for different materials.

First the production, transport and construction costs in function of each of the materials are calculated. The breakwater is consequently split up in several parts, as can be seen on Figure 6:

- Armour units at the seaside
- Armour units at the leeside
- Armour units in the crest
- First filter layer
- Second filter layer
- Core material
- Toe material at the seaside
- Toe material at the leeside
- Roundhead material

Subsequently, these costs can be added up per material, to calculate the total cost for a certain material.

Production costs

Since the total geometry of the breakwater is determined, the CE-Cloud can automatically calculate the total volume and weight of the different materials per meter breakwater. Note that the inserted porosities are taken into account for the calculation of the total weight per meter of a particular material. The production cost of a certain material per meter breakwater is calculated by multiplying the amount of used material [t or m³] with the corresponding production cost [€/t or €/m³] from the cost list. By adding all these costs for the different materials (except for the roundhead), a total production cost per meter trunk section is found. By replacing the cost of the leeside armour units with the cost of the roundhead material, the total production cost per meter head section is generated. As such, a cost per meter trunk and head section is available in the CE-Cloud. Note that the head section is round and can not really be expressed per meter.

Transport costs

At the top of the cost sheet, the transport distances for the different materials need to be inserted by the user as general input. For each of these materials, the transport cost is calculated by use of the

cost list. Analogous to the production cost, a total transport cost per meter trunk and head section is calculated.

Dependent on the project, the transport cost for the armour units can be very high. Therefore, it could be more profitable to install a concrete production line near the breakwater site. As a result, the production costs will decrease significantly, but the production costs will increase. It is up to the user to make a proper decision and change the cost list accordingly.

Construction costs
The construction costs per meter breakwater are calculated in a similar way as for the other process steps. Here it is however assumed that the construction cost for the trunk and head section are the same.

Material costs
At this point the cost breakdown is generated in function of the different process steps (production, transport and construction). By adding up all these costs for the same materials, the total cost for each of the materials is determined. Consequently, the user can easily find the most expensive features within the considered breakwater design.

3.9.3. Final output
First the cost breakdown is determined in function of the different process steps. Subsequently the total production, transport and construction cost per meter trunk or head section is generated. Secondly, the different costs for each of the used materials are calculated by adding the costs of the different process step costs per material. Of course a total cost per meter trunk and head section is calculated by adding all the costs.

The CE-Cloud generates two column diagrams which visualize each of the cost breakdown approaches. In the first graph the total costs of the armour units, first and second filter layer and core material are shown. Since the costs of the other materials (toe and bedprotection) are almost negligible compared to the above-mentioned materials, they are not shown in this graph. It can automatically be assumed that the core and armour materials will be the most expensive materials within the design. An example of such a column diagram is shown in Figure 40 below:
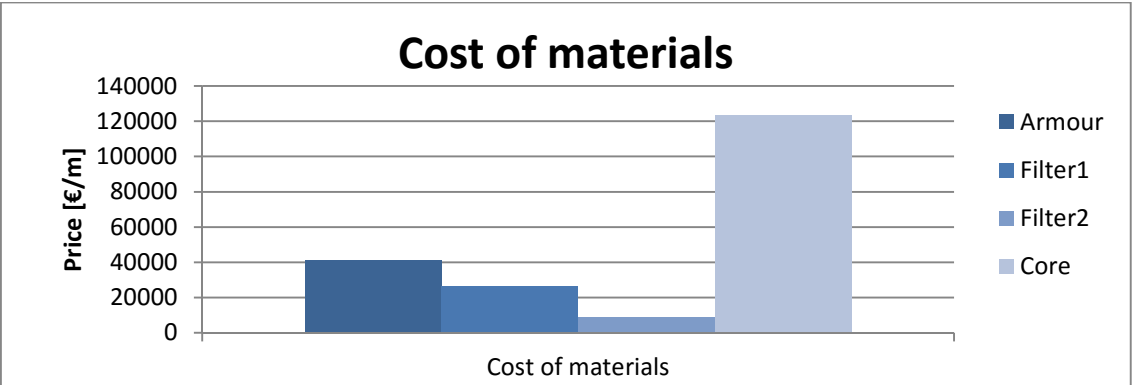
Figure 40: Material cost breakdown graph (CE-Cloud)

In a second column diagram, the costs of each process step is visualized. This could be helpful to decide whether a concrete production line near the breakwater could be profitable or not. An example of such a graph is shown in Figure 41 below:
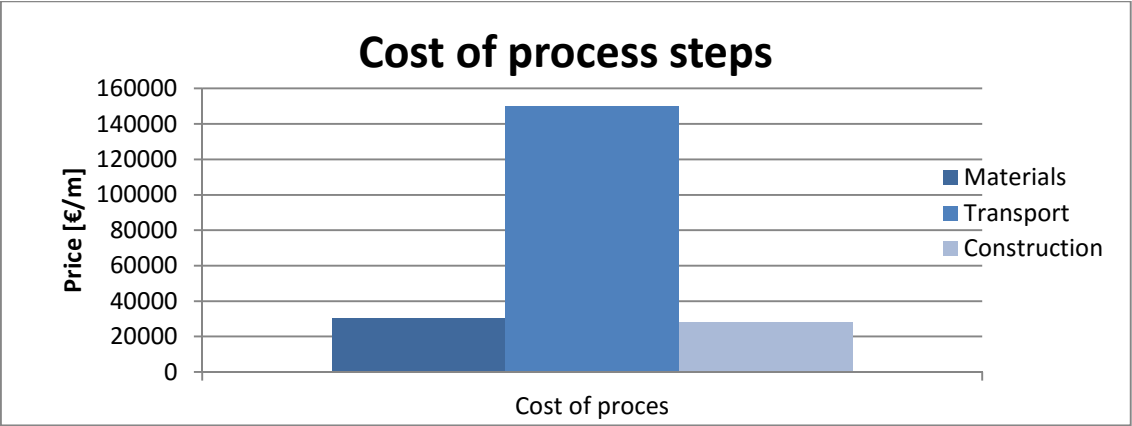
Figure 41: Process steps cost breakdown graph (CE-Cloud)

3.10. Final design

3.10.1. Introduction

Once the cost assessment is finished, all aspects of the breakwater are generated. Subsequently the final design sheet is created which gathers all the most important information in one, easily printable design sheet. For the design of the caisson breakwater a similar sheet will be created in order to easily compare both designs.

3.10.2. Content of the final design sheet

The final design sheet consists of four main sections: hydraulic boundaries, layer information, dimensioning and the cost breakdown.

The hydraulic boundaries provide the main information about the design sea state. This gives the engineer a general idea of the environmental design parameters for this particular design. An example of the hydraulic boundaries output is given in Figure 42 below:

Hydraulic Boundaries						
ρ_w	1,025	t/m³				
d	15	m				
Seaside				Leeside		
H_s	3	m		H_s	1,2	m
T_p	9	s		T_p	7	s
s_m	0,0426	[-]		s_m	0,0254	[-]

Figure 42: Example of the hydraulic boundaries in the final design sheet (CE-Cloud)

In the next step, the layer information is gathered. This section is split into seven breakwater elements:

- Armour layer units (sea- & leeside)
- First filter layer
- Second filter layer
- Core material
- Bedprotection
- Toe material (sea- & leeside)
- Roundhead units

For each of these elements, the following characteristics are automatically generated:

- Type of units
- Grading or specifications
- Placement method
- ρ_s [t/m³]: Density of the material
- D_{n50} [m]: Median size of the equivalent cube
- M_{50} [kg]: Weight corresponding to the equivalent cube
- r [m]: The thickness of the layer
- V_{tot}/m [m³/m]: The total volume of the used material per meter breakwater
- M_{tot}/m [t/m]: The total mass of the used material per meter breakwater
- €/m: The total cost of the material per meter breakwater

Thanks to this design window, the engineer has a clear overview of each of the used materials with their corresponding properties and costs. An example of such an output can be seen on Figure 43 below.

Layer information												
	Armour		Filter 1		Filter 2		Core	Bedprotection	Toe		Round-head	Units
	Sea	Lee	Sea	Lee	Sea	Lee			Sea	Lee		
Type	Rocks	Rocks	Rocks	Rocks	Rocks	Rocks	Rocks	Sand	Rocks	Rocks	Rocks	[-]
Grading	Smooth & rounded	nooth & rounded	300 - 1000	300 - 1000	5 - 40	5 - 40	45/125	/	300 - 1000	N/A	/	kg
Placement	Randomly	Randomly	/	/	/	/	/	/	/	/	/	[-]
ρ_s	2,6	2,6	2,3	2,3	2,3	2,3	2,3	1,6	2,3	2,3	2,6	t/m³
D_n50	1,27	1,27	0,68	0,68	0,24	0,24	0,11	/	0,68	0,68	1,42	m
M_50	5,33	5,33	716	716	32	32	3,23	/	716	716	7,44	kg/t
r	2,59	2,54	1,36	1,36	0,48	0,48		0,5	1,36	1,36	2,84	m
V_tot/m	51,74	19,98	76,31		26,19		348,59	34,25	2,49	2,5	47,21	m³/m
M_tot/m	134,52	51,95	175,51		60,24		801,76	54,8	5,73	5,75	122,75	kg/t/m
€/m	41127,34		26563,1		8815,95		17638,7	0	1187,87		202737	€/m

Figure 43: Example of layer information in the final design sheet (CE-Cloud)

In the third section, several dimensional parameters are gathered. This dimensional window presents the total width and height of the breakwater, considering a mean overtopping discharge q. This feature also informs the engineer whether a berm is installed or not. If there is a berm installed, it presents the width B and the height of the berm with respect to the SWL d_b (positive downwards). A button which reads "Draw the breakwater" has also been installed. It will open a new sheet to visualize the breakwater in AutoCAD as will be explained further in section 3.10.3. An example of the dimensioning window is shown in Figure 44 below:

Dimensioning							
q	0,01	m³/s/m	Berm?	Yes			
R_c	8,65	m	d_b	6	m	Draw the breakwater	This button will redirect you to the sheet
h_tot	23,65	m	B	6	m		which can generate an Autocad drawing
B_tot	88,43	m					

Figure 44: Example of the dimensioning in the final design sheet (CE-Cloud)

In the last section, a general overview of the different costs is given with the same two column diagrams which were generated in the "Cost assessment"-sheet. The total cost of the breakwater per meter trunk and head section is also mentioned, as can be seen on Figure 45 below:
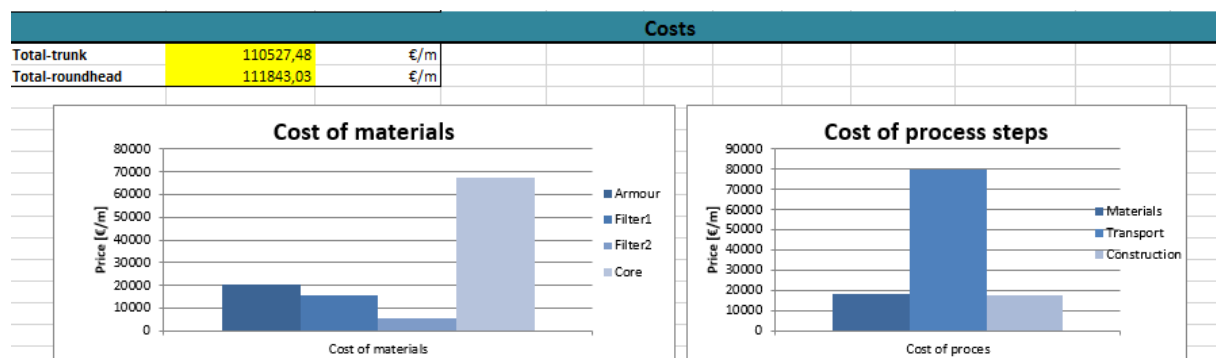
Figure 45: Example of the cost breakdown in the final design sheet (CE-Cloud)

At the bottom of the final design sheet, several buttons have been implemented to select the designed breakwater as a final cross-section of the whole breakwater. This will thoroughly be explained in section 5 . By clicking on the "Set as 1st breakwater"-button, the user can select the designed breakwater cross-section as the first section of a bigger breakwater which consists of multiple different cross-sections over its length. In this window, there is also a button implemented which will redirect the user to the final design sheet of the caisson breakwater. As such, the user can easily compare both final design sheets.

3.10.3. Drawing the breakwater

It is the intention of the CE-Cloud to be as clear and user-friendly as possible. Therefore, the user can automatically open the designed cross-section in AutoCAD. This is done by use of an extension in VBA which recognizes AutoCAD codes. To be able to use this feature, the following requirements should be met:

- AutoCAD xxxx, (xxxx is a year) is installed on the user's computer. (Make sure that the license is not expired). For students, the necessary software is freely available on the website of AutoCAD (http://www.autodesk.com/education/free-software/autocad).
- AutoCAD xxxx library is activated within VBA. If this is not the case, follow the next steps:
  - Press ALT + F11 to open the Visual Basic Editor
  - Click on Tools > References > AutoCAD xxxx Type Library for the English version
  - Or Click on Extra > Verwijzingen > AutoCAD xxxx Type Library for the Dutch version

Once this has been done, the engineer is able to use the drawing tool. By clicking on the "Draw the breakwater"-button in the final design sheet, the user is redirected to a new sheet on which all the breakwater coordinates are generated. The origin of the reference system lies in the lower left corner of the bedprotection, with the x-axis and y-axis being the horizontal and vertical axis respectively. Note that it does not matter whether a berm is installed or not, the CE-Cloud will automatically detect this and yield the corresponding coordinates. Now the user needs to click on the "Draw in AutoCAD"-button. The CE-Cloud will automatically open AutoCAD and draw a polyline through all the generated coordinates. These coordinates are imported in AutoCAD in such a sequence that the drawing is made with one single polyline.

Note that the generated drawing only gives a general sketch of the cross-section of the designed breakwater. To modify the proposed sketch, the user should first select the whole breakwater and explode the polyline. Subsequently hatches and dimensions can be added by the user. Note that it is assumed that the user has a background knowledge of AutoCAD to modify the conceptual sketch.

3.10.4. Write to notepad

If AutoCAD is not available, the user can save the generated coordinates in a textfile by clicking on the "Write to notepad"-button. The file will then be saved on the following location: "C:\Users\Username\Documents\coordinates.txt". Note that if the user wants to design and save multiple cross-sections, this file will be overwritten each time the button is selected. Therefore, it is recommended to save the coordinate file under another name each time it is generated.

4. Design and analysis of a caisson breakwater with the CE-Cloud

4.1. Introduction

A caisson breakwater consists of a concrete caisson, filled with sand, which is founded on a rubble-mound foundation. This type of breakwater mainly transfers the incoming energy by three different processes: wave reflection, wave breaking and energy transmission by overtopping. An example of a caisson breakwater configuration is shown in Figure 46 below:

1: SWL (seaside)
2: SWL+H_s/2 (seaside)
3: SWL (leeside)
4: Armour layer
5: First filter layer

6: Core
7: Geotextile+bedprotection
8: Foot protection blocks
9: Bedding layer
10: Caisson
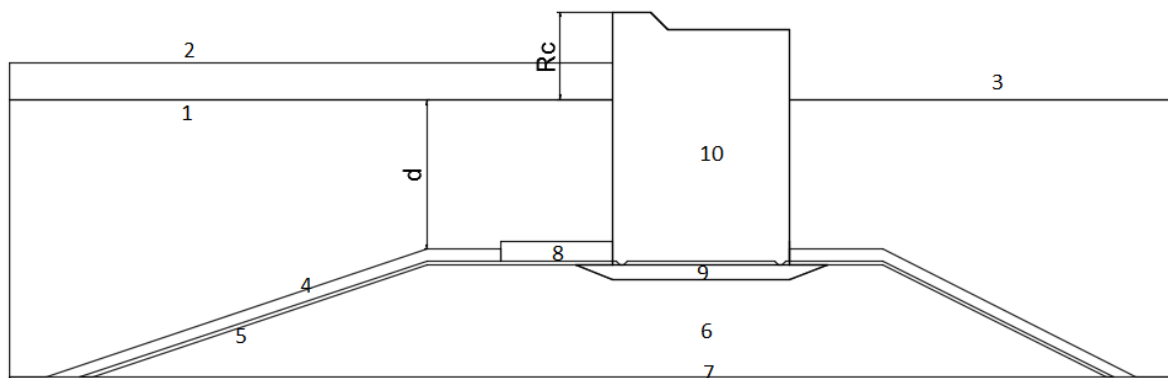
Figure 46: Caisson breakwater configuration (CE-Cloud)

To start designing the caisson breakwater, its hydraulic boundary conditions are defined to get a clear overview of the incoming energy. This is done in a similar manner as for the rubble-mound breakwater. In a next design step the water depth d at the toe of the caisson is determined by defining a possible range of values for which certain design criteria are fulfilled. Subsequently it is up to the user to insert a final value for d, based on the provided range. As such, the height of the foundation is implicitly calculated.

In the next design step, a value for the total height of the caisson is determined by calculating the necessary crest freeboard R_c, based on the mean overtopping discharge q which needs to be defined by the user. This crest freeboard for a caisson breakwater will generally be much larger than the crest freeboard for a rubble-mound breakwater, since the roughness of the armour layer units of the latter will significantly reduce the overtopping discharge. The user can additionally insert a concrete reduction factor to define the configuration of the top cap, as will be explained in section 4.4.5.

As the hydraulic boundary conditions and several geometric parameters have been determined, the pressures on the caisson can be calculated by use of two different approaches: Sainflou (1928) or Goda (1974). The latter is assumed to give the most realistic results. Subsequently, the forces and moments per meter, acting on the caisson, are calculated. Since the width of the caisson B is still parametric at this stage, these forces and moments are expressed in function of B.

This structure needs a well-designed foundation consisting of an armour layer, a filter layer, core material, bedprotection and concrete foot protection blocks. First, the stability of the armour layer units is checked by use of two approaches. Note that only rocks can be designed as armour units in the CE-Cloud. This is a realistic assumption since the wave forces near the foundation are very low. Once these units have been designed, the filter and core materials can be determined, based on several filter criteria. Subsequently, the foot protection blocks are generated in the CE-Cloud according to Japanese practice. These blocks need to prevent erosion near the toes of the caisson.

As soon as the foundation has been designed, the width of the caisson can be determined, based on three different safety requirements, corresponding to three failure modes. The first failure mode consists of sliding of the caisson, which is a function of its weight and the friction factor between the caisson and its foundation. For the latter, a design of the levelling method is made first. The second mode consists of overturning the caisson. The last mode is foundation-related and expresses that there is not enough bearing capacity to install the caisson.

Once all previous steps have been finished, the caisson breakwater is fully designed. The CE-Cloud subsequently provides a clear cost overview of the different process steps and materials.

Finally, a final design sheet is generated, similar to the rubble-mound breakwater design. As such, the user can easily compare both designs and make a thought-through decision between both. The CE-Cloud can also automatically generate the caisson breakwater in AutoCAD or save its coordinates in a textfile. Each of the different design steps for the assessment of the caisson breakwater which are executed in the CE-Cloud are clearly indicated on Figure 47.

Figure 47: Design steps for the caisson breakwater

4.2. Hydraulic boundary conditions

Analogous to the design of a rubble-mound breakwater, the hydraulic boundary conditions need to be properly defined. These conditions can be inserted in four different ways: the manual input, the Pierson-Moskowitz spectrum, the JONSWAP spectrum and an imported data file. The considered design sheet is practically the same as the corresponding sheet for the rubble-mound breakwater, discussed in section 3.2. There is however no need to define the leeside hydraulic boundary conditions since the waves at this side are assumed to be very moderate.

Note that the water depth next to the foundation is denoted as h_s. In comparison to the rubble-mound breakwater where this parameter is denoted as d.

4.3. Design water depth at the toe of the caisson

4.3.1. Introduction

The design water depth at the toe of the caisson d is defined as the water depth just next to the caisson, as is indicated on Figure 48. It is not the same as the water depth next to the foundation h_s which has already been defined by the user on the previous sheet considering the hydraulic boundary conditions. Note that the definition of the parameter d for the caisson approach differs from its definition for the rubble-mound approach.
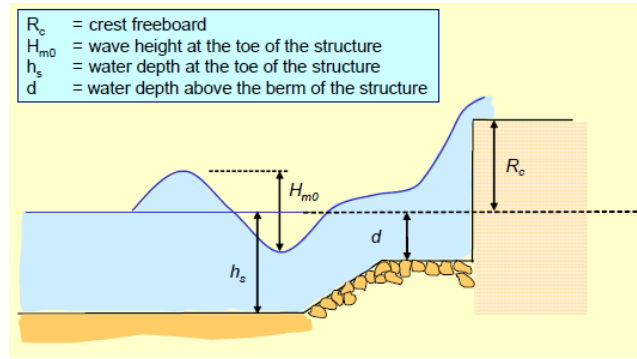
Figure 48: Design water depth at the toe of the caisson definition (EurOtop)

4.3.2. Calculation of the design water depth at the toe of the caisson

Several criteria are considered to select an appropriate value for the design water depth at the caisson d. The CE-Cloud uses these criteria to provide the user with a range of possible values for d. Subsequently, it is up to the user to insert a final design value, based on the provided range.

The first criterion expresses the need of the design ship to berth in low water conditions. This is to prevent the hull from touching the rubble-mound foundation. Note that it is also possible to prohibit ships from mooring in low water conditions. To express this criterion, the draught T of the design ship and the minimal ratio of the design water depth at the caisson with respect to this draught $(d/T)_{min}$ need to be inserted by the user. The default value of the latter parameter is 1,15. Note that this ratio considers the design water depth at the toe of the caisson d, and not the lowest water level, which should be more correct. Since it is not possible to implement the latter water level in the CE-Cloud, the user should take this into account by implementing a conservative value for $(d/T)_{min}$.

By multiplying $(d/T)_{min}$ with the actual draught T of the design ship, a lower limit for the design water depth at the caisson is found.

$$d \geq \left(\frac{d}{T}\right)_{min} \cdot T$$

The second criterion prevents large wave forces from acting on the rubble-mound foundation. The design water depth at the caisson should consequently be higher than half of the total water depth h_s:

$$d \geq \frac{h_s}{2}$$

The third criterion considers the impulsiveness of the incoming waves. Since the foundation influences the flow conditions near the caisson, it can cause the waves to break on the caisson. This phenomenon must to be avoided at all times since it results in a very expensive and conservative design. Forces of impulsive waves can be significantly larger than non-impulsive waves. The EurOtop Manual defines the impulsiveness parameter d_* to express this wave behavior:

$$d_* = 1,35 \cdot \frac{d}{H_{m0}} \cdot \frac{2\pi \cdot h_s}{g \cdot T_{m-1,0}^2} \tag{87}$$

If $d_* > 0,3$; the waves are non-impulsive. Therefore, equation (87) can be rewritten as a lower limit for the design water depth at the caisson d:

$$d > \frac{0.3}{1.35} \cdot \frac{H_{m0} \cdot g \cdot T_{m-1,0}^2}{2\pi \cdot h_s} \tag{88}$$

The fourth and last criterion states that the rubble-mound foundation should be sufficiently thick to efficiently spread the loads of the caisson's selfweight. The foundation height is the same as the design water depth at the caisson d substracted from the total water depth h_s. A minimal value for the foundation height $(h_s\text{-}d)_{min}$ needs to be inserted by the user as general input. Note that the total mass of the caisson is not yet determined, therefore, the user should insert an estimated value for $(h_s\text{-}d)_{min}$. This consequently yields an upper value for d:

$$d \leq h_s - (h_s - d)_{min}$$

Once all four criteria (three lower and one upper value for d) have been determined, the CE-Cloud generates a range of values for d which fit all criteria, if possible. An example of such an output can be seen on Figure 49. Now it is up to the user to insert a final value for the design water depth at the caisson, taking into account the generated range. It could be possible that there is no possible range which fits all four criteria. In that case it is up to the user to insert an appropriate design water depth at the toe of the caisson which fits certain criteria.

Lower limits of d				Upper limits of d		
1. Draught design ship	5,75	m		4. Min RM thickness	13,5	m
2. Waves on RM	7,5	m				
3. Non-impulsive cond	7,9	m				
		7,9	<= d <=	13,5		

Figure 49: Design water depth at the toe of the caisson selection (CE-Cloud)

4.4. Crest freeboard

4.4.1. Introduction

For the assessment of the crest freeboard, a similar approach as for the rubble-mound breakwater is considered. The crest freeboard is calculated in function of the mean allowable overtopping discharge per meter q [m³/s/m], taking into account an estimated reduction factor for the crest width C_r. The calculations can be split up in two main sections: formulas coming from the EurOtop Manual and formulas coming from the Coastal Engineering Manual. The calculations considering the EurOtop Manual are subsequently split up in a deterministic and a probabilistic approach for impulsive and non-impulsive wave conditions. Additionally, an expression regarding oblique wave attack is available in the CE-Cloud. The CEM, on the other hand, only provides one design approach: Franco and Franco (1999).

Once the crest freeboard has been selected, the user can insert a concrete top cap reduction factor δ_{red} to save concrete by defining a certain top cap configuration, which will be explained in more detail in section 4.4.5.

4.4.2. General input

Two parameters need to be inserted as general input: the mean overtopping discharge q [m³/s/m] and an overtopping reduction factor C_r [-] for the crest width. An appropriate value for the discharge q can be selected by use of Figure 23. Note that the allowable overtopping for the caisson breakwater is generally less than for the rubble-mound breakwater since damage to ships that are moored to the

leeside should be prevented. Similar to the rubble-mound approach, the experienced user can insert an estimated value for the overtopping reduction factor due to the crest width C_r. If the user does not have any experience with this parameter, its value should be kept equal to unity.

4.4.3. EurOtop Manual

In the EurOtop Manual, multiple design formulas are available to express the overtopping of several different vertical breakwater configurations. In the CE-Cloud a deterministic and a probabilistic approach are available for two types of incoming waves: impulsive and non-impulsive waves. Note that in most cases the waves are non-impulsive due to the selection of the design water depth at the toe of the caisson d, as was discussed in section 4.3.2.

For non-impulsive wave conditions, the rubble-mound foundation has negligible influence on the wave characteristics. Therefore, the deterministic and probabilistic formulas considering plain vertical walls can be used in this case. Additionally, a formula considering oblique wave attack is implemented in the CE-Cloud.

For impulsive wave conditions, the CE-Cloud provides a deterministic and a probabilistic approach for a composite vertical wall. The influence of the rubble-mound foundation on the wave characteristics can not be disregarded in this case.

The previously mentioned impulsiveness parameter d_*, given in equation (87), is applicable for composite vertical walls. There is however a variant for plain vertical walls: h_*. The latter parameter can be calculated as:

$$h_* = 1{,}35 \cdot \frac{1}{H_{m0}} \cdot \frac{2\pi \cdot h_s^2}{g \cdot T_{m-1,0}^2} \tag{89}$$

Note that d_* is considered to define whether the waves are impulsive or not.

Non-impulsive waves: deterministic design

The first available formula considering overtopping in the CE-Cloud is the deterministic approach for plain vertical walls. This formula is expressed below:

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0{,}04 \cdot exp\left(-1{,}8 \cdot \frac{R_c}{H_{m0}}\right) \tag{90}$$

Equation (90) is only valid for the following range:

$$0{,}1 \leq \frac{R_c}{H_{m0}} \leq 3{,}5$$

If the ratio of R_c and H_{m0} is not within the defined range, the CE-Cloud will yield a "N/A"-value. The crest freeboard R_c can consequently be isolated as follows:

$$R_c = ln\left(\frac{q}{0{,}04 \cdot \sqrt{g \cdot H_{m0}^3}}\right) \cdot \left(\frac{-H_{m0}}{1{,}8}\right) \tag{91}$$

Non-impulsive waves: probabilistic design

The second formula which is available in the CE-Cloud, is the probabilistic approach for plain vertical walls. The overtopping can be expressed similarly to the deterministic design:

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0{,}04 \cdot exp\left(-2{,}6 \cdot \frac{R_c}{H_{m0}}\right)$$

(92)

Equation (92) is only valid for the following range:

$$0{,}1 \leq \frac{R_c}{H_{m0}} \leq 3{,}5$$

If the ratio of R_c and H_{m0} does not meet the above-mentioned requirement, the CE-Cloud will return a "N/A"-value. The crest freeboard R_c can subsequently be expressed as:

$$R_c = ln\left(\frac{q}{0{,}04 \cdot \sqrt{g \cdot H_{m0}^3}}\right) \cdot \left(\frac{-H_{m0}}{2{,}6}\right)$$

(93)

When comparing equation (91) and (93), it becomes clear that the deterministic and probabilistic design only differ by a ratio of 1,8/2,6. The deterministic approach incorporates a factor of safety of one standard deviation for the overtopping discharge and is therefore more conservative.

Oblique waves

If the waves never reach the breakwater perpendicular to the caisson, the necessary crest freeboard will be smaller than for head-on waves. The above-mentioned deterministic and probabilistic approaches are consequently more conservative since they consider head-on waves. This formula makes use of the general probabilistic design, equation (92), combined with a reduction factor for oblique wave attack γ:

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0{,}04 \cdot exp\left(\frac{-2{,}6 \cdot R_c}{\gamma \cdot H_{m0}}\right)$$

(94)

In which γ is a reduction factor for the angle of wave attack β, given by:

$$\gamma = \begin{cases} 1 - 0{,}0062 \cdot \beta & for\ 0° < \beta < 45° \\ 0{,}72 & for\ \beta \geq 45° \end{cases}$$

(95)

Similar to the other approaches, the crest freeboard can be isolated:

$$R_c = ln\left(\frac{q}{0{,}04 \cdot \sqrt{g \cdot H_{m0}^3}}\right) \cdot \left(\frac{H_{m0} \cdot \gamma}{-2{,}6}\right)$$

(96)

Impulsive waves: deterministic design

For impulsive wave conditions, the deterministic design for composite vertical walls is available in the CE-Cloud and is given by:

$$\frac{q}{d_*^2 \cdot \sqrt{g \cdot h_s^3}} = 7{,}8 \cdot 10^{-4} \cdot \left(d_* \cdot \frac{R_c}{H_{m0}} \right)^{-2,6} \tag{97}$$

The crest freeboard can subsequently be expressed as:

$$R_c = \left[\frac{q}{d_*^2 \cdot \sqrt{g \cdot h_s^3} \cdot 7{,}8 \cdot 10^{-4}} \right]^{-1/2,6} \cdot \frac{H_{m0}}{d_*} \tag{98}$$

The latter formula is only valid for the following ranges:

$$0{,}05 < d_* \cdot \frac{R_c}{H_{m0}} < 1{,}0$$

$$h_* < 0{,}3$$

If the results do not meet the above-mentioned requirements, the CE-Cloud will yield a "N/A"-value.

Impulsive waves: probabilistic design

For the impulsive wave conditions, the probabilistic design for composite vertical walls is available in the CE-Cloud and is given by:

$$\frac{q}{d_*^2 \cdot \sqrt{g \cdot h_s^3}} = 4{,}1 \cdot 10^{-4} \cdot \left(d_* \cdot \frac{R_c}{H_{m0}} \right)^{-2,9} \tag{99}$$

The crest freeboard can subsequently be expressed as:

$$R_c = \left[\frac{q}{d_*^2 \cdot \sqrt{g \cdot h_s^3} \cdot 4{,}1 \cdot 10^{-4}} \right]^{-1/2,9} \cdot \frac{H_{m0}}{d_*} \tag{100}$$

The latter formula is only valid for the following ranges:

$$0{,}05 < d_* \cdot \frac{R_c}{H_{m0}} < 1{,}0$$

$$h_* < 0{,}3$$

If the results do not meet the above-mentioned requirements, the CE-Cloud will yield a "N/A"-value.

4.4.4. Coastal Engineering Manual

Franco and Franco (1999)

The CEM provides an overtopping formula for impermeable and permeable vertical walls in case of non-breaking, oblique, long- and short-crested waves. This formula, derived by Franco and Franco (1999), is given below:

$$\frac{q}{\sqrt{g \cdot H_s^3}} = 0{,}082 \cdot exp\left(-3 \cdot \frac{R_c}{H_s} \cdot \frac{1}{\gamma_\beta \cdot \gamma_s}\right) \tag{101}$$

The crest freeboard can subsequently be expressed as:

$$R_c = ln\left(\frac{q}{0{,}082 \cdot \sqrt{g \cdot H_s^3}}\right) \cdot \left(-\frac{H_s \cdot \gamma_\beta \cdot \gamma_s}{3}\right) \tag{102}$$

In which:

- γ_β [-]: Oblique waves reduction factor, given by:

$$\gamma_\beta = \begin{cases} \begin{cases} cos(\beta) \; for \; 0° \leq \beta \leq 37° \\ 0{,}79 \; for \; \beta > 37° \end{cases}; for \; long-crested \; waves \\ \begin{cases} 0{,}83 \; for \; 0° \leq \beta \leq 20° \\ 0{,}83 \cdot cos(20° - \beta) \; for \; \beta > 20° \end{cases}; for \; short-crested \; waves \end{cases} \tag{103}$$

Since it is assumed that the incoming waves are long-crested, the CE-Cloud only makes use of the upper expression in equation (103).

- γ_s [-]: Reduction factor for the front geometry, values for this parameter can be found in the Table 17 below:

Table 17: Reduction factors for the front geometry of the caisson (CEM)

Front geometry	γ_s
Plain impermeable wall	1.00
Plain impermeable wall with recurved nose	0.78
Perforated front (20% hole area) and deck	0.72 – 0.79
Perforated front (20% hole area) and open deck	0.58

The CE-Cloud only considers impermeable walls, γ_s is consequently set equal to unity.

4.4.5. Configuration of the top cap

Since the design wave height at the leeside is assumed to be much smaller than at the seaside, the caisson does not need to be as high at the leeside as at the seaside. Therefore, the user can define a specific configuration of the top cap by inserting a concrete cap reduction factor δ_{red}. This is the ratio between the area of the concrete that can be saved in the cross-section (indicated in red on Figure 50) and the total area of the rectangular cross-section.
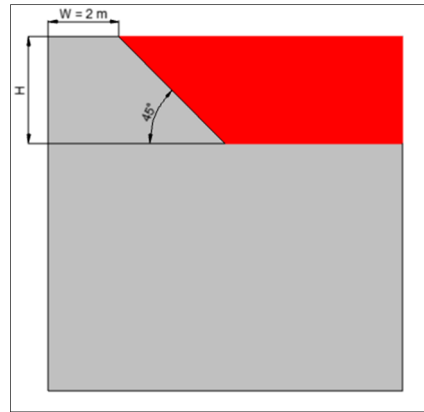
Figure 50: Top cap configuration (CE-Cloud)

The CE-Cloud assumes a width W of 2 m for the toe of the top cap and a leeward slope of 45°, as is shown on Figure 50. Since the total width of the caisson is not known at this stage, it is not possible to fully generate the top cap configuration. The value of x, indicated in Figure 50, will automatically be generated once the total width is designed, explained in section 4.9

4.4.6. Final output

The user can select one of the results of the six above-mentioned approaches as final crest freeboard. When adding the design water depth at the toe of the caisson d to the crest freeboard R_c, the total height of the caisson is found. An additional meter is added to this height to take into account the armour layer, as can be seen on Figure 46.

Finally, the concrete top cap reduction factor δ_{red} is defined. This parameter will be used for the calculation of the total amount of concrete in the caisson and the assessment of the final caisson geometry.

4.5. Pressures on the caisson

4.5.1. Introduction

In the next design step, the pressures acting on the caisson are calculated. They are determined by use of two different approaches: Sainflou (1928) or Goda (1974). These pressures will be very important for determining the different forces acting on the caisson. Since all necessary parameters have already been defined in prior assessments, no general input is required in this section.

4.5.2. Design formulas

As already mentioned, two different methods are available in the CE-Cloud. The first method considers the approach of Sainflou (1928). This approach is based on standing, regular waves acting on the caisson. This gives an indication of the applied pressures, but does not result in realistic values. The second method, the method of Goda (1974), accounts for irregular waves which yield much more realistic values. Consequently, it is advised to use the Goda approach and consider the Sainflou results as theoretical background information.

Sainflou (1928)

Sainflou theoretically derived expressions for the pressures on a vertical wall for the case of regular, standing waves. These pressure formulas are however not valid for depth-limited waves and if there is overtopping. The latter is however kept to a minimum, as was discussed in section 4.4. Figure 51

shows the theoretical pressure distribution on the caisson. Note that no upward pressure is considered in comparison to Goda (1974).
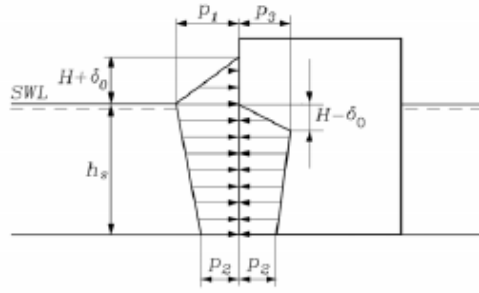
Figure 51: Pressure distribution on the caisson (Sainflou, 1928)

First, the vertical shift in the wave crest and trough δ_0 at the wall is calculated:

$$\delta_0 = \frac{\pi \cdot H_s^2}{L_m} \cdot \coth\left(\frac{2\pi \cdot h_s}{L_m}\right)$$

(104)

Once δ_0 has been generated, the different pressures p_1, p_2 and p_3 (indicated on Figure 51) can be determined:

$$p_1 = (p_2 + \rho_w \cdot g \cdot d) \cdot \frac{H_s + \delta_0}{h_s + H_s + \delta_0}$$

(105)

$$p_2 = \frac{\rho_w \cdot g \cdot H_s}{\cosh\left(\frac{2\pi \cdot h_s}{L_m}\right)}$$

(106)

$$p_3 = \rho_w \cdot g \cdot (H_s - \delta_0)$$

(107)

In which:

- p_1 [kN/m²]: Wave pressure at the SWL, corresponding to the wave crest.
- p_2 [kN/m²]: Wave pressure at the base of the vertical wall.
- p_3 [kN/m²]: Wave pressure at the SWL, corresponding to the wave trough.

Please note that the above-mentioned formulas are entirely theoretical. Therefore, it is not recommended to use their results as final output for the pressures on the caisson.

Goda (1974)

Goda defined formulas for the pressures, exerted on a caisson, in case of irregular and non-impulsive waves. The pressure distribution is shown in Figure 52 below:
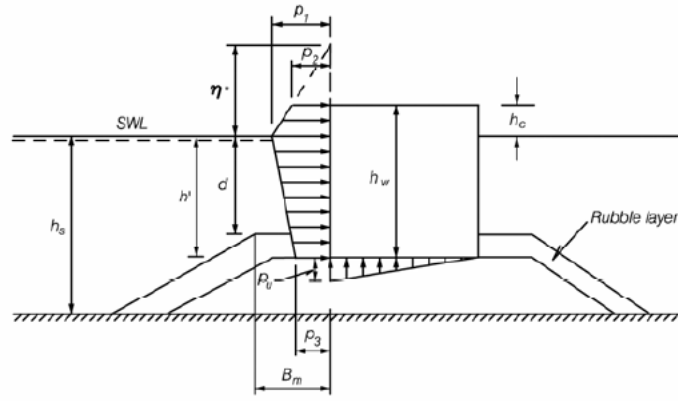
Figure 52: Pressure distribution on the caisson (Goda, 1974)

For the assessment of the pressures p_1, p_2, p_3 and p_u, the intermediate parameters α_1, α_2, α_3 and η^* are calculated first:

$$\alpha_1 = 0{,}6 + 0{,}5 \cdot \left[\frac{\frac{4\pi \cdot h_s}{L}}{sinh\left(\frac{4\pi \cdot h_s}{L_p}\right)} \right]^2 \tag{108}$$

$$\alpha_2 = min\left(\frac{h_b - d}{3 \cdot h_b} \cdot \left(\frac{H_{design}}{d}\right)^2, \frac{2 \cdot d}{H_{design}} \right) \tag{109}$$

$$\alpha_3 = 1 - \frac{h_w - h_c}{h_s} \cdot \left[1 - \frac{1}{cosh\left(\frac{2\pi \cdot h_s}{L_p}\right)} \right] \tag{110}$$

$$\alpha_* = \alpha_2 \tag{111}$$

$$\eta^* = 0.75 \cdot (1 + cos(\beta)) \cdot \lambda_1 \cdot H_{design} \tag{112}$$

With:

- α_1, α_2, α_3 and α_* [-]: Goda parameters.
- h_s, d, h_w, η^* and h_c [m]: Geometric parameters which are defined in Figure 52. Note that it is assumed that the armour layer has a thickness of 1 meter.
- h_b [m]: Water depth at a distance $5 \cdot H_s$ seaward of the caisson. This parameter is automatically calculated, taking into account the mean slope of the sea bottom α which was already defined.
- L_p [m]: Local wavelength at a water depth h_b, corresponding to the peak wave period T_p.
- H_{design} [m]: Design wave height, defined as the highest wave in the design state at a location just in front of the breakwater. Goda recommends a practical design value of $1{,}8 \cdot H_s$
- λ_1 [-]: Modification factor, depending on the structure type. Conventionally, this value is equal to unity, unless the user changes it.

Equations (109) and (111) are only valid for non-impulsive waves. Takahashi, Tanimoto and Shimosako (1994a) defined equation (113) in case of impulsive waves. The CE-Cloud will automatically detect the impulsiveness of the waves and calculate the parameter α_* with the corresponding approach.

$$\alpha_* = max(\alpha_2, \alpha_I) \tag{113}$$

$$\alpha_I = \alpha_{I0} \cdot \alpha_{I1} \tag{114}$$

$$\alpha_{I0} = \begin{cases} \dfrac{H_{design}}{d} \; for \; \dfrac{H_{design}}{d} \leq 2 \\ 2,0 \; for \; \dfrac{H_{design}}{d} > 2 \end{cases} \tag{115}$$

$$\alpha_{I1} = \begin{cases} \dfrac{\cos(\delta_2)}{\cos(\delta_1)} \; for \; \delta_2 \leq 0 \\ \dfrac{1}{\cosh(\delta_1) \cdot \cosh(\delta_2)^{1/2}} \; for \; \delta_2 > 0 \end{cases} \tag{116}$$

$$\delta_1 = \begin{cases} 20 \cdot \delta_{11} \; for \; \delta_{11} \leq 0 \\ 15 \cdot \delta_{11} \; for \; \delta_{11} > 0 \end{cases} \tag{117}$$

$$\delta_{11} = 0,93 \cdot \left(\frac{B_{m,sea}}{L_p} - 0,12 \right) + 0,63 \cdot \left(\frac{h_s - d}{h_s} - 0,6 \right) \tag{118}$$

$$\delta_2 = \begin{cases} 4,9 \cdot \delta_{22} \; for \; \delta_{22} \leq 0 \\ 3 \cdot \delta_{22} \; for \; \delta_{22} > 0 \end{cases} \tag{119}$$

$$\delta_{22} = -0,36 \cdot \left(\frac{B_{m,sea}}{L_p} - 0,12 \right) + 0,93 \cdot \left(\frac{h_s - d}{h_s} - 0,6 \right) \tag{120}$$

With:

- $B_{m,sea}$ [m]: The width of the rubble-mound berm in front of the caisson at the seaside (see Figure 52). This parameter needs to be inserted by the user as specific input. A default value of 10 m is implemented in the CE-Cloud.

As all Goda parameters (α_1, α_2, α_3 and η^*) have been defined in case of non-impulsive or impulsive wave conditions, the different pressures can be calculated:

$$p_1 = 0,5 \cdot (1 + \cos(\beta)) \cdot (\lambda_1 \cdot \alpha_1 + \lambda_2 \cdot \alpha_* \cdot \cos(\beta)^2) \cdot \rho_w \cdot g \cdot H_{design} \tag{121}$$

$$p_2 = \begin{cases} \left(1 - \dfrac{h_c}{\eta^*} \right) \cdot p_1 \; for \; \eta^* > h_c \\ 0 \; for \; \eta^* \leq h_c \end{cases} \tag{122}$$

$$p_3 = \alpha_3 \cdot p_1 \tag{123}$$

$$p_u = 0.5 \cdot (1 + \cos(\beta)) \cdot \lambda_3 \cdot \alpha_1 \cdot \alpha_3 \cdot \rho_w \cdot g \cdot H_{design}$$

(124)

With:

- λ_2, λ_3 [-]: Modification factors depending on the structure type, taken equal to unity. The option is however given to the user to change these parameters.
- p_1, p_2, p_3 and p_u [kN/m²]: Pressures on the caisson, indicated on Figure 52.

4.5.3. Final output

As already mentioned, it is recommended to select the pressure values of Goda as final output by clicking on the "Select"-button. Note that Goda also defines an upward pressure p_u on the caisson, while this is not the case for the Sainflou approach. This upward pressure will be an important parameter to check the safety of the breakwater design against overturning of the caisson.

4.6. Forces and moments

4.6.1. Introduction

For the calculation of the forces and moments, acting on the caisson per meter, the CE-Cloud uses the pressures calculated by Goda and Takahashi (explained in section 4.5.2). Since the different pressures (p_1, p_2, p_3 and p_u) and the caisson geometry have been determined, only the concrete density ρ_c needs to be inserted by the user as general input.

The width of the caisson, however, is still parametric at this stage. Subsequently, the final values for the forces and moments can not yet be determined. All forces and moments are therefore expressed in function of this width. In section 4.9, a value for B will be calculated and the final values for the forces and moments will be generated.

4.6.2. Calculation of the forces and moments

In order to analyze the stability of the caisson in a later stage, all forces acting on it need to be calculated. This is expressed as the horizontal force F_H, uplift force F_U and the reduced weight F_G per running meter breakwater. Also the corresponding moments per meter around the heel of the caisson, M_H, M_U and M_G are determined. Since the configuration of the caisson is not yet determined, it is assumed that the caisson is full of concrete for the calculation of F_G. This will be adjusted in a later stage when the safety factors for sliding and overturning of the caisson are determined. The formulas can be found below:

$$F_H = U_{F_H} \cdot \left[\frac{1}{2} \cdot (p_1 + p_2) \cdot h_c + \frac{1}{2} \cdot (p_1 + p_3) \cdot h' \right]$$

(125)

$$F_U = U_{F_U} \cdot \frac{1}{2} \cdot p_u \cdot B$$

(126)

$$F_G = g \cdot B \cdot (\rho_c \cdot h_w - \rho_w \cdot h')$$

(127)

$$M_H = U_{M_H} \cdot \left[\frac{1}{6} \cdot (2 \cdot p_1 + p_3) \cdot h'^2 + \frac{1}{2} \cdot (p_1 + p_2) \cdot h' \cdot h_c + \frac{1}{6} \cdot (p_1 + 2 \cdot p_2) \cdot h_c^2 \right]$$

(128)

$$M_U = U_{M_U} \cdot \frac{1}{3} \cdot p_u \cdot B^2$$

(129)

$$M_G = \frac{1}{2} \cdot B^2 \cdot g \cdot (\rho_c \cdot h_w - \rho_w \cdot h')$$

(130)

In which:

- h' [m]: The submerged height of the caisson from the toe to the SWL, as can be seen on Figure 52.
- h_w [m]: The total caisson height, see Figure 52.
- p_1, p_2, p_3 and p_u[kN/m²] : Goda pressures, defined in section 4.5.2.
- U_{F_H} [-]: Stochastic variable signifying the bias and uncertainty related to the horizontal force.
- U_{F_U} [-]: Stochastic variable signifying the bias and uncertainty related to the uplift force.
- U_{M_H} [-]: Stochastic variable signifying the bias and uncertainty of the horizontal moment.
- U_{M_U} [-]: Stochastic variable signifying the bias and uncertainty of the uplift moment.

The stochastic variables U_{X_Y} were defined by a reanalyzation of the Goda and Takahashi formulas by Juhl and Van der Meer (1992), Bruining (1994) and Van der Meer, Juhl and van Driel (1994). The different standard deviations and mean values for these stochastic variables U_{X_Y}, which were derived at the Danish Hydraulic Institute and Delft Hydraulics are shown in Table 18 below:

Table 18: Stochastic variables for the calculation of forces and moments on the caisson (CEM)

Stochastic variable	Mean value	no model tests		model test performed	
		Stand. dev.		Stand. dev.	
X_i	μ_{X_i}	σ_{X_i}	$\frac{\sigma_{X_i}}{\mu_{X_i}}\%$	σ_{X_i}	$\frac{\sigma_{X_i}}{\mu_{X_i}}\%$
U_{F_H}	0.90	0.25	0.22	0.05	0.055
U_{F_U}	0.77	0.25	0.32	0.05	0.065
U_{M_H}	0.81	0.40	0.49	0.10	0.12
U_{M_U}	0.72	0.37	0.51	0.10	0.14

In the CE-Cloud, the user needs to select whether model tests have been performed or not by clicking on the corresponding checkbox. By selecting one of these options, the corresponding standard deviations $\sigma_{U_{X_Y}}$ of the stochastic variables U_{X_Y} are generated, according to Table 18. The user can subsequently define a value for the parameter a to insert a certain safety. This parameter is defined in equation (131) below:

$$U_{X_Y} = \mu_{U_{X_Y}} + a \cdot \sigma_{U_{X_Y}}$$

(131)

All forces and moments can subsequently be calculated in function of the width of the caisson. Note that this width is not present in equations (125) and (128) for the horizontal force F_H and corresponding moment M_H. The remaining equations can subsequently be rewritten as:

$$\frac{F_U}{B} = U_{F_U} \cdot \frac{1}{2} \cdot p_u$$

(132)

$$\frac{F_G}{B} = g \cdot (\rho_c \cdot h_w - \rho_w \cdot h')$$

(133)

$$\frac{M_U}{B^2} = U_{M_U} \cdot \frac{1}{3} \cdot p_u$$

(134)

$$\frac{M_G}{B^2} = \frac{1}{2} \cdot g \cdot (\rho_c \cdot h_w - \rho_w \cdot h') \tag{135}$$

4.6.3. Final output

The user does not need to select the generated results as final values since only one approach is available.

4.7. Selection of the armour layer units

4.7.1. Introduction

Since the caisson can be very heavy, a well-designed rubble-mound foundation needs to be installed. To protect this foundation from erosion, an appropriate design for the armour layer units should be executed. Note that these units will logically be smaller than the armour layer units on a rubble-mound breakwater since they are less subjected to wave forces. Therefore, only rocks are considered as armour material in the CE-Cloud. To express the stability of these rocks, two approaches are available in the CEM: Madrigal and Valdés (1995) and Tanimoto, Yagyu and Goda (1982).

4.7.2. General input

Since a lot of parameters are already defined at this stage, only the width of the foundation berm at the leeside $B_{m,lee}$ needs to be inserted as general input. Since the wave height is generally moderate at this side, a default value of 5 m is implemented in the CE-Cloud. This value is also a general lower limit for $B_{m,lee}$.

Note that the width of the foundation berm at the seaside $B_{m,sea}$ has already been defined in Goda's approach for the design of the pressures exerted on the caisson in section 4.5.2.

Additionally, the roughness of the rocks needs to be defined in the general input. By use of two checkboxes, the user can select whether the installed rocks are smooth or rough. This will influence the layer coefficient k_Δ which is necessary to calculate the thickness of the armour layer in a later stage. A value for k_Δ of 1,02 and 1 is considered for smooth and rough rocks respectively.

4.7.3. Armour layer assessment

As mentioned before, two approaches are implemented in the CE-Cloud to design the armour layer units: Madrigal & Valdés (1995) and Tanimoto, Yagyu and Goda (1982). Both approaches are applicable for two layers of rocks. Each of these methods is based on hydraulic tests on a specific foundation configuration. This is partly disregarded in the CE-Cloud by letting the user insert a realistic and conservative value for the sea- and leeside slope of the foundation him/herself. This will however not have any influence on the design of the rocks in the armour layer. Note that these slopes will be defined as general input in the next design step considering the foundation details, explained in section 4.8.

Madrigal and Valdés (1995)

This first approach designs rocks which are stable on the rubble-mound foundation in front of the vertical wall of the caisson. As specific input, the user needs to insert the density ρ_s of the rocks and the damage factor N_{od}. The formula is expressed as:

$$\frac{H_s}{\Delta \cdot D_{n50}} = \left(5,8 \cdot \frac{h'}{h_s} - 0,6\right) \cdot N_{od}^{0,19}$$

(136)

In which:

- N_{od} [-]: Number of units displaced out of the armour layer within a strip width of D_{n50}, as is given in equation (80).

A general overview of the tested cross-section can be found in Figure 53 below:
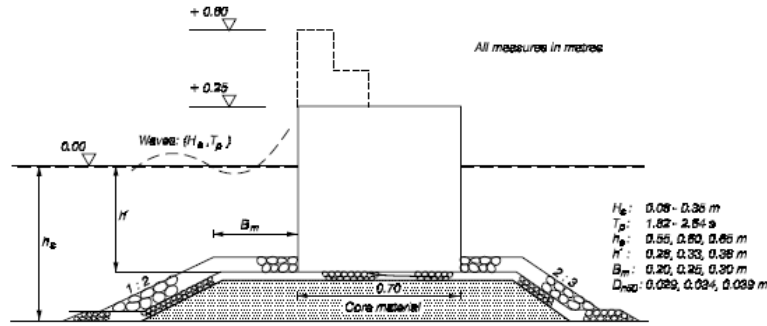
Figure 53: Tested cross-section (Madrigal and Valdés, 1995)

From equation (136), the value of D_{n50} can be isolated:

$$D_{n50} = \frac{H_s}{\Delta \cdot \left[5,8 \cdot \dfrac{h'}{h_s} - 0,6\right] \cdot N_{od}^{0,19}}$$

(137)

Once this value has been determined, the median rock weight M_{50} is calculated by use of equation (26). Subsequently, the corresponding standard grading is automatically generated in the CE-Cloud analogous to the filter assessment of the rubble-mound foundation (discussed in section 3.5.3).

Finally, the thickness of the armour layer is calculated by use of equation (77) in which the amount of installed layers n is set equal to two.

Tanimoto, Yagyu and Goda (1982)
This second approach also considers rocks as armour units. Since there is no need for additional parameters, the CE-Cloud automatically calculates the equivalent cube length D_{n50}. In a first step three intermediate parameters κ_1, κ_2 and κ are determined:

$$\kappa_1 = \frac{2 \cdot k \cdot h'}{\sinh(2 \cdot k \cdot h')}$$

(138)

$$\kappa_2 = max\left\{0,45 \cdot \sin(\beta)^2 \cdot \cos(k \cdot B_m \cdot \cos(\beta))^2, \cos(\beta)^2 \right. \\ \left. \cdot \sin\left(k \cdot B_{m,sea} \cdot \cos(\beta)\right)^2\right\}$$

(139)

$$\kappa = \kappa_1 \cdot \kappa_2$$

(140)

With:

- k [1/m]: The wave number, defined as:

$$k = \frac{2\pi}{L_p} \tag{141}$$

Subsequently the stability of the rocks is expressed as:

$$\frac{H_s}{\Delta \cdot D_{n50}} = max \left\{ 1,8; 1,3 \cdot \frac{1-\kappa}{\kappa^{\frac{1}{3}}} \cdot \frac{h'}{H_s} + 1,8 \cdot exp\left(-1,5 \cdot \frac{(1-\kappa)^2}{\kappa^{\frac{1}{3}}} \cdot \frac{h'}{H_s} \right) \right\} \tag{142}$$

In equation (142) it is assumed that $\Delta = 1,65$ [-]. Now D_{n50} can be isolated as:

$$D_{n50} = \frac{H_s}{\Delta \cdot max \left\{ 1,8; 1,3 \cdot \frac{1-\kappa}{\kappa^{\frac{1}{3}}} \cdot \frac{h'}{H_s} + 1,8 \cdot exp\left(-1,5 \cdot \frac{(1-\kappa)^2}{\kappa^{\frac{1}{3}}} \cdot \frac{h'}{H_s} \right) \right\}} \tag{143}$$

Analogous to the Madrigal and Valdés approach, the corresponding grading and layer thickness is automatically generated in the CE-Cloud.

4.7.4. Final output

Once one or two of the above-mentioned approaches have been finished, the user can select the corresponding results as final output by clicking on the accompanying "Select"-button. Note that the same armour layer units are applied at the sea- and leeside.

4.8. Foundation design

4.8.1. Introduction

As soon as the armour layer has been designed, a filter and core material assessment is executed. This is done in a similar manner as the design of the filter and core materials of the rubble-mound breakwater in section 3.5.

In this case however, it is assumed that only one filter layer is installed between the armour layer and the core material. This is a realistic assumption since the size of the armour layer units is generally moderate due to the low wave forces acting on it.

Another feature of the rubble-mound foundation are the foot protection blocks. These are concrete blocks which are installed near the toe of the caisson to provide sufficient protection against erosion.

Finally, also the bedprotection of the breakwater is characterized by inserting the density and thickness of this layer.

4.8.2. General input

In order to execute the design of the filter and core materials, two weight ratios need to be inserted as general input. These ratios consist of the unit weight W of the design armour unit, divided by the unit weight of the filter W_{filter} or core material W_{core}.

Subsequently, the slopes of the foundation at the sea- and leeside need to be inserted by the user. Default values of 1:3 and 1:2 are assumed respectively. The latter two parameters do not have any influence on the design of the rubble-mound foundation, except for its geometric configuration. Therefore, the user should insert conservative values for these slopes.

4.8.3. Filter and core material selection

In a first step the median weight of the filter material W_{filter} is calculated as:

$$W_{filter} = \frac{W}{\left[\frac{W}{W_{filter}}\right]} \tag{144}$$

Once the weight W_{filter} has been determined, the standard rock grading, of which the median weight M_{50} is closest and higher to/than W_{filter}, is automatically generated by use of the Rosin-Rammler (1993) curves, explained in section 3.5.3. Subsequently, the retention, permeability and internal stability criterion of this filter are checked. In order to do this, the following parameters are automatically generated in the CE-Cloud: D_{n50}, D_{n10}, D_{n15}, D_{n60} and D_{n80}. With D_{nx} the diameter of the grading for which x% of the material is smaller.

In a next step, the thickness of the filter layer is calculated by use of equation (77). Therefore the user needs to insert the amount of units n which are placed on top of each other in the filter layer as specific input. Similar to the armour layer design, the user needs to define whether the installed rocks are smooth or rough by selecting the corresponding checkbox.

To design the appropriate grading for the core material, the same procedure as for the filter material assessment is executed. Note that for the filter and core material, the user has the ability to select a wider grading by clicking on the corresponding button. More information about this wider grading can be found in section 3.5.3.

4.8.4. Bedprotection

Before the rubble-mound foundation is installed, a geotextile and granular bedprotection are applied in a first stage. This is to prevent excessive settlement of the foundation and to even out the bottom irregularities. It is however not possible to define the filter properties of the bedprotection and geotextile in the CE-Cloud. Only the density of the granular material and a mean value of the height of the bedding layer can be inserted. Note that the application of this layer is very inaccurate in real-life applications.

4.8.5. Foot protection blocks

Since the flow conditions near the toe of the caisson can be very dangerous, foot protection blocks are installed near the caisson to prevent erosion. Consequently, it is up to the user to insert the amount of installed blocks at the sea- and leeside as specific input. Please keep in mind that the available widths of the foundation berm at the sea- and leeside have already been defined. Additionally, it is assumed that all the installed blocks have the same dimensions at the sea- and leeside.

The Coastal Engineering Manual provides the Japanese practice approach for the design of these blocks. In a first calculation, the necessary thickness t' of the blocks is generated by use of Figure 54.
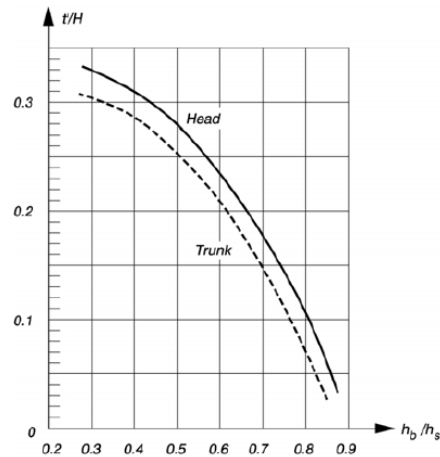
Figure 54: Assessment of the thickness t' of the foot protection blocks (Japanese practice, CEM)

In which:

- t' [m]: The thickness of the foot protection blocks
- H [m]: The significant wave height (equal to H_s)
- h_b [m]: The vertical distance between the top of the berm and the SWL (equal to d)

The CE-Cloud automatically gathers all the necessary parameters and calculates the corresponding thickness t'. This thickness subsequently corresponds to a specific standard foot protection block geometry. The different sizes and corresponding masses of the possible blocks are given in Table 19 below:

Table 19: Foot protection block geometries (CEM)

l	x	b	x	t'	app. mass t
2.5		1.5		0.8	6
3.0		2.5		1.0	15
4.0		2.5		1.2	25
5.0		2.5		1.4	37
5.0		2.5		1.6	42
5.0		2.5		1.8	48
5.0		2.5		2.0	53
5.0		2.5		2.2	58

The CE-Cloud automatically links the generated thickness t' to the other block dimensions (l: length, b: width) and mass. On Figure 55, the placement configuration of the concrete blocks can be seen at the seaside.

Figure 55: Foot protection blocks placement (CEM)

Subsequently it is checked whether the designed width of the foundation berm is sufficiently large to install the inserted amount of foot protection blocks at the sea- and leeside. The CE-Cloud clearly presents the available widths and generates a warning if the blocks cannot be installed. An example of such an output is given in Figure 56 below:

Figure 56: Available width calculation window (CE-Cloud)

The user can subsequently decrease the amount of foot protection blocks, or make the foundation wider by clicking on the "Change berm width"-button. After having changed the berm width, the user can easily go back by clicking on the "Berm width altered"-button.

4.8.6. Final output

Once this sheet is finished, an overview is given considering the used materials and dimensions for the different elements of the breakwater foundation: armour units, filter material, core material, foot protection blocks and bedprotection.

4.9. Width assessment and safety analysis

4.9.1. Introduction

At this stage of the design, the total foundation has been designed as well as the pressures, forces and moments (parametric in B) on the caisson. The only parameter which still needs to be calculated is the width of the caisson. This width will iteratively be determined in function of the safety factors SF_x against sliding and overturning of the caisson, and providing sufficient bearing capacity for the caisson.

At the top of the sheet, the user needs to insert an estimated value for the caisson width. Subsequently, the three corresponding safety factors are generated. At this stage these factors are however meaningless. Thereafter, the user needs to fill in all the green cells (specific inputs) in the rest of the sheet in order to calculate the correct safety factors. Once this has been done, the user can iteratively change the inserted value of B in order to define a safe, but economic value which meets all three safety requirements.

4.9.2. Mass of the caisson

If the first estimated value for the width B is inserted, the mass of the caisson filled with sand, can be calculated. To calculate this value, several parameters considering the dimensions of the caisson and densities of its materials need to be inserted:

- t_{bottom} [m]: The thickness of the bottom slab of the caisson.
- t_{outer} [m]: The thickness of the outer (vertical) walls of the caisson. This thickness is the same at the sea- as at the leeside of the caisson.
- $\#_{part}$ [-]: Number of partition walls which are present in the caisson. Note that these partition walls are parallel to the outer walls.
- t_{part} [m]: The thickness of the partition walls.
- t_{slab} [m]: The thickness of the top cap of the caisson breakwater. Note that the largest thickness of the top cap needs to be inserted. The altered top cap configuration due to the concrete reduction factor δ_{red} is not yet taken into account here.
- $\rho_{c,dry}$ [t/m³]: The density of dry concrete.
- $\rho_{s,dry}$ [t/m³]: The density of dry sand in the caisson.
- $\rho_{c,wet}$ [t/m³]: The density of wet concrete.
- $\rho_{s,wet}$ [t/m³]: The density of wet sand in the caisson.

If all above-mentioned parameters are inserted, the program calculates the total weight M of the caisson. In this calculation, it is assumed that the separation between the wet and dry sand or concrete is at the SWL. Note that the concrete reduction factor for the top cap, which has been defined earlier, is also considered in this weight assessment. If the inserted value of the thickness of the top cap t_{slab} is too small to provide sufficient concrete savings, the CE-Cloud will generate a negative value for the top cap volume and mass. If this is the case, the user should reduce the concrete reduction factor or increase the thickness of the top slab. Please remark that the Archimedes force is not taken into account in the weight calculation of the caisson. This upward force will be taken into account later.

4.9.3. Levelling method

The caisson is not directly applied onto the core material, but first a levelling bedding layer is installed. This levelling layer will define the friction factor μ between the caisson and its foundation, which is important for the assessment of the safety factor SF_1 against sliding of the caisson. To find this friction factor, two methods are available in the CE-Cloud: Marihira, Kihara and Harikawa (1988) and a manual input.

Marihari, Kihara and Horikawa (1988)

Marihari, Kihara and Horikawa derived the dynamic friction factor μ in function of the levelling method, the bottom configuration of the caisson and its settlement. The different values are given in Table 20 below:

Table 20: Dynamic friction factors (Marihari, Kihara and Harikawa, 1988)

Levelling	Bottom pattern	μ_{max}	$\overline{\mu}_{mar}$	μ_{const}	μ			
					S=5 cm	S=10 cm	S=20 cm	S=30 cm
rough	flat	0.75	0.70	0.70	0.53	0.59	0.65	0.70
		0.73	0.70	0.70	0.70	0.70	0.70	0.70
	clog-shaped	1.19	1.13	1.16	0.76	0.91	0.98	1.08
		1.11	1.02	1.01	0.76	0.90	1.01	1.00
	spike	0.85	0.79	0.80	0.62	0.80	0.80	0.80
		0.97	0.81	0.84	0.70	0.70	0.83	0.95
	clog-shaped with foot protection	1.45	1.36	>1.4	1.11	1.30	1.41	
		1.34	1.19	>1.3	0.94	1.09	1.28	
fine	flat	0.68	0.63	0.65	0.63	0.64	0.64	0.55
		0.70	0.60	0.60	0.59	0.60	0.60	0.60
	clog-shaped	1.18	1.08	1.08	0.95	1.03	1.08	1.08
		1.15	1.01	1.06	0.90	0.94	0.97	1.04
	spike	0.87	0.78	0.82	0.72	0.72	0.75	0.82
		1.04	0.87	0.82	0.78	0.95	1.01	0.85

Note that the CE-Cloud considers the mean value of the two dynamic friction coefficient corresponding to the different settlements in Table 20. It would however be more correct to consider the static friction factor since this will result in the friction just before the caisson starts sliding. Since the dynamic friction factor is generally smaller than this static friction, the approach in the CE-Cloud is more conservative.

In a first input, the user needs to define whether the levelling is rough or fine. A rough levelling consists of a layer of moderate rocks (50 – 200 kg/unit). The thickness of this layer measures 0,8 m. A fine levelling consists of the same layer as the rough levelling but with smaller rocks (10 kg/unit) on top of it. The latter layer adds another 0,2 m to the total thickness. Both levelling methods extent about 2 meters from the caisson in horizontal direction, as can be seen on Figure 46. These configurations are shown in Figure 57 below:
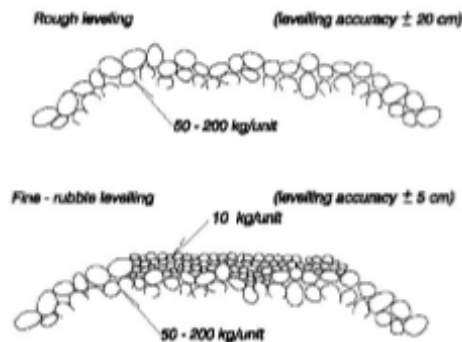
Figure 57: Rough and fine levelling configurations (Marihari, Kihara and Harikawa, 1988)

In the next step, the user needs to define the bottom pattern of the caisson by selecting the corresponding checkbox. There are three configurations possible: flat, clog-shaped or spike. These different possibilities are shown in Figure 58 below:

Figure 58: Bottom configurations of the caisson (Marihari, Kihara and Harikawa, 1988)

Finally, the user needs to insert the expected caisson displacement S after settlement. Note that only the values: 5, 10, 20 and 30 cm are possible. This is however clearly indicated in the CE-Cloud.

Once all the above-mentioned parameters are defined, the CE-Cloud will automatically generate the corresponding value for the dynamic friction factor μ from Table 20. The chosen geometry for the levelling method and the configuration of the bottom of the caisson will also be considered in the drawing tool of the CE-Cloud.

Manual input

It is also possible for the user to insert an estimated value for the friction factor μ. The default value is set equal to 0,636 which corresponds to the average friction coefficient for a plane concrete slab, resting on quarried rubble stones, according to Takayama (1992). Table 21 provides the user with some additional information to insert an appropriate value for the friction factor. Subsequently, a rough levelling method with a flat caisson bottom is automatically assumed for the manual input.

Table 21: Friction factors (Stückrath, 1996)

Table VI-5-62
Experimental Test Results of Friction Coefficient Conducted in Japan
(taken from Stückrath 1996)

No.	Stone type	Stone size (mm)	Condition of mound	μ	Average of μ
1	Crushed stone	30	Screeded surface	0.460-0.801	-
2	Rubble stone	120	Not screeded	0.564-0.679	0.624
3	Rubble stone	50	Surface smoothed with smaller stone	0.45-0.69	-
4	Rubble stone	30-80	Screeded	0.77-0.89	0.82
5	Cobble stone	30-50	Not screeded	0.69-0.75	0.70
6	Crushed stone	20-30	Not screeded	0.607-0.790	0.725
7	Crushed stone	10-50	Not screeded	0.486-0.591	0.540
8	Crushed stone	13-30	Not uniform	0.41-0.56	-

4.9.4. Safety assessment

Before starting the safety assessment, the final values of the forces (F_H, F_U, F_G) and moments (M_H, M_U, M_G) acting per meter caisson are calculated. These forces and moments have already been determined in function of the caisson width by use of equations (132) to (135). Note that the value of F_G can now correctly be calculated since the amount of sand in the caisson is known. Subsequently, the different safety factors against sliding, overturning and the bearing capacity of the foundation can be calculated.

Safety against sliding

To express the safety against sliding of the caisson, a safety factor SF_1 is introduced which consists of the ratio between the horizontal resistance friction force and the horizontal force acting on the caisson. If this value is larger than 1,2; the design is sufficiently safe against sliding. The formula is expressed as:

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$$SF_1 = \frac{\mu \cdot (M \cdot g - F_U)}{F_H} > 1.2$$

(145)

Safety against overturning

The second safety assessment considers overturning of the caisson due to the incoming wave energy. To express this safety, the moments acting around the heel (at the leeside) of the caisson are considered, as can be seen on Figure 59. The safety factor is expressed as the ratio between two moments. In the numerator the moment due to the selfweight of the caisson, substracted with the moment due to the uplifting force, is expressed. In the denominator the moment due to the horizontal pressures on the caisson can be found. In order for the design to be safe, the safety factor SF_2 should exceed the value of 1,2. The formula is given by:

$$SF_2 = \frac{M \cdot g \cdot t - M_U}{M_H} > 1.2$$

(146)

With:

- t: The lever arm of the weight of the caisson around its heel, set equal to $\frac{B}{2}$. This implicitly implies that the breakwater is symmetrical. If this is not the case, because of the configuration of the top cap, the value of t should actually be larger. Assuming the value of $\frac{B}{2}$, is consequently always conservative.
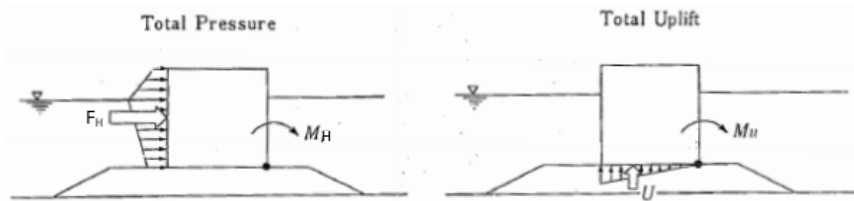
Figure 59: Horizontal and uplifting moment around the heel of the caisson (CEM)

Providing sufficient bearing capacity for the caisson

Since the weight of the caisson can be very large, it is important to check whether the rubble-mound foundation provides sufficient bearing capacity for this structure. It is up to the user to define a maximum pressure p_{max} which can be exerted on the foundation. A default value of 600 kPa is implemented in the CE-Cloud. Subsequently, the total pressure p_e exerted on the foundation is calculated as follows:

$$p_e = \begin{cases} \dfrac{2 \cdot W_e}{3 \cdot t_e} & if \ t_e \leq \dfrac{1}{3} \cdot B \\ \dfrac{2 \cdot W_e}{B} \cdot \left(2 - \dfrac{3 \cdot t_e}{B}\right) & if \ t_e > \dfrac{1}{3} \cdot B \end{cases}$$

(147)

With:

$$t_e = \frac{M_e}{W_e}$$

(148)

$$M_e = M \cdot g \cdot t - M_U - M_H$$

(149)

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$$W_e = M \cdot g - F_U$$

<div align="right">(150)</div>

Once the pressure p_e has been generated, it is checked whether it is larger or smaller than the maximum allowed pressure p_{max}.

4.9.5. Width selection

Since all safety factors are known at this stage, the user can interpret the influence of the caisson width B on these factors. By clicking on the "Change caisson width"-button, the user is redirected back to the top of the sheet where a new value for B can be inserted. If the user inserts a new value for B, the CE-Cloud will automatically generate the total mass of the caisson and the three safety factors, as can be seen on Figure 60 below.

B	9,5	m	Width of the caisson		
M	211,59	t	Total weight of the caisson, filled with sand		
Safety factors					
	Value	OK/NOT OK?			
SF_1	1,4	OK	Safety factor for sliding of the caisson		
SF_2	1,82	OK	Safety factor for overturning of the caisson		
SF_3	1	NOT OK	Safety factor for the bearing capacity of the RM foundation		

Figure 60: Main window of the width and safety assessment (CE-Cloud)

By use of this tool the user is able to select a safe, but economic value for the caisson width B. The latter is very important since the caisson is the most expensive part of the whole breakwater.

4.9.6. Final output

Once the sheet is completed, the final output values are generated automatically since there is only one design approach available. The final output consists of:

- The berm width and caisson mass
- The levelling method characteristics
- The forces acting per meter caisson and the pressure p_e
- The moments acting per meter caisson around its heel
- The caisson geometry

In the last section, considering the final caisson geometry, the configuration of the concrete top cap is generated as was already shown on Figure 50. It is possible that the inserted concrete reduction factor yields impossible results. If this is the case, the CE-Cloud will automatically generate a warning. The user can subsequently reduce the value of the concrete reduction factor by clicking on the "Change concrete reduction factor"-button. When this value is changed, the user can easily go back by clicking on the "Go back to width assessment"-button. Note that there is no feature available in the CE-Cloud to check whether the height of the caisson at the leeside is sufficient. It is only assumed that the incoming waves at the leeside are moderate.

4.10. Cost analysis

4.10.1. Introduction

At this stage, the total breakwater design is finished and a cost assessment can be executed. Similar to the rubble-mound breakwater, the cost breakdown is approached in two different ways. First the

breakdown is calculated in function of the three process steps: production, transport and construction. Secondly, these sections are split into the different segments of the caisson breakwater, which have already been indicated on Figure 46. For the calculation of each of these segments, the same cost list as for the rubble-mound breakwater is used. The user can easily modify this list by clicking on the "Cost list"-button at the top of the sheet. Once the appropriate data are inserted, the user can go back by clicking on the "Back to cost assessment caisson breakwaters"-button at the top or bottom of the cost list.

Analogous to the cost assessment of the rubble-mound breakwater, the user only needs to insert the transport distances and porosities of the different materials as general input.

4.10.2. Generating the cost breakdown

For the calculation of the different process steps, the breakwater is split up in seven different segments:

- Armour layer units at the seaside
- Armour layer units at the leeside
- First filter layer
- Core material
- Foot protection blocks
- Concrete in the caisson
- Sand in the caisson

Production cost

For each of the breakwater sections, the total volume and mass of the used materials per meter breakwater are automatically generated. The cost list subsequently provides the necessary costs per volume or mass. As such, the production cost for each of the above-mentioned materials is determined. All these costs are subsequently added to find the total production cost per meter for the caisson breakwater. Note that there is no division between the trunk and head sections for the caisson breakwater, as is the case for the rubble-mound breakwater. This is mainly because the cost of the rubble-mound foundation at the head of a caisson breakwater is not significant with respect to the total cost of the breakwater.

Transport cost

The second part of the breakwater cost analysis considers the transport costs. At the top of the sheet, the user can insert the different transport distances for each of the used materials. Note that the transport cost for the caisson can be very high. Dependent on the project, the caisson is floated from a certain construction site after which it is sunk under controlled conditions. The user should take these expensive phases into account for the calculation of the transport cost of the caisson, expressed as a mean value per km.

The transport costs are split up in function of the same breakwater segments as for the production cost assessment. The transport cost for the sea- and leeside armour layers is however put together.

Construction cost

The third part of the cost breakdown consists of the construction costs. It can be expected that the caisson cost is a major expense within this section. The same material division as for the transport cost calculation is used here.

Material costs

At this point the cost breakdown is generated in function of the different process steps (production, transport and construction). By adding up all these costs for the same materials, the total cost for each of the materials is determined. Consequently, the user can easily find the most expensive features within the considered breakwater design.

4.10.3. Final output

As soon as all the costs are calculated, they are visualized in two column diagrams. The first diagram visualizes the different costs in function of the used materials. Note that the bedprotection is not included since its cost is generally negligible. An example of such a diagram is shown in Figure 61 below:
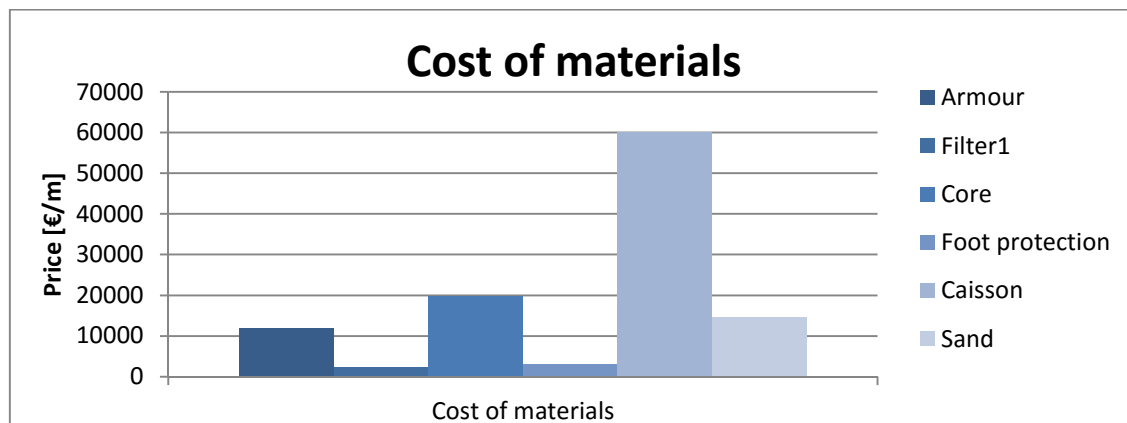
Figure 61: Material cost breakdown graph (CE-Cloud)

In a second graph, the cost breakdown is visualized in function of the different construction steps. Note that the transport cost will generally be the most expensive factor, depending on where the caisson comes from. An example of such a graph is given in Figure 62 below:
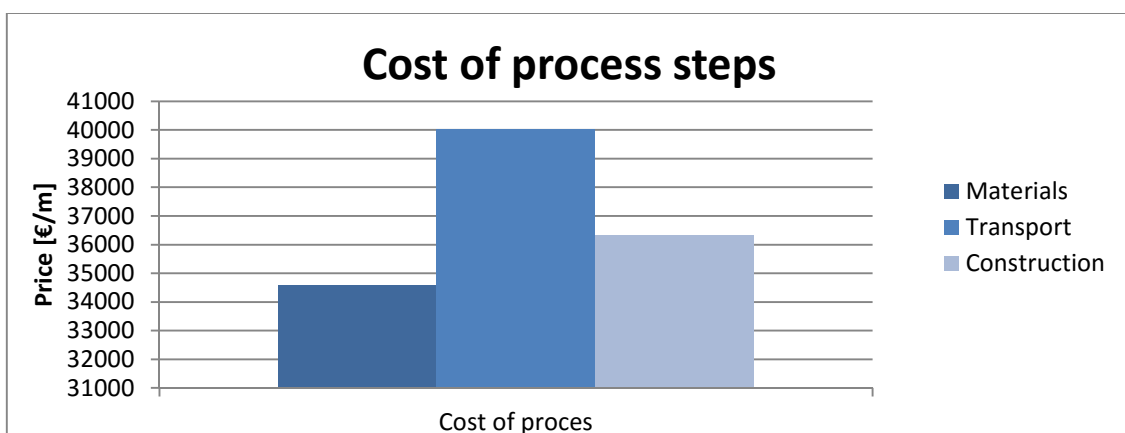
Figure 62: Process steps cost breakdown graph (CE-Cloud)

4.11. Final design

4.11.1. Introduction

Once the engineer has finished the cost assessment, all aspects of the caisson breakwater are designed and calculated. Now a clear overview is given of all the chosen materials and the geometric properties of the caisson and its foundation. This information is gathered in an easily printable final design sheet. The lay-out is very similar to the one of the rubble-mound breakwater in order to efficiently compare both breakwater designs.

4.11.2. Content of the final design sheet

Similar to the rubble-mound breakwater, the final design sheet consists of four main sections: hydraulic boundaries, layer information, dimensioning and cost breakdown.

The hydraulic boundaries provide the main information about the design sea state. This gives the engineer a general overview of the design parameters for this particular project site. Figure 63 shows an example of a hydraulic boundaries window.

Hydraulic Boundaries		
ρ_w	1,025	t/m³
h_s	15	m
Seaside		
H_s	3	m
T_p	9	s
s_m	0,0426	[-]

Figure 63: Example of the hydraulic boundaries in the final design sheet (CE-Cloud)

In the next step, the layer information is gathered. This section is split up in seven different breakwater elements:

- The armour layer (sea- & leeside)
- The filter layer (sea- & leeside)
- Core material
- Bedprotection
- Foot protection blocks (sea- & leeside)
- The concrete of the caisson
- The sand in the caisson

For each of the materials the same characteristics are gathered as for the design sheet of the rubble-mound breakwater. For more information, please read section 3.10.2. Using this sheet, the engineer has a clear overview of the amount of used materials and their costs. An example is provided in Figure 64 below:

Layer information												
	Armour		Filter 1		Core	Bedprotection	Footprotection blocks		Caisson	Caisson	Units
	Sea	Lee	Sea	Lee			Sea	Lee	concrete	sand	
Type	Rocks	Rocks	Rocks	Rocks	Rocks	Sand	Concrete	Concrete	Concrete	Sand	[-]
Grading	300 - 1000	300 - 1000	5 - 40	5 - 40	5 - 40	/	/	/	/	/	kg
Placement	/	/	/	/	/	/	/	/	/	/	[-]
ρ_s	2,6	2,6	2,6	2,6	2,6	1,6	2		2,4	1,6	t/m³
D_n50	0,68	0,68	0,23	0,22	0,23	/	/	/	/	/	m
M_50	716	716	32	32	32	/	6		/	/	kg or t
r	1,33	1,33	0,22	0,22	/	0,5	0,8		/	/	m
V_tot/m	15,16	10,77	11,87		108,35	/	6	2	52,46	101,71	m³/m
M_tot/m	39,42	28	30,86		281,71	/	12	4	132,18	185,37	kg/m or t/m
€/m	1820,34		678,92		6197,62	/	1920		25180,8	1017,1	€/m

Figure 64: Example of the layer information in the final design sheet (CE-Cloud)

In the third section, several dimensional parameters are gathered. This roughly consists of the total width and height of the breakwater, considering a mean allowable overtopping discharge q. This feature also presents the dimensions of the foot protection blocks and the caisson as can be seen on Figure 65 below:

Dimensioning									
General dimensions				Foot protection blocks			Caisson dimensions		
q	0,001	m³/s/m		Sea	Lee		h	17,48	
R_c	7,48	m	#	3	1		B	8	
h_tot	22,48	m	l	2,5			t_bottom	0,5	Draw the breakwater
B_tot	50,5	m	b	1,5			t_slab	2	
h_s	9	m	t'	0,8			t_outer	0,5	
							#_part	2	
							t_part	0,5	

Figure 65: Example of the dimensioning parameters in the final design sheet (CE-Cloud)

The CE-Cloud also provides the possibility to draw the caisson breakwater in AutoCAD, by clicking on the "Draw the breakwater"-button. The user will subsequently be redirected to a new sheet in which all the coordinates of the caisson breakwater are automatically generated. More information is given in section 4.11.3. Instead of automatically drawing the coordinates in AutoCAD, the CE-Cloud can also save these coordinates in a textfile.

In the last section, the total cost of the breakwater per meter trunk is generated together with the column graphs of the "Cost assessment"-sheet. Figure 66 shows an example of the final cost output.
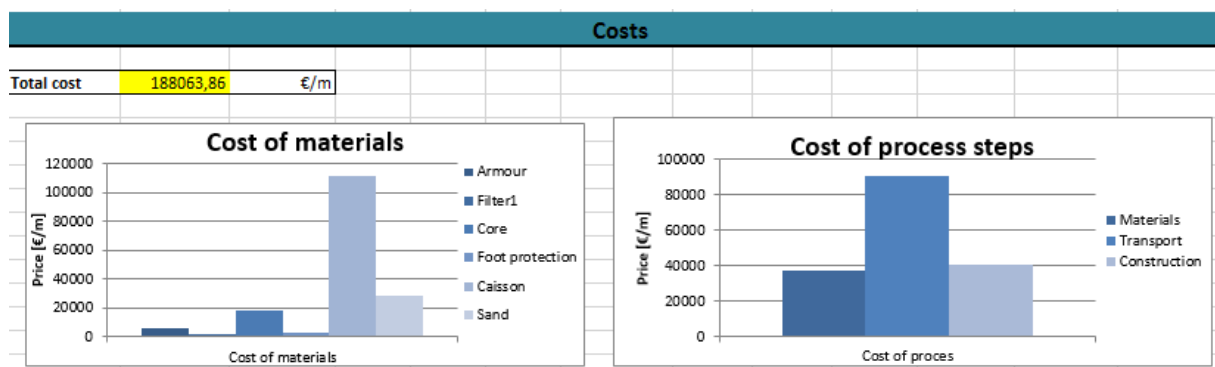
Figure 66: Example of the cost overview in the final design sheet (CE-Cloud)

As already mentioned, the user can easily compare the design sheets of the rubble-mound and caisson breakwater by clicking on the "Compare with RM breakwater"-button at the bottom of the sheet.

Since the CE-Cloud also provides the possibility to define multiple cross-sections within the same breakwater, one can find several buttons at the bottom of the final design sheet to select these cross-sections. The use of these buttons is explained in more detail in section 5.

4.11.3. Drawing the breakwater

Analogous to the rubble-mound breakwater, the CE-Cloud can automatically generate a drawing of the caisson breakwater in AutoCAD by clicking on the "Draw in AutoCAD"-button in the sheet with all the coordinates. For more background information and Excel-settings, please read section 3.10.3.

4.11.4. Write to notepad

If the user has no access to AutoCAD, the CE-Cloud provides a tool to save the generated coordinates in a textfile. This can be done by clicking on the "Write to notepad"-button on the coordinates sheet. For more information, please read section 3.10.4.

5. Cost and material assessment of the total breakwater

5.1. Introduction

At this point, the user has designed a cross-section for a rubble-mound and a caisson breakwater. Both designs can easily be compared by analyzing the corresponding final design sheets to make a motivated choice between both breakwaters. Each of the final design sheets has a link to the other sheet by use of the "Compare with RM/caisson breakwater"-button, as is shown in Figure 67. Note that it is assumed that the user has a coastal engineering background and can subsequently make a correct decision. This decision is based on the information which is provided by the CE-Cloud and the practical engineering insight of the user. The CE-Cloud consequently gives an indication of the best (most profitable) design, but it is still up to the user to select a certain breakwater in the end.

For certain projects, it is possible that the cross-section of the breakwater changes over its length due to changing boundary conditions. This is for example the case if the water depth changes significantly. Therefore, the user can design and insert five different cross-sections of a total breakwater in the CE-Cloud. This can be done by use of the buttons at the bottom of each of the design sheets, shown in Figure 67 for the caisson breakwater design.
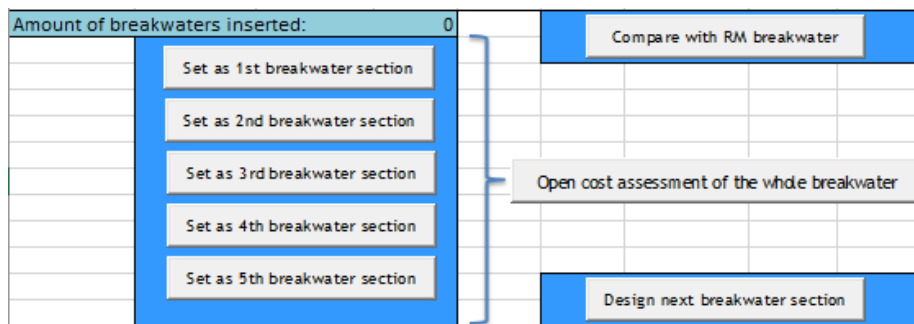
Figure 67: Breakwater cross-section selection for a caisson breakwater (CE-Cloud)

If the user starts a new project, the CE-Cloud will indicate that 0 cross-sections are selected as can be seen on Figure 67. Once the user has inserted all necessary parameters to generate a first final design sheet, this design can be selected as first cross-section by clicking on the "Set as 1st breakwater section"-button. By clicking on the "Open cost assessment of the whole breakwater"-button, a total cost sheet is generated. This sheet will gather all costs and materials of the whole breakwater.

At this point, only one cross-section of the total breakwater has been selected. To start designing a second section, the user needs to click on the "Design next breakwater section"-button and generate a second design analogous to the first design. At the end, the user can insert the second design for the total cost sheet by clicking on the "Set as 2nd breakwater section"-button. Note that it is not possible to switch from a rubble-mound to a caisson design and vice versa. The user should also insert the different cross-sections in the correct sequence. A counter is available in the final design sheets which shows how many cross-sections are already designed.

For the assessment of further cross-sections, the same strategy can be followed. A maximum of 5 breakwater cross-sections can be implemented in the CE-Cloud. Note that it is not necessary to insert 5 different sections, the user could also consider 3 different sections for example.

Since it is very expensive and impractical to install a transition between two different cross-sections of a breakwater over a long length, this is generally done over a moderate length. As such the breakwater consists of, for example, two constant cross-sections with a linear transition between both sections over a distance of 2 meter. Consequently, it is up to the user to design and insert the correct cross-sections in the total cost assessment sheet. The only parameters that still need to be defined are the distances between the different cross-sections, as will be explained in the next section.

5.2. The total cost sheet

5.2.1. General information

As already mentioned, the total cost sheet will generate all information about the costs and used materials for the whole breakwater. Once all cross-sections have been designed and selected, the total breakwater cost sheet is automatically generated. This sheet can be accessed by clicking on the "Open cost assessment of the total breakwater"-button in one of the final design sheets or by clicking on the "Total cost"-button in the main menu.

In the first part of this sheet, the general input needs to be inserted by the user. This input consists of the different distances between the designed cross sections. Note that if the breakwater is curved, the user should insert the curve length. This should also be taken into account in the cost list since constructing a curved breakwater will generally be more expensive than a straight one.

In the second part of the sheet a feature is implemented which can visualize the total cost breakdown per meter breakwater by use of graphs. This tool is explained in section 5.2.2.

In the third part, the different costs of the breakwater are generated. In order to analyze the different costs easily, the CE-Cloud gathers the costs in two different approaches. In the first approach, the costs per meter of each of the selected cross-sections is gathered. This is actually a copy of the general cost sheet of each of these cross-sections. In the second approach, the costs of the materials of the trunk-sections between these selected cross-sections are calculated. These costs are generated by use of linear interpolation between the costs per meter of the neighbouring cross-sections. If, for example, the cost of the armour material for the first and second selected cross-section equals c_1 [€/m] and c_2 [€/m] respectively, the total armour material cost c_{1-2} [€] for the first trunk-section is calculated as:

$$c_{1-2} = \frac{c_1 + c_2}{2} \cdot l_{1-2}$$

(151)

With l_{1-2} [m] the spacing between section 1 and 2, which has priorly been inserted in the general input.

Similar to the other cost sheets, each of these two approaches is split up in function of the process steps (production, transport and construction) and used materials, which are shown on Table 22 below:

Table 22: Material breakdown for the total cost assessment

	Rubble-mound breakwater	Caisson breakwater
Armour material	✓	✓
First filter layer	✓	✓
Second filter layer	✓	✗
Core material	✓	✓
Toe protection	✓	✗
Roundhead	✓	✗
Foot protection blocks	✗	✓
Caisson concrete	✗	✓
Caisson sand	✗	✓

Since a roundhead design is available for the rubble-mound breakwater, the program will automatically take into account the roundhead costs for the outer sections of the breakwater. There is however no roundhead design available for the caisson breakwater.

In the fourth and last part, the different materials and their corresponding weights (in tons) for the different breakwater elements are generated. This part is split in two approaches as well. In the first approach, the type of materials with their corresponding weight per meter for each of the cross-sections is determined. In the second approach, the total weight of these materials within the different trunk-sections is calculated.

5.2.2. Cost breakdown visualization tool

The cost breakdown visualization tool can easily be accessed by clicking on the "Analyze cost-breakdown"-button in the "Total cost breakdown"-sheet. Subsequently, a window pops up which can generate several graphs which show the costs per meter of the process steps or materials in function of the designed trunk-sections of the breakwater. In order to generate a certain graph, the user needs to select a certain process step or material in the dropdown menu and click on the "Generate graph"-button as can be seen on Figure 68 below.
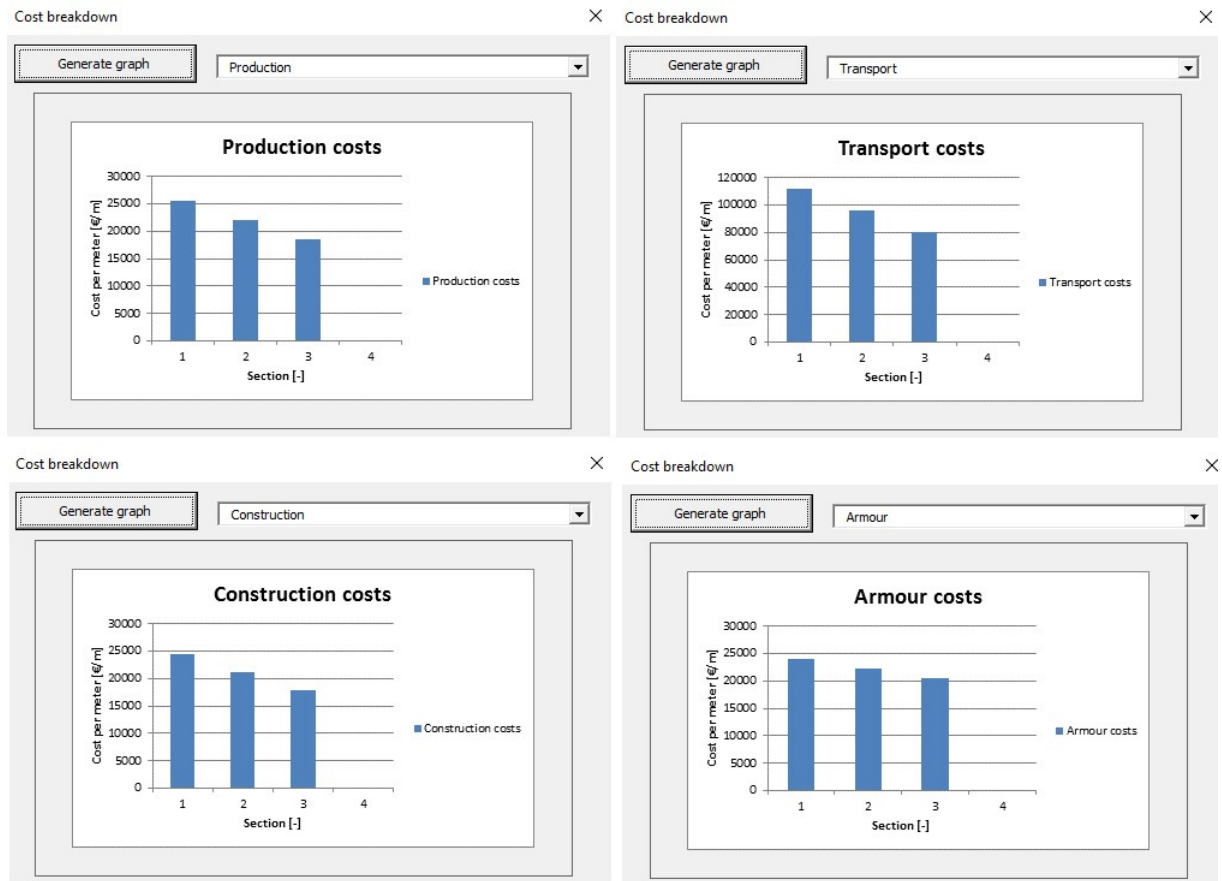
Figure 68: Cost breakdown visualization window (CE-Cloud)

Figure 68 above clearly shows the cost breakdown of the process steps and armour costs per meter breakwater for three different trunk sections. These graphs are also available in function of the first filter, second filter, core, toe, roundhead, foot protection, concrete in the caisson and sand in the caisson material costs.

5.3.   Final output

If all the designed cross-sections are selected and their corresponding spacings inserted, the CE-Cloud automatically generates the final design sheet for the total breakwater. This sheet gathers all the information considering costs, type of materials and their weight. It also provides a user-friendly tool to generate graphs of the different cost breakdowns in function of the designed trunk sections.

6. Final remarks and conclusions

The CE-Cloud is a powerful and user-friendly, Excel-based design program which assists the engineer in calculating a proper and realistic design for a rubble-mound and/or a caisson breakwater. It subsequently helps the engineer in selecting one of the breakwater designs by generating final design sheets of both breakwater types which are easily comparable. Note that the CE-Cloud only generates numerical information considering the dimensions and costs of the breakwater cross-sections. The user should be aware of the practical advantages and disadvantages of the different designs. A ship can for example easily moor next to a caisson breakwater. On the other hand, the caisson breakwater can cause difficult navigation conditions, since the waves are almost fully reflected on the caisson. Subsequently, it is up to the user to decide which breakwater will be installed, based on practical engineering insight and the provided design parameters and costs in the CE-Cloud. Consequently, the user does not need to be a coastal engineering expert, but a certain background and engineering insight is required.

Note that the selection of the type of breakwater is based on one cross-section of the rubble-mound breakwater and one cross-section of the caisson breakwater. It is not possible, within the same CE-Cloud-file, to determine two complete designs for both breakwater types (if they consist of varying cross-sections). It is assumed that the first two designs of the first section for the rubble-mound and caisson breakwater already give a good indication of the proportions of costs and used materials for the total breakwater.

Multiple additional tools are implemented in the CE-Cloud to assist the engineer in analyzing and visualizing the design characteristics. The first tool is able to automatically generate an AutoCAD drawing of the designed cross-section. The second tool can save the corresponding coordinates of the cross-section in a textfile. By use of another tool, the user can easily analyze the different costs per meter of the total breakwater for the different trunk sections. This cost breakdown is expressed in function of the process steps (production, transport and construction) and used materials.

All applied formulas are clearly ordered in the VBA editor in function of the different design sheets. Annex A gives an overview of all these formulas. If certain expressions and approaches would be updated over the years, the corresponding formulas can easily be found and adjusted.

Note that the CE-Cloud provides a first conceptual design of the rubble-mound and caisson breakwater. If the program is extended later, the following features could be implemented further:

- Make it possible to insert a custom wave spectrum to define the hydraulic boundary conditions.
- Design of the crownwalls for the case of rubble-mound breakwaters.
- Let the user define the filter and core material, the CE-Cloud subsequently checks the different filter criteria.
- Filter criteria for the geotextile and bedprotection of the rubble-mound breakwater.
- Optimization of the caisson breakwater superstructure geometry by use of parapets.
- Wave conditions near the breakwater.
- Optimization of designing multiple cross-sections (assume same armour units for example)
- Let the user decide whether a roundhead is installed on the rubble-mound breakwater or not. Now it is automatically assumed that there are two roundheads at the ends of the rubble-

mound breakwater. This will almost never be the case, but the influence on the total breakwater cost of these roundheads is mostly negligible.

If the reader has any questions considering using or expanding the CE-Cloud, he/she can always contact me on laurensdesmet93@gmail.com.

Laurens De Smet, June 2016

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ANNEXES

ANNEX A: List of VBA functions

Table 23: Implemented functions - Hydraulic boundary conditions (RM+CB)

Hydraulic boundary conditions (RM+CB)		
Modules: RM_hydr and CB_hydr		
Function name	**Arguments**	**Description**
wlength0	T_p	Calculates the wave length in deep water by use of the linear wave theory
wlength	T_p, d	Calculates the wave length in water depth d by use of the linear wave theory
wdepth	d, L_m	Calculates whether the water is deep, shallow or transitional
surfs	ξ_m	Calculates whether the waves are spilling, plunging, collapsing or surging on an impermeable slope
PM_Tp	U_{10}	Calculates the peak period of the Pierson-Moskowitz spectrum based on a given wind velocity U_{10}
PM_m0	U_{10}	Calculates the total energy of the Pierson-Moskowitz spectrum
PM_values	U_{10}, f	Calculates the spectral density for a specific frequency and wind speed according to the Pierson-Moskowitz spectrum
JON_alpha	U_{10}, f	Calculates the parameter α in the expression for the JONSWAP spectral density
JON_wp	U_{10}, f, α	Calculates the peak rotational velocity of the JONSWAP wave spectrum
JON_m0	U_{10}, f	Calculates the total energy of the JONSWAP spectrum
JON_value	U_{10}, ω, T_p, γ, f	Calculates the spectral density of the JONSWAP spectrum
dataimport	/	Detects whether data are available or not for the seaside, RM
dataimportlee	/	Detects whether data are available or not for the leeside, RM
designheight	/	Calculates $H_{1/3}$ of a given set of wave heights for the seaside, RM
designhlee	/	Calculates $H_{1/3}$ of a given set of wave heights for the leeside, RM
designperiod	/	Calculates the design period $T_{1/3}$ of a given dataset for the seaside, RM
designplee	/	Calculates the design period $T_{1/3}$ of a given dataset for the leeside, RM
Bubblesort	Array	Sorts a given array from min to max
dataimport2	/	Detects whether data are available or not for the seaside, CB
designheight2	/	Calculates $H_{1/3}$ of a given set of wave heights for the seaside, CB

| designperiod2 | / | Calculates the design period $T_{1/3}$ of a given data set for the seaside, CB |

Table 24: Implemented functions - Armour layer unit selection (RM)

Armour layer unit selection (RM)		
Module: RM_ALU		
Function name	**Arguments**	**Description**
rockdn	H_s, γ_b, $\tan(\alpha)$, index1, $\triangle$	Calculates the equivalent cube length of a median rock which is stable for a rock (Hudson, 1974)
rockvdm	ξ_m, $\tan(\alpha)$, P, H_s, $\triangle$, S, N_z, s_m	Calculates the equivalent cube length of a median rock which is stable (Van der Meer, 1988)
rockvdmmod	R_c, H_s, s_{0p}	Calculates the coefficient f_i (Van der Meer, 1991)
cubesvdm	H_s, $\triangle$, N_{od}, N_z, s_m	Calculates the median cube length (Van der Meer, 1988b)
cubesbbl	H_s, $\triangle$, d, γ_b, $\tan(\alpha)$	Calculates the median cube length (Brorson, Burcharth and Larsen, 1974)
dolos1	H_s, $\triangle$, N_{od}, N_z, r, φ, s_{0m}	Calculates the equivalent cube length of the median rock for dolos (Burcharth and Liu, 1992)
accropode7	H_s, $\triangle$, γ_b	Calculates the equivalent cube length of accropodes (Van der Meer, 1988b)
accropode72	H_s, $\triangle$, d, s_m	Calculates the equivalent cube length of accropodes (Burcharth et al., 1998)
armourkd	H_s, $\triangle$, $\tan(\alpha)$, index	Calculates the equivalent cube length of CORE-LOCs (Melby and Turk, 1994)
tetrapodsvdm	H_s, N_{od}, $\triangle$, N_z, s_{0m}, γ_b, s_m	Calculates the equivalent cube length for tetrapods (Van der Meer, 1988b)

Table 25: Implemented functions - Crest freeboard assessment (RM)

Crest freeboard assessment (RM)		
Module: RM_overtopping		
Function name	**Arguments**	**Description**
findgammaf	ALU (string)	Calculates the roughness reduction factor or a particular armour layer unit (CEM)
overtopdet	q, H_{m0}, ξ_{m0}, $\tan(\alpha)$, γ_b, γ_f, γ_β, γ_v	Calculates the needed crest freeboard for a given mean overtopping discharge according to the deterministic approach (EurOtop Manual)
overtopprob	q, H_{m0}, ξ_{m0}, $\tan(\alpha)$, γ_b, γ_f, γ_β, γ_v	Calculates the needed crest freeboard for a given mean overtopping discharge according to the probabilistic approach (EurOtop Manual)
overtopowenastr	$\tan(\alpha)$	Calculates the coefficient "a" for straight smooth slopes (Owen, 1980/1982)
overtopowenbstr	$\tan(\alpha)$	Calculates the coefficient "b" for straight smooth slopes (Owen, 1980/1982)
overtopowenaberm	$\tan(\alpha)$, h_B, b	Calculates the coefficient "a" for bermed smooth slopes (Owen, 1980/1982)
overtopowenbberm	$\tan(\alpha)$, h_B, b	Calculates the coefficient "b" for bermed smooth slopes (Owen, 1980/1982)
overtopowen	q, H_s, T_{0m}, $\tan(\alpha)$, s_{0m}, a, b, γ_r, γ_b	Calculates the needed crest freeboard for a given mean overtopping discharge (Owen, 1980/1982)
overtopbradbury	q, H_s, T_{0m}, $\tan(\alpha)$, s_{0m}, d, index1, γ_b, ALU (string)	Calculates the needed crest freeboard for a given mean overtopping discharge (Bradbury and Allsop, 1988)
overtopaminti	q, H_{m0}, T_{0m}, $\tan(\alpha)$, s_{0m}, index1, index2, γ_b	Calculates the needed crest freeboard for a given mean overtopping discharge (Aminti and Franco, 1988)
overtoppederson	q, H_s, T_{0m}, L_{0m}, $\tan(\alpha)$, A_c, b, ALU (string)	Calculates the needed crest freeboard for a given mean overtopping discharge for a rock armoured permeable slope with a berm in front of a crown wall (Pedersen and Burcharth, 1992)
gammabeta	β	Calculates the oblique waves reduction factor (EurOtop)
overtopRu2	γ_b, γ_f, γ_β, ξ_m, H_{m0}, index	Calculates the wave run-up height exceeded by 2% of the incoming waves (EurOtop)
gammab	r_B, d_B, R_{u2det}, H_{m0}, R_{u2prob}, index	Calculates the berm reduction factor (EurOtop)
gammabetacem	β	Calculates the oblique waves reduction factor (CEM)

| gammahcem | H_s, γ_b, ξ_{op}, γ_r, γ_β | Calculates shallow water runup reduction factor (CEM) |
| overtopvdmandj | q, H_s, s_{0p}, $\tan(\alpha)$, γ_r, γ_b, γ_β, γ_h, ξ_{op} | Calculates the needed crest freeboard for a given mean overtopping discharge (Van der Meer and Janssen, 1995) |

Table 26: Implemented functions - Crest freeboard assessment (CB)

Crest freeboard assessment (CB)		
Module: CB_overtopping		
Function name	**Arguments**	**Description**
overtopdetcb	q, H_{m0}	Calculates the needed crest freeboard for a given mean overtopping discharge according to the deterministic design (EurOtop)
overtopprobcb	q, H_{m0}	Calculates the needed crest freeboard for a given mean overtopping discharge according to the probabilistic design (EurOtop)
gammabetacb	β	Calculates the oblique waves reduction factor (EurOtop)
overtopfrancocb	q, H_s, γ_β, γ_s, γ_b	Calculates the needed crest freeboard for a given mean overtopping discharge (Franco and Franco, 1999)
overtopdetcb2	q, H_{m0}, d, h_s, h	Calculates the needed crest freeboard for a given mean overtopping discharge according to the deterministic design for a composite vertical wall (EurOtop)
overtopprobcb2	q, H_{m0}, d, h_s, h	Calculates the needed crest freeboard for a given mean overtopping discharge according to the probabilistic design for a composite vertical wall (EurOtop)

Table 27: Implemented functions - Pressures on the caisson (CB)

Pressures on the caisson (CB)		
Module: CB_pressures		
Function name	**Arguments**	**Description**
alphaasterisk	h_{toe}, d, $B_{M,sea}$, L_p, H_s, h_b, index	Calculates the α_* factor for the Goda approach to calculate the pressures on the caisson (Goda, 1974)

Table 28: Implemented functions - Foundation design (CB)

Foundation design (CB)		
Module: CB_dimensions		
Function name	**Arguments**	**Description**
footprot	H_{m0}, h_b, h_s	Calculates the needed type of footprotection according to Japanese practice (CEM)
footprotl	index	Calculates the length of a foot protection block (CEM)
footprotb	index	Calculates the width of a foot protection block (CEM)
footprott	index	Calculates the thickness of a foot protection block (CEM)
Footprotm	index	Calculates the weight of a foot protection block (CEM)

Table 29: Implemented functions - Filter layer assessment (RM+CB)

Filter layer assessment (RM + CB)		
Module: RM_filters		
Function name	**Arguments**	**Description**
findkd	alu, rough	Calculates the layer coefficient k_Δ of the selected ALU (CEM)
grading1	W	Calculates whether the used filter material is heavy, light or coarse (Rosin-Rammler, 1993)
grading2	W, size, ρ_s	Calculates the grading of the used filter and/or core material (Rosin-Rammler, 1993)
M_50	grading, ρ_s	Calculates the mass of the median rock
D_n10	grading	Calculates the diameter for which 10% of the rocks are smaller
D_n15	grading	Calculates the diameter for which 15% of the rocks are smaller
D_n60	grading	Calculates the diameter for which 60% of the rocks are smaller
D_n85	grading	Calculates the diameter for which 85% of the rocks are smaller
plot_filter	grading, y	Gives the value of M_y for a certain grading and fraction y

Table 30: Implemented functions - Toe design (RM)

Toe design (RM)		
Module: RM_toe		
Function name	**Arguments**	**Description**
toevdm	H_s, d_B, ρ_w, N_{od}, h_{toe}, berm, d	Calculates the D_{n50} of stable rocks for the toe protection (Van der Meer, d'Angremond and Gerding, 1995)
findmat	D_{n50}, ρ_s	Calculates the grading for the proposed rocks for the toe protection
toeburch	H_s, h, ρ_w, N_{od}, h_{toe}, berm,d, ρ_s	Calculates D_{n50} of stable rocks or concrete cubes for the toe protection (Burcharth et al., 1995a)

Table 31: Implemented functions - Width and safety assessment (CB)

Width and safety assessment (CB)		
Module: CB_Bands		
Function name	**Arguments**	**Description**
bearingp	B, M, M_U, M_H, F_u	Calculates the bearing capacity of the rubble-mound foundation (CEM)
findbsf1	R_c, t_{slab}, n_{part}, t_{part}, t_{outer}, t_{bottom}, hh, $\rho_{c,dru}$, $\rho_{s,dry}$, $\rho_{c,wet}$, $\rho_{s,wet}$, F_H, μ, F_{Ub}	Calculates the necessary width of the caisson corresponding to safety against sliding (not used in the CE-Cloud)
findbfromm	M, R_c, t_{slab}, n_{part}, t_{part}, t_{outer}, t_{bottom}, hh, $\rho_{c,dru}$, $\rho_{s,dry}$, $\rho_{c,wet}$, $\rho_{s,wet}$	Calculates the necessary width of the caisson, for a certain mass M (not used in the CE-Cloud)
mumax	S, index1, index2	Calculates the dynamic friction factor between the caisson and the levelling material (Marihari, Kihara and Harikawa, 1988)

Table 32: Implemented functions - Cost assessment (RM)

Cost assessment (RM)		
Module: RM_costs		
Function name	**Arguments**	**Description**
costmat	mat, M_{50}, V, M, r,c	Calculates the cost price of the used material
costconstr	mat, M_{50}, V, M, r, c	Calculates the construction cost based on the used materials

Table 33: Implemented functions - Cost assessment (CB)

Cost assessment (CB)		
Module: CB_costs		
Function name	**Arguments**	**Description**
cbcostalu	M_{50}, M, c, r	Calculates the construction cost for the rocks which are used as armour layer units for the rubble-mound caisson foundation

Table 34: Implemented functions - Additional tools (RM+CB)

Additional tools (RM + CB)		
Module: mACADPolyline		
Function name	**Arguments**	**Description**
Drawpolyline2	/	Automatically generates an AutoCAD drawing of the breakwater as a polyline which passes through each of the generated coordinates/nodes.
exceltonotpad	/	Saves the generated coordinates in a textfile ""C:\Users\Username\Documents\coordinates.txt"

ANNEX B: Progress overview

B.1. Rubble-mound breakwater
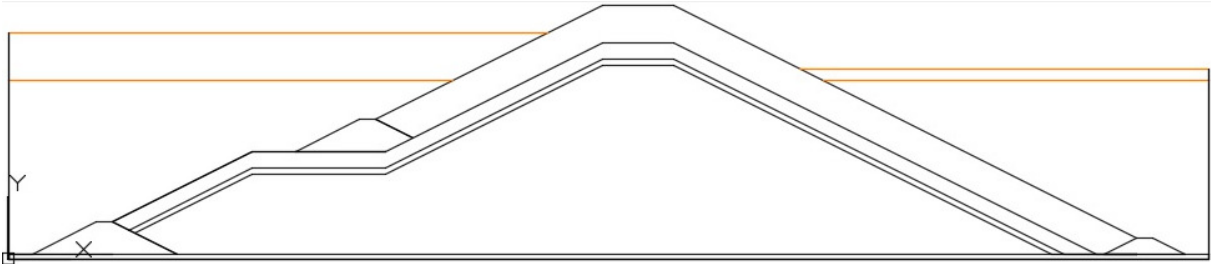
Figure 69: RM progress - Hydraulic boundary conditions
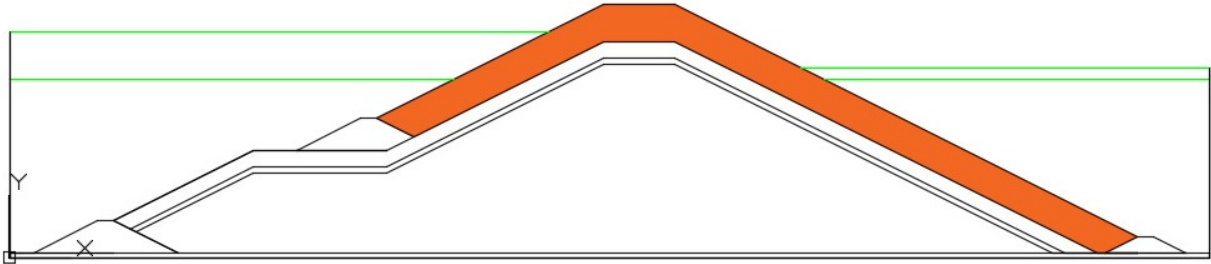
Figure 70: RM progress - Armour layer units assessment
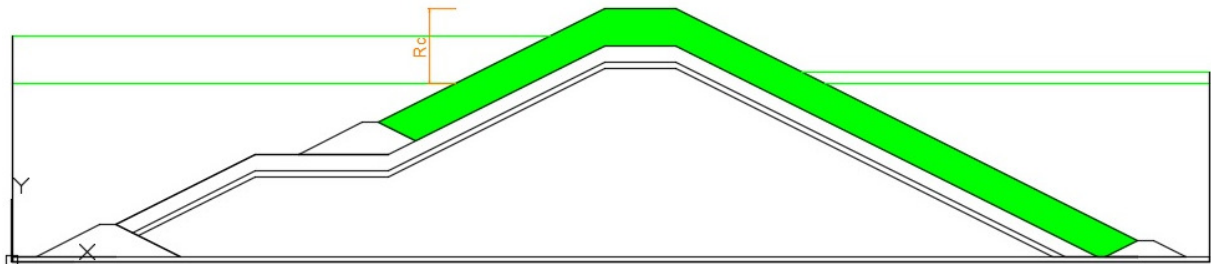
Figure 71: RM progress - Height assessment
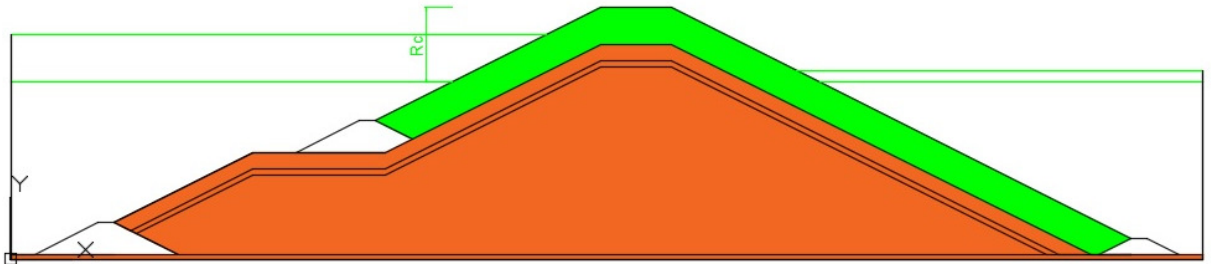
Figure 72: RM progress - Filter and core selection
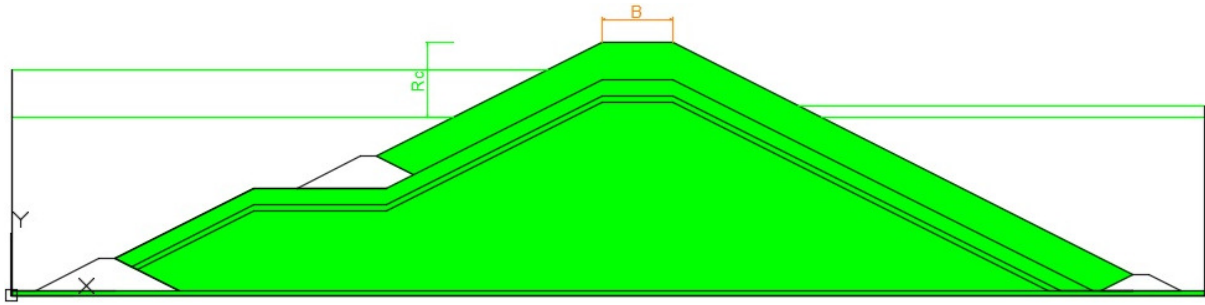
Figure 73: RM progress - Crest width
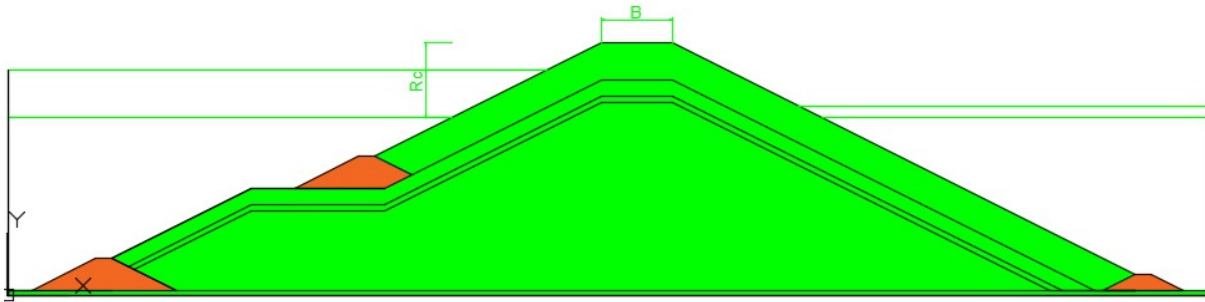
Figure 74: RM progress - Toe stability
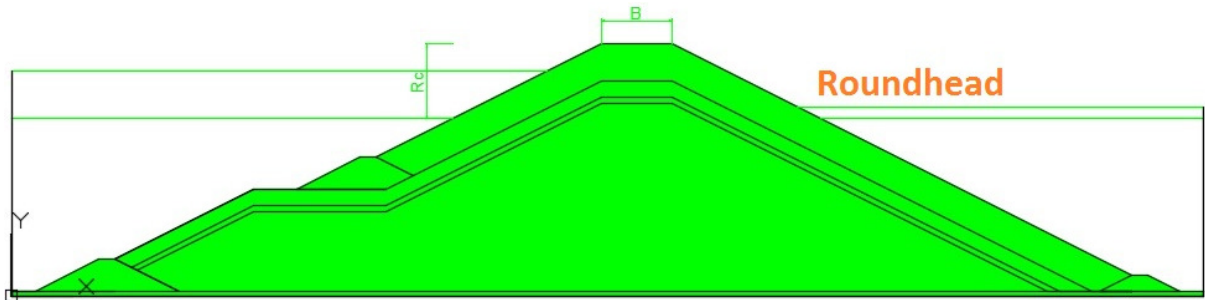
Figure 75: RM progress - Roundhead design
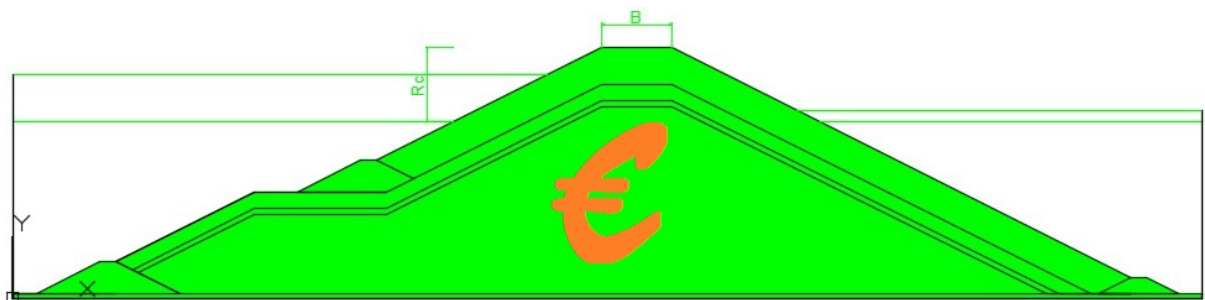
Figure 76: RM progress - Cost assessment

B.2. Caisson breakwater
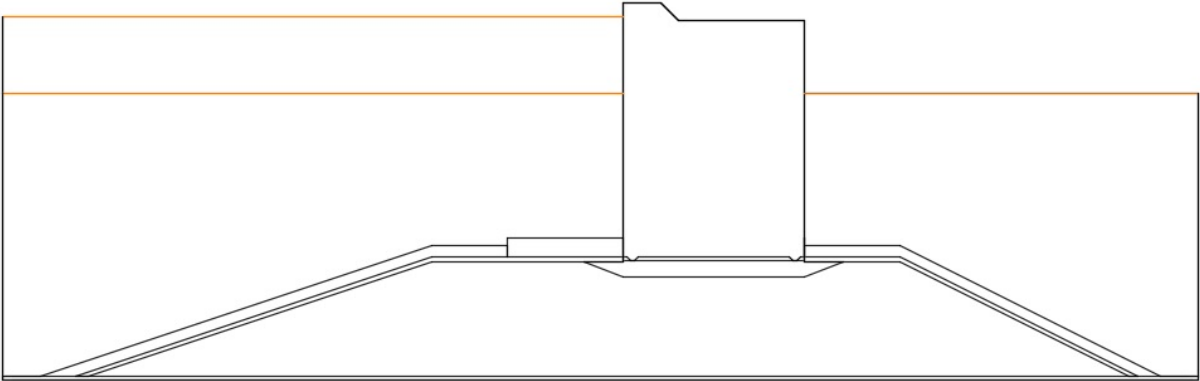
Figure 77: CB progress - Hydraulic boundary conditions
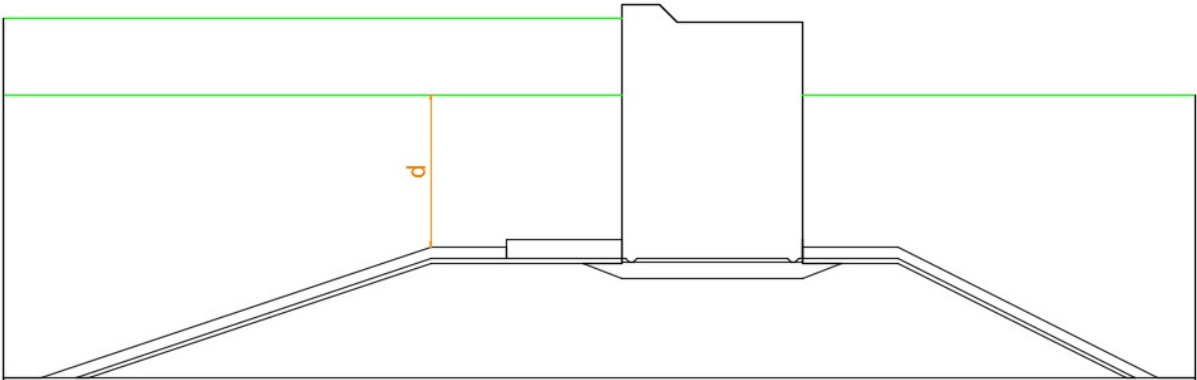
Figure 78: CB progress - Design water depth at the toe of the caisson
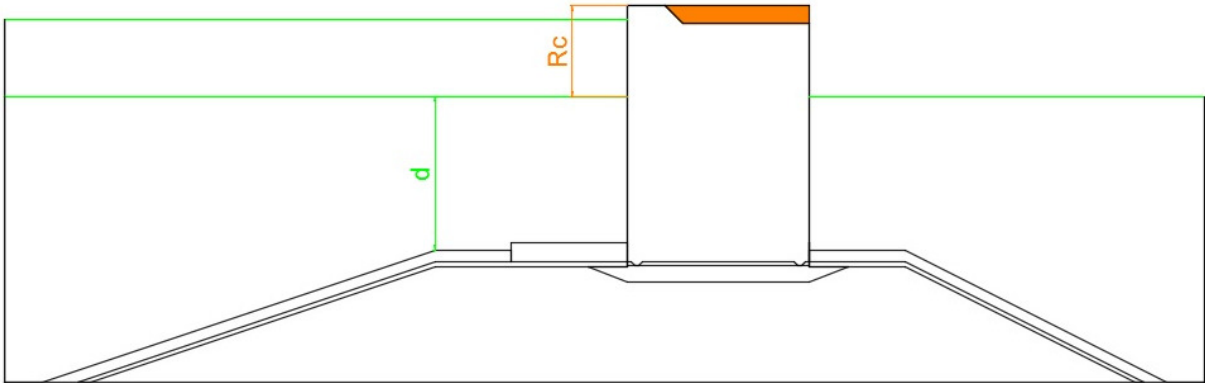
Figure 79: CB progress - Height assessment
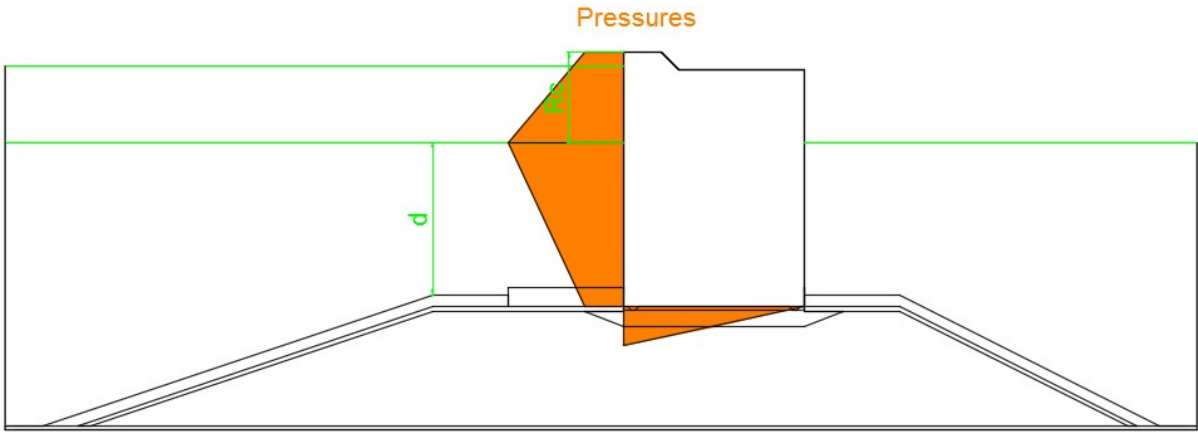
Pressures

Figure 80: CB progress - Pressures on the caisson
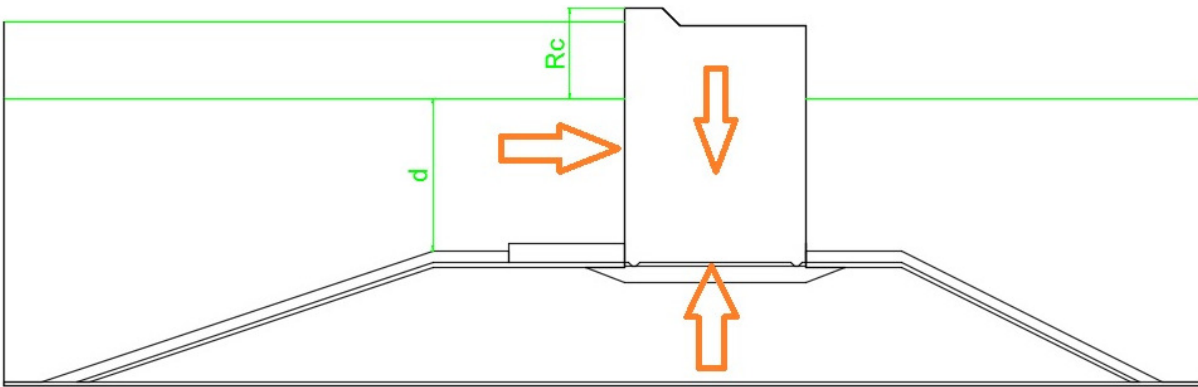
Figure 81: CB progress - Forces and moments
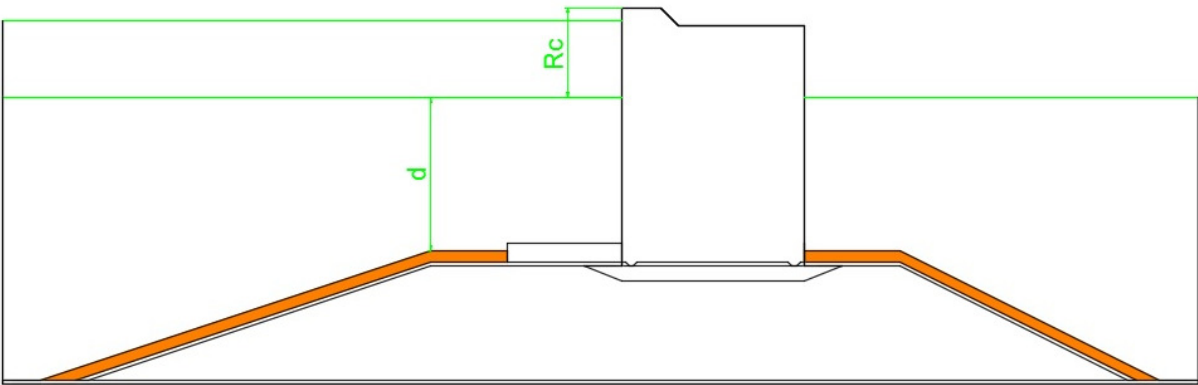
Figure 82: CB progress - Armour unit selection
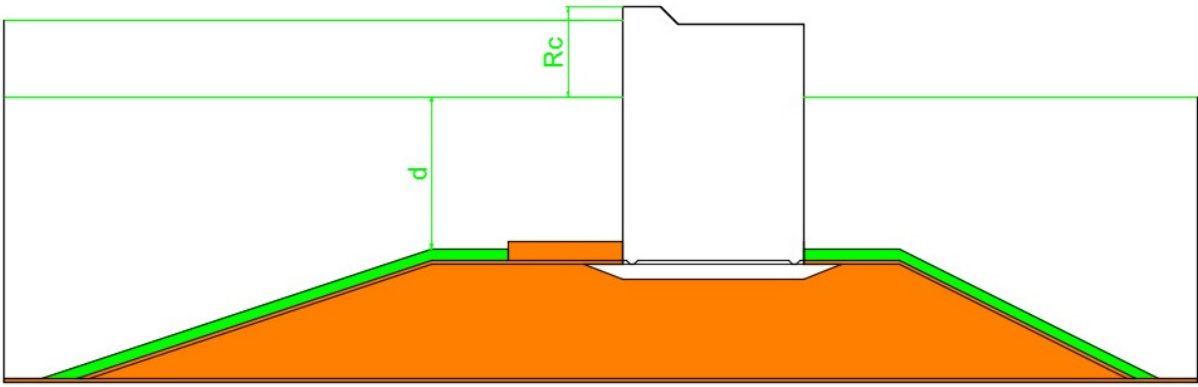
Figure 83: CB progress - Foundation details
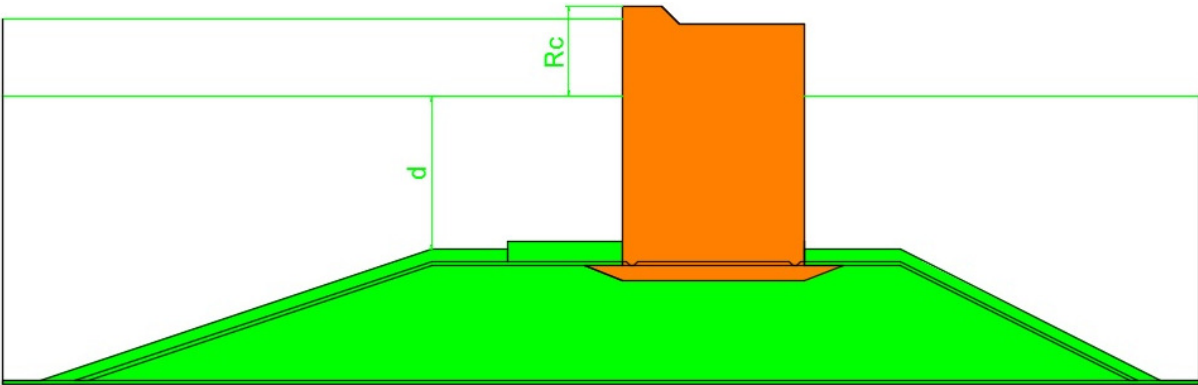
Figure 84: CB progress - Width and safety assessment
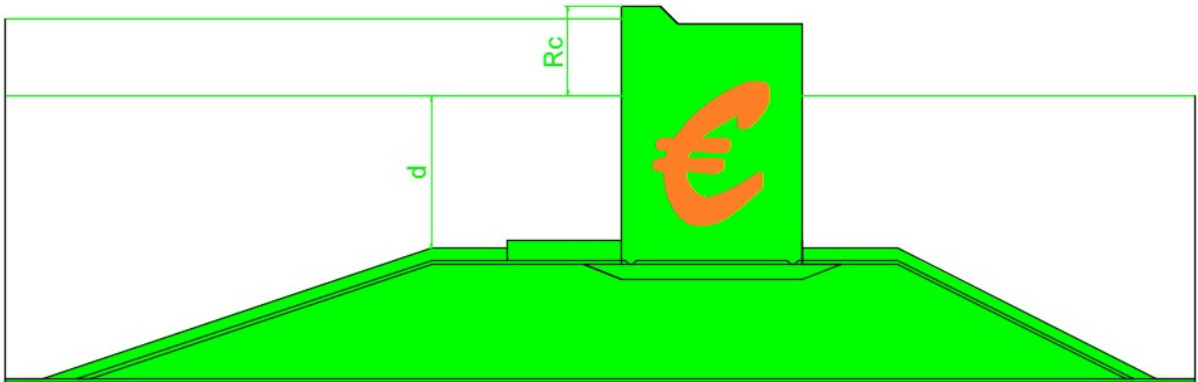
Figure 85: CB progress - Cost assessment

ANNEX C: Design example

CE ≈ cloud

®LWI/UGent, 2014

Coastal Engineering ~ collection of university research and design tools

Introduction

CE~cloud is an Excel-based calculation tool for many tasks in coastal engineering applications.

Press one of the buttons on the right side to continue.

Enjoy!

Waves

- Wave Hincdast
- Linear Wave Theory

Energy

Dikes

- Runup & Overtopping

Prob. & Risk

- Distrib. function
- Monte Carlo Sim.

Rubble-mound breakwater

- Hydr boundaries
- Armour units
- Height assessment
- Filter layers
- Crest width
- Toe stability
- Roundhead design
- Cost assessment
- Final design

Caisson breakwater

- Hydr boundaries
- Design waterdepth
- Height assessment
- Pressures
- Forces and moments
- Armour units
- Foundation details
- Width and safety
- Cost assessment
- Final design

Total cost

115

Implementation of the boundary conditions (sea+lee)
Source: CEM, Goda
Author: L. De Smet

Input of the user is required		Main Menu
Parameters for intermediate results		
Parameters which can be selected as final result		See progress

SEASIDE

General input

ρ_w	1,025	t/m³	Density of the water
d	15	m	Water depth
α	0	°	Bottom slope
β	10	°	Angle of wave incidence (0° is head-on)
T_p/T_m	1,25	[-]	Mean wave period ratio **(default: 1,25)**
T_p/T_m-1,0	1,1	[-]	Spectral wave period ratio **(default: 1,1)**

Further input

1. Manual input

H_s	3	m	Design wave height
T_p	9	s	Peak wave period
T_m	7,2	s	Mean wave period
T_m-1,0	8,18	s	Spectral wave period
L_p0	126,47	m	Wave length in deep water
L_p	95,57	m	Local wave length
Intermediate water			Type of water
s_p0	0,0237	[-]	Deep water wave steepness
s_p	0,0314	[-]	Local wave steepness
L_m0	80,94	m	Wave length in deep water
L_m	70,49	m	Local wave length
Intermediate water			Type of water
s_m0	0,0371	[-]	Deep water wave steepness
s_m	0,0426	[-]	Local wave steepness
L_m-1,0	104,47	m	Wave length in deep water
L_m-1	84,3	m	Local wave length
Intermediate water			Type of water
s_m-1,0	0,0287	[-]	Deep water wave steepness
s_m-1	0,0356	[-]	Local wave steepness

Set as parameters

2. Pierson-Moskowitz spectrum

U_10	12	m/s	Wind speed at 10 m above sea level
m_0	0,6542	m²	Total wave energy
H_s	3,24	m	Design wave height based on m_0
T_p	8,99	s	Peak wave period
T_m	7,19	s	Mean wave period
T_m-1,0	8,17	s	Spectral wave period
L_p0	126,19	m	Deep water wave length
L_p	95,44	m	Local wave length
Intermediate water			Type of water
s_p0	0,0257	[-]	Deep water wave steepness
s_p	0,0339	[-]	Local wave steepness
L_m0	80,71	m	Wave length in deep water
L_m	70,35	m	Local wave length
Intermediate water			Type of water
s_m0	0,0401	[-]	Deep water wave steepness
s_m	0,0461	[-]	Local wave steepness
L_m-1,0	104,22	m	Wave length in deep water
L_m-1	84,16	m	Local wave length
Intermediate water			Type of water
s_m-1,0	0,0311	[-]	Deep water wave steepness
s_m-1	0,0385	[-]	Local wave steepness

Set as parameters

PM and JONSWAP spectrum

3. JONSWAP spectrum

U_10	12	m/s	Wind speed at 10 m above sea level
F	250000	m	Length of fetch
gamma	3,3	[-]	Peak enhancement **(between 1 and 3,3)**
m_0	0,6128	m²	Total wave energy
H_s	3,13	m	Design wave height based on m_0
T_p	8,99	s	Peak wave period
T_m	7,19	s	Mean wave period
T_m-1,0	8,17	s	Spectral wave period
L_p0	126,19	m	Deep water wave length
L_p	95,44	m	Local wave length
Intermediate water			Type of water
s_p0	0,0248	[-]	Deep water wave steepness
s_p	0,0328	[-]	Local wave steepness
L_m0	80,71	m	Wave length in deep water
L_m	70,35	m	Local wave length
Intermediate water			Type of water
s_m0	0,0388	[-]	Deep water wave steepness
s_m	0,0445	[-]	Local wave steepness
L_m-1,0	104,22	m	Wave length in deep water
L_m-1	84,16	m	Local wave length
Intermediate water			Type of water
s_m-1,0	0,03	[-]	Deep water wave steepness
s_m-1	0,0372	[-]	Local wave steepness

Set as parameters

4. Imported file

Import wave heights and periods by clicking on the "Import data" button

Import data

→ Data are available

H_1/3	3,63	m	Design wave height according to Goda
T_1/3	7,77	s	Design wave period according to Goda
T_p	9,71	s	Peak wave period estimation
T_m-1,0	8,83	s	Spectral wave period
L_p0	147,21	m	Deep water wave length
L_p	105,17	m	Local wave length
Intermediate water			Type of water
s_p0	0,0247	[-]	Deep water wave steepness
s_p	0,0345	[-]	Local wave steepness
L_m0	94,26	m	Deep water wave length
L_m	78,57	m	Local wave length
Intermediate water			Type of water
s_m0	0,0385	[-]	Deep water wave steepness
s_m	0,0462	[-]	Local wave steepness
L_m-1,0	121,73	m	Wave length in deep water
L_m-1	93,25	m	Local wave length
Intermediate water			Type of water
s_m-1,0	0,0298	[-]	Deep water wave steepness
s_m-1	0,0389	[-]	Local wave steepness

Set as parameters

Final output

			Delete final values

ρ_w	1,025	t/m³	Density of the water
d	15	m	Water depth
α	0	°	Bottom slope angle
β	10	°	Angle of wave incidence
H_s	3	m	Design wave height
T_p	9	s	Peak wave period
T_m	7,2	s	Mean wave period
$T_{m-1,0}$	8,18	s	Spectral wave period
L_{p0}	126,47	m	Deep water wave length
L_p	95,57	m	Local wave length
s_{p0}	0,0237	[-]	Deep water wave steepness
s_p	0,0314	[-]	Local wave steepness
L_{m0}	80,94	m	Deep water wave length
L_m	70,49	m	Local wave length
s_{m0}	0,0371	[-]	Deep water wave steepness
s_m	0,0426	[-]	Local wave steepness
$L_{m-1,0}$	104,47	m	Wave length in deep water
L_{m-1}	84,3	m	Local wave length
$s_{m-1,0}$	0,0287	[-]	Deep water wave steepness
s_{m-1}	0,0356	[-]	Local wave steepness

LEESIDE

General input

β	10	°	Angle of wave incidence
T_p/T_m	1,25	[-]	Mean wave period ratio **(default: 1,25)**
$T_p/T_{m-1,0}$	1,1	[-]	Spectral wave period ratio **(default: 1,1)**

Further input

1. Manual input

H_s	1,2	m	Wave height
T_p	7	s	Peak wave period
T_m	5,6	s	Mean wave period
$T_{m-1,0}$	6,36	s	Spectral wave period
L_{p0}	76,5	m	Wave length in deep water
L_p	67,63	m	Local wave length
Intermediate water			Type of water
s_{p0}	0,0157	[-]	Deep water wave steepness
s_p	0,0177	[-]	Local wave steepness
L_{m0}	48,96	m	Wave length in deep water
L_m	47,19	m	Local wave length
Intermediate water			Type of water
s_{m0}	0,0245	[-]	Deep water wave steepness
s_m	0,0254	[-]	Local wave steepness
$L_{m-1,0}$	63,15	m	Wave length in deep water
L_{m-1}	58,35	m	Local wave length
Intermediate water			Type of water
$s_{m-1,0}$	0,019	[-]	Deep water wave steepness
s_{m-1}	0,0206	[-]	Local wave steepness

Set as parameters

2. Pierson-Moskowitz spectrum

U_{10}	7	m/s	Wind speed at 10 m above sea level
m_0	0,0758	m²	Total wave energy
H_s	1,1	m	Design wave height based on m_0
T_p	5,25	s	Peak wave period
T_m	4,2	s	Mean wave period
$T_{m-1,0}$	4,77	s	Spectral wave period
L_{p0}	43,03	m	Deep water wave length
L_p	42,07	m	Local wave length
Intermediate water			Type of water
s_{p0}	0,0256	[-]	Deep water wave steepness
s_p	0,0261	[-]	Local wave steepness
L_{m0}	27,54	m	Wave length in deep water
L_m	27,48	m	Local wave length
Deep water			Type of water
s_{m0}	0,0399	[-]	Deep water wave steepness
s_m	0,04	[-]	Local wave steepness
$L_{m-1,0}$	35,52	m	Wave length in deep water
L_{m-1}	35,19	m	Local wave length
Intermediate water			Type of water
$s_{m-1,0}$	0,031	[-]	Deep water wave steepness
s_{m-1}	0,0313	[-]	Local wave steepness

Set as parameters

3. JONSWAP spectrum

U_{10}	7	m/s	Wind speed at 10 m above sea level
F	100000	m	Length of fetch
gamma	3,3	[-]	Peak enhancement **(between 1 and 3,3)**
m_0	0,0834	m²	Total wave energy
H_s	1,16	m	Design wave height based on m_0
T_p	5,53	s	Peak wave period
T_m	4,42	s	Mean wave period
$T_{m-1,0}$	5,03	s	Spectral wave period
L_{p0}	47,75	m	Deep water wave length
L_p	46,16	m	Local wave length
Intermediate water			Type of water
s_{p0}	0,0243	[-]	Deep water wave steepness
s_p	0,0251	[-]	Local wave steepness
L_{m0}	30,5	m	Wave length in deep water
L_m	30,38	m	Local wave length
Intermediate water			Type of water
s_{m0}	0,038	[-]	Deep water wave steepness
s_m	0,0382	[-]	Local wave steepness
$L_{m-1,0}$	39,5	m	Wave length in deep water
L_{m-1}	38,89	m	Local wave length
Intermediate water			Type of water
$s_{m-1,0}$	0,0294	[-]	Deep water wave steepness
s_{m-1}	0,0298	[-]	Local wave steepness

Set as parameters

4. Imported file

Import wave heights and periods by clicking on the "Import data" button

Import data

→ Data are available

$H_{1/3}$	3,63	m	Design wave height according to Goda
$T_{1/3}$	7,77	s	Design wave period according to Goda
T_p	9,71	s	Peak wave period estimation
$T_{m-1,0}$	8,83	s	Spectral wave period

PM and JONSWAP spectrum

Chart: S(f) [-] vs Frequency [1/s], legend: Pierson-Moskowitz Spectrum (blue), JONSWAP spectrum (red)

L_p0	147,21	m	Deep water wave length
L_p	105,17	m	Local wave length
Intermediate water			Type of water
s_p0	0,0247	[-]	Deep water wave steepness
s_p	0,0345	[-]	Local wave steepness
L_m0	94,26	m	Deep water wave length
L_m	78,57	m	Local wave length
Intermediate water			Type of water
s_m0	0,0385	[-]	Deep water wave steepness
s_m	0,0462	[-]	Local wave steepness
L_m-1,0	121,73	m	Wave length in deep water
L_m-1	93,25	m	Local wave length
Intermediate water			Type of water
s_m-1,0	0,0298	[-]	Deep water wave steepness
s_m-1	0,0389	[-]	Local wave steepness

Set as parameters

Final output

Click on one of the "Set a parameter" buttons
to select the appropriate parameters

Delete final values

ρ_w	1,025	t/m³	Density of the water
d	15	m	Water depth
α	0	°	Bottom slope angle
β	10	°	Angle of wave incidence
H_s	1,2	m	Design wave height
T_p	7	s	Peak wave period
T_m	5,6	s	Mean wave period
T_m-1,0	6,36	s	Spectral wave period
L_p0	76,5	m	Deep water wave length
L_p	67,63	m	Local wave length
s_p0	0,0157	[-]	Deep water wave steepness
s_p	0,0177	[-]	Local wave steepness
L_m0	48,96	m	Deep water wave length
L_m	47,19	m	Local wave length
s_m0	0,0245	[-]	Deep water wave steepness
s_m	0,0254	[-]	Local wave steepness
L_m-1,0	63,15	m	Wave length in deep water
L_m-1	58,35	m	Local wave length
s_m-1,0	0,019	[-]	Deep water wave steepness
s_m-1	0,0206	[-]	Local wave steepness

Go to the next design step

CE cloud

Armour layer selection
Source: CEM
Author: L. De Smet

Input of the user is required
Parameters for intermediate results
Parameters which can be selected as final result

Main Menu
See progress

SEASIDE

General input

ρ_s	2,6	t/m³	Density of the armour units (default: 2,6)
Δt	43200	s	Duration of design storm (default 12h = 43200 s)
Δ	1,54	s	ρ_s/ρ_w-1
N_z	6000	[-]	Amount of waves
H_s	3	m	Design wave height
s_m	0,0426	[-]	Local wave steepness
s_0m	0,0371	[-]	Deep water wave steepness
s_0p	0,0314	[-]	Deep water wave steepness
γ_b_sea	0,2	[-]	Breaker index for the seaside
Breaking?	No	[-]	Are the seawaves depth-limited?

Rocks: Hudson - Van der Meer 1988 - Modified Van der Meer 1991

Input Van der Meer 1988
| P | 0,4 | [-] | Notional permeability |

Input Van der Meer 1991
| R_c | 3,8 | m | Crest freeboard |

Stone shape	Placement	tan(α)	ξ_m	Hudson D_n50	Hudson M_50		Van der Meer (1988) D_n50	Van der Meer (1988) M_50		Van der Meer (1991) D_n50	Van der Meer (1991) M_50	
		[-]	[-]	m	t		m	t		m	t	
Smooth & rounded	random	1:1	4,85	1,46	8,09	Select	1,7	12,77	Select	2,07	23,06	Select
		1:1,33	3,64	1,32	5,98	Select	1,47	8,26	Select	1,79	14,91	Select
		1:1,5	3,23	1,27	5,33	Select	1,38	6,83	Select	1,68	12,33	Select
		1:2	2,42	1,15	3,95	Select	1,2	4,49	Select	1,46	8,09	Select
		1:3	1,62	1,01	2,68	Select	0,98	2,45	Select	1,19	4,38	Select
		1:4	1,21	0,92	2,02	Select	0,78	1,23	Select	0,95	2,23	Select
Rough & angular	random	1:1	4,85	1,23	4,84	Select	1,7	12,77		2,07	23,06	
		1:1,33	3,64	1,12	3,65	Select	1,47	8,26		1,79	14,91	
		1:1,5	3,23	1,07	3,19	Select	1,38	6,83		1,68	12,33	
		1:2	2,42	0,97	2,37	Select	1,2	4,49		1,46	8,09	
		1:3	1,62	0,85	1,6	Select	0,98	2,45		1,19	4,38	
		1:4	1,21	0,77	1,19	Select	0,78	1,23		0,95	2,23	
Rough & angular	special	1:1	4,85	1,02	2,76	Select	1,7	12,77		2,07	23,06	
		1:1,33	3,64	0,93	2,09	Select	1,47	8,26		1,79	14,91	
		1:1,5	3,23	0,89	1,83	Select	1,38	6,83		1,68	12,33	
		1:2	2,42	0,81	1,38	Select	1,2	4,49		1,46	8,09	
		1:3	1,62	0,71	0,93	Select	0,98	2,45		1,19	4,38	
		1:4	1,21	0,64	0,68	Select	0,78	1,23		0,95	2,23	

Cubes: Van der Meer 1988b - Brorsen, Burcharth and Larsen (1974) - Hudson

Input Van der Meer
| N_od | 1 | [-] | Number of units displaced out of the armour layer within a strip width of one cube length D_n |

Input Brorsen, Burcharth, Larsen
| tan(α) | 0,50 | [-] | Tangens of the breakwater slope, only 1/1,5 and 1/2 is possible |
| D | 5 | % | Damage level |

Input Hudson
| K_D | 7,5 | [-] | Stability coefficient |
| tan(α) | 0,5 | [-] | Tangens of the breakwater slope, only 1/1,5; 1/2 and 1/3 is possible |

	D_n50	M_50	
Van der Meer	1,79	14,91	Select
Brorsen, Burcharth ...	0,85	1,6	Select
Hudson	0,79	1,28	Select

Tetrapods: Van der Meer 1988b - Hudson

Input van der Meer
| N_od | 1 | [-] | Number of units displaced out of the armour layer within a strip width of one cube length D_n |

Input Hudson
| K_D | 2 | [-] | Stability coefficient |
| tan(α) | 0,67 | [-] | Tangens of the breakwater slope |

	D_n50	M_50	
Van der Meer	N/A	N/A	Select
Hudson	1,35	6,4	Select

Dolos: Burcharth and Liu 1992

Burcharth input
N_od	1	[-]	Number of units displaced out of the armour layer within a strip width of one cube length D_n
r	0,35	[-]	Dolos waist ratio (values between 0,32 and 0,42)
φ	0,7	[-]	Packing density (values between 0,61 and 1)

	D_n50	M_50	
Burcharth and Liu	0,75	1,1	Select

Accropode: Van der Meer 1988b - Burcharth et al. 1998 - Sogreah/Hudson

Input Burcharth et al.
| D | 5 | [-] | Relative number of units displaced more than a distance D_n |

Input Hudson
| K_D | 15 | [-] | Stability coefficient |

	D_n50	M_50	
Van der Meer	0,53	0,39	Select
Burcharth et al.	0,47	0,27	Select
Hudson	0,72	0,97	Select

Core-Loc: Melby and Turk 1994/1997

Melby and Turk			
	trunk		
tan(α)	D_n50	M_50	
	m	t	
1:1	0,77	1,19	Select
1:1,33	0,7	0,89	Select
1:1,5	0,68	0,82	Select
1:2	0,61	0,59	Select
1:3	0,54	0,41	Select
1:4	0,49	0,31	Select

Tribar: Hudson

Input Hudson			
Placed randomly?	Random	Pattern	
Slope	1:1,5	☐	/
	1:2	☑	☐
	1:3	☐	/

tan(α)	0,5	[-]	Tangens of the breakwater slope
K_D	10	[-]	Stability coefficient

	D_n50	M_50	
Hudson	0,72	0,97	Select

Xbloc: Hudson

Input Hudson			
N_s	2,8	[-]	Stability number

	D_n50	M_50	
Hudson	0,7	0,89	Select

Final values

Type of armour unit	Rocks	[-]	Type of armour layer unit
Stone shape	Smooth & rounded	[-]	Shape of the unit
Placement	Randomly	[-]	How are the units placed?
Theory	Hudson	[-]	Which theory was used
ρ_s	2,6	t/m³	Density of the rocks/units
tan(α)	1:1,5	[-]	Tangens of the breakwater slope
D_n50	1,27	m	Diameter of the median rock size
M_50	5,33	t	Median rock/unit weight
Amount of layers	2	[-]	Number of ALU layers

LEESIDE

If you want to use the same design at the leeside, please click on the button below

Same as the seaside

Otherwise you can implement rocks below:

General input

ρ_s	2,6	t/m³	Density of the units
Δt	43200	[-]	Duration of design storm
Δ	1,54	s	ρ_s/ρ_w-1
N_z	7714	[-]	Amount of waves
H_s	1,2	m	Design wave height
s_m	0,0254	[-]	Local wave steepness
s_0m	0,0245	[-]	Deep water wave steepness
s_0p	0,0157	[-]	Deep water wave steepness
γ_b_sea	0,08	[-]	Breaker index for the seaside
Breaking?	No	[-]	Are the seawaves depth-limited?

Rocks: Hudson - Van der Meer 1988 - Modified Van der Meer 1991

Input Van der Meer 1988			
P	0,4	[-]	Notional permeablility

Input Van der Meer 1991			
R_c	3,8	m	Crest freeboard

Stone shape	Placement	tan(α)	ξ_m	breaking?	Hudson			Van der Meer (1988)			Van der Meer (1991)		
					D_n50	M_50		D_n50	M_50		D_n50	M_50	
		[-]	[-]		m	t		m	t		m	t	
Smooth & rounded	random	1:1	6,27		0,58	0,51	Select	0,71	0,93	Select	1,45	7,93	Select
		1:1,33	4,72		0,53	0,39	Select	0,68	0,82	Select	1,39	6,98	Select
		1:1,5	4,18		0,51	0,34	Select	0,64	0,68	Select	1,31	5,85	Select
		1:2	3,14		0,46	0,25	Select	0,56	0,46	Select	1,14	3,85	Select
		1:3	2,09		0,4	0,17	Select	0,46	0,25	Select	0,94	2,16	Select
		1:4	1,57		0,37	0,13	Select	0,36	0,12	Select	0,73	1,01	Select
Rough & angular	random	1:1	6,27		0,49	0,31	Select	0,71	0,93		1,45	7,93	
		1:1,33	4,72		0,45	0,24	Select	0,68	0,82		1,39	6,98	
		1:1,5	4,18		0,43	0,21	Select	0,64	0,68		1,31	5,85	
		1:2	3,14		0,39	0,15	Select	0,56	0,46		1,14	3,85	
		1:3	2,09		0,34	0,1	Select	0,46	0,25		0,94	2,16	
		1:4	1,57		0,31	0,08	Select	0,36	0,12		0,73	1,01	
Rough & angular	special	1:1	6,27		0,41	0,18	Select	0,71	0,93		1,45	7,93	
		1:1,33	4,72		0,37	0,13	Select	0,68	0,82		1,39	6,98	
		1:1,5	4,18		0,36	0,12	Select	0,64	0,68		1,31	5,85	
		1:2	3,14		0,32	0,09	Select	0,56	0,46		1,14	3,85	
		1:3	2,09		0,28	0,06	Select	0,46	0,25		0,94	2,16	
		1:4	1,57		0,26	0,05	Select	0,36	0,12		0,73	1,01	

Final values

Type of armour unit	Rocks	[-]	Type of armour layer unit
Stone shape	Smooth & rounded	[-]	Shape of the unit
Placement	Randomly	[-]	How is the unit placed?
Theory	Hudson	[-]	Which theory was used

p_s	2,6	t/m³	Density of the rocks/units
tan(α)	1:1,5	[-]	Tangens of the breakwater slope
D_n50	1,27	m	Diameter of the median rock size
M_50	5,33	t	Median rock/unit weight
Amount of layers	2	[-]	Number of ALU layers

Go to the next design step

Height assessment			Input of the user is required
Source:	EUrOtop, CEM		Parameters for intermediate results
Author:	L. De Smet		Parameters which can be selected as final result

Main Menu

See progress

General input

C_r	1	[-]	Reduction factor for overtopping, crest width **(default =1)**
q	0,001	m³/s/m	Mean overtopping discharge **(default = 0,001)**
H_s	3	m	Significant wave height
T_m	7,2	s	Mean wave period
s_0m	0,0371	[-]	Deep water wave steepness
L_0m	80,94	m	Deep water wave length
tan(α)	1:1,5	[-]	Tangens of the breakwater slope angle
tan(α)	0,67	[-]	Tangens of the breakwater slope angle
ξ_m0	3,46	[-]	Surf-similarity parameter for deep water (based on s_m)
β	10	°	Angle of wave incidence
R_u2%_prob	3,61	m	Wave run-up height exceeded by 2% of the incoming waves
ALU	Rocks	[-]	Type of armour layer unit
ξ_0p	4,33	[-]	Surf-similarity parameter for deep water (based on s_p)
s_0p	0,0237	[-]	Deep water wave steepness
R_u2%_det	3,89	m	Wave run-up height exceeded by 2% of the incoming waves
ξ_m-1,0	3,53	[-]	Surf similarity parameter for deep water (based on s_m-1,0)

h	-10	m	Depth of the water bottom in TAW (**positive upwards, negative downwards**)
d	15	m	Total water depth
h'	5	m	SWL in TAW (**positive upwards, negative downwards**)

Since the width of the berm is not yet designed at this stage,
the user can insert an estimated reduction factor in advance

Eurotop: Deterministic & probabilistic design

Berm	☐ Yes ☑ No		Is there a berm installed?
B	N/A	m	Width of the berm
d_b	N/A	m	Height of berm wrt SWL **(positive downwards)**
r_B	N/A	[-]	Berm parameter

Since there is no berm selected, you can neglect this window

Safety factors			
γ_f	0,4	[-]	Roughness reduction factor
γ_β	0,94	[-]	Oblique waves reduction factor
γ_b	1	[-]	Berm reduction factor
γ_v	1	[-]	Vertical wall reduction factor

Deterministic			
R_c	3,97	m	Crest freeboard
h_tot	18,97	m	Total breakwater height wrt bottom
h_tot'	8,97	m	Total breakwater height wrt TAW

Select

Probabilistic			
R_c	3,51	m	Crest freeboard
h_tot	18,51	m	Total breakwater height wrt bottom
h_tot'	8,51	m	Total breakwater height wrt TAW

Select

CEM: Owen 1980/1982, Bradbury and Allsop (1988), Aminti and Franco (1988), Pedersen and Burcharth (1992), Van der Meer and Janssen (1995)

Owen 1980/1982
Impermeable smooth, rough, straight and bermed slopes

Specific input			
γ_r	1	[-]	Surface roughness reduction factor

γ_r	Description
1	Smooth, impermeable slope (including smooth concrete and asphalt)
0,8	One layer of stone rubble on an impermeable base
0,7	Gravel, gabion mattresses
0,55	Rock riprap with thickness greater than 2.D_n

Berm	☐ Yes ☑ No		Is there a berm?
B	N/A	m	Width of the berm (**5, 10, 20 or 40**)
d_b	N/A	m	Position of the berm wrt SWL **(positive downwards)**

Make sure that the value of d_b is higher than 1,5.H_s to guarantee
the stability of the materials beneath the slope, so d_b >   4,5

Coefficients			
a	0,01	[-]	Owen parameters
b	20	[-]	Owen parameters
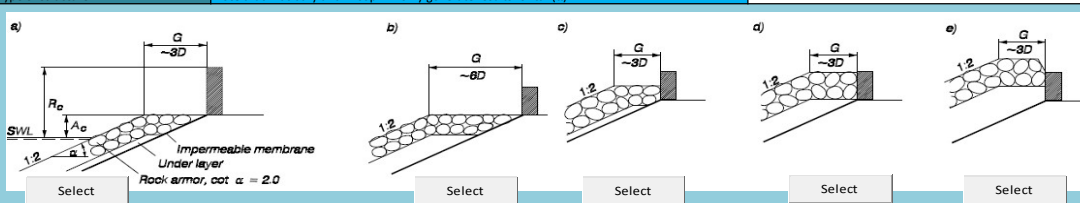
Overtopping: Owen			
R_c	14,95	m	Crest freeboard
h_tot	29,95	m	Total breakwater height wrt bottom
h_tot'	19,95	m	Total breakwater height wrt TAW

Select

Bradbury and Allsop (1988)
Rock armoured impermeable slopes with crown walls

Type of structure	Note that Bradbury and Allsop will only generate results for tan(α)=1:2

Select	Select	Select	Select	Select

Chosen configuration:		a

Overtopping: Bradbury and Allsop			
R_c	N/A	m	Crest freeboard
h_tot	N/A	m	Total breakwater height wrt bottom
h_tot'	N/A	m	Total breakwater height wrt TAW

Select

Aminti and Franco (1988)
Straight slope with a berm in front of a crown wall

Specific input			
G/D_n50	3	[-]	Amount of stone diameters in the berm (**possible values: 3, 5 or 7**)

Overtopping: Bradbury and Allsop			
R_c	N/A	m	Crest freeboard

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h_tot	N/A	m	Total breakwater height wrt bottom	Select
h_tot'	N/A	m	Total breakwater height wrt TAW	

Pederson and Burcharth (1992)

Rock armoured permeable slopes with a berm in front of a crown wall

Specific input				
A_c	3	m	See figure on the right	
B	5	m	See figure on the right	
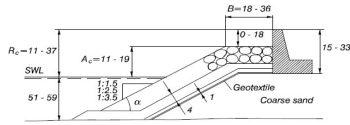
Overtopping: Pederson and Burcharth				
R_c	6,8	m	Crest freeboard	Select
h_tot	21,8	m	Total breakwater height wrt bottom	
h_tot'	11,8	m	Total breakwater height wrt TAW	

Van der Meer and Janssen (1995)

Straight and bermed impermeable slope

Berm	☐ Yes ☑ No		Is there a berm installed?		Make sure that the value of d_b is higher than 1,5.H_s to guarantee	
B	N/A	m	Width of the berm		the stability of the materials beneath the slope, so d_b >	4,5
d_b	N/A	m	Distance from the berm to SWL **(positive downwards)**			
r_B	N/A	[-]	Berm parameter			
r_dB	N/A	[-]	Berm parameter			

Surface Roughness Reduction Factor γ_r in Equation VI-5-3, Valid for $1 < \xi_{op} < 3$-4

Safety factors					ξ_{0p}	4,33
γ_r	1	[-]	Surface roughness reduction factor		H_s/D	2,36
γ_β	1	[-]	Oblique waves reduction factor			
γ_b	1	[-]	Berm reduction factor			
γ_h	1	[-]	Vertical walls reduction factor			

Type of Slope Surface	γ_r
Smooth, concrete, asphalt	1.0
Smooth block revetment	1.0
Grass (3 cm length)	0.90 - 1.0
1 layer of rock, diameter D, ($H_s/D = 1.5$ - 3.0)	0.55 - 0.6
2 or more layers of rock, ($H_s/D = 1.5$ - 6.0)	0.50 - 0.55

Roughness elements on smooth surface
(length parallel to waterline = P, width = b, height = h)

Overtopping: Van der Meer and Janssen				
R_c	9,33	m	Crest freeboard	Select
h_tot	24,33	m	Total breakwater height wrt bottom	
h_tot'	14,33	m	Total breakwater height wrt TAW	

Final values

R_c	3,97	m	Crest freeboard
h_tot	18,97	m	Total breakwater height wrt bottom
h_tot'	8,97	m	Total breakwater height wrt TAW
Berm	No	[-]	Denotes whether a berm was selected
B	N/A	m	Width of the berm
d_b	N/A	m	Height of berm wrt SWL **(positive below SWL)**

Go to the next design step

Filter layer and core selection
Source: CEM, Rock Manual
Author: L. De Smet

Input of the user is required	
Parameters for intermediate results	
Parameters which can be selected as final result	

Main Menu

See progress

SEASIDE

General input

W/W_filter1	10	[-]	Ratio W on W of filter 1
W/W_filter2	200	[-]	Ratio W on W of filter 2
W/W_core	4000	[-]	Ratio W on W of core material
ρ_f1	2,3	t/m³	Density of filter layer 1
ρ_f2	2,3	t/m³	Density of filter layer 2
ρ_core	2,3	t/m³	Density of the core material
ρ_s	2,6	t/m³	Density of the armour units
D_n50	1,27	m	Equivalent cube length of median rock
W	5,33	t	Weight of the armour layer unit
D_n15	0,38	m	Diameter of which 15% are smaller
D_n85	2,16	m	Diameter of which 85% are smaller
n	2	[-]	Amount of armour layers, seaside
k_Δ	1,02	[-]	Layer coefficient, seaside
n_1	2	[-]	Amount of first filter layers
k_Δ1	1	[-]	Layer coefficient of first filter layer
n_2	2	[-]	Amount of second filter layers
k_Δ2	1	[-]	Layer coefficient of second filter layer
n	2	[-]	Amount of armour layers, leeside
k_Δ	1	[-]	Layer coefficient, leeside

Note that the default values are for rocks!

FILTER LAYER 1

W_filter1	0,533	t	Unit weight of the filter layer 1 material
Rock size	Heavy	[-]	Rock size of filter 1
Filter grading	300 - 1000	kg	Standard grading of filter 1
M_50	716	kg	Median rock weight
D_n50	0,68	m	Equivalent cube length of median rock
D_n10	0,63	m	Diameter of which 10% are smaller
D_n15	0,65	m	Diameter of which 15% are smaller
D_n60	0,8	m	Diameter of which 60% are smaller
D_n85	1,97	m	Diameter of which 85% are smaller

Retention criterion

D_15_filter	0,38	m	Diameter of which 15% are smaller
D_85_found	1,97	m	Diameter of which 85% are smaller
ratio	0,19	[-]	d_15_filter/d_85_foundation
criterium	OK	[-]	Retention criterion (I)
W_50_filter	5330	kg	Median rock weight for the filter
W_50_found	716	kg	Median rock weight for the foundation
ratio	7,44	[-]	W_50_filter/W_50_foundation
criterium	OK	[-]	Retention criterion (II)

Permeability criterion

D_15_filter	0,38	m	Diameter of which 15% are smaller
D_15_found	0,65	m	Diameter of which 15% are smaller
ratio	0,58	[-]	d_15_filter/d_15_found
criterium	NOT OK	[-]	Permeability criterion

Internal stability criterion

D_60_filter	0,8	m	Diameter of which 60% are smaller
D_10_filter	0,63	m	Diameter of which 10% are smaller
ratio	1,27	[-]	d_60_filter/d_10_filter
criterium	OK	[-]	Internal stability criterion

Use wider grading	Use gabions
Undo	Undo

WARNING: If you select a wider grading or gabions, you can undo these steps by clicking on "Undo"
It is however not possible to adjust values of prior steps once one of these buttons is selected.
This is because the values are overwritten by clicking on these buttons, so the formula behind it
is lost.

FILTER LAYER 2

W_filter1	0,0267	t	Unit weight of the filter layer 2 material
Rock size	Light	[-]	Rock size of filter 2
Filter grading	5 - 40	kg	Standard grading of filter 2
M_50	32	kg	Median rock weight
D_n50	0,24	m	Equivalent cube length of median rock
D_n10	0,18	m	Diameter of which 10% are smaller
D_n15	0,19	m	Diameter of which 15% are smaller
D_n60	0,28	m	Diameter of which 60% are smaller
D_n85	0,38	m	Diameter of which 85% are smaller

Retention criterion

D_15_filter	0,65	m	Diameter of which 15% are smaller
D_85_found	0,38	m	Diameter of which 85% are smaller
ratio	1,71	[-]	d_15_filter/d_85_foundation
criterium	OK	[-]	Retention criterion (I)
W_50_filter	716	kg	Median rock weight for the filter
W_50_found	32	kg	Median rock weight for the foundation
ratio	22,38	[-]	W_50_filter/W_50_foundation
criterium	NOT OK	[-]	Retention criterion (II)

Permeability criterion

D_15_filter	0,65	m	Diameter of which 15% are smaller
D_15_found	0,19	m	Diameter of which 15% are smaller
ratio	3,42	[-]	d_15_filter/d_15_found
criterium	NOT OK	[-]	Permeability criterion

Internal stability criterion			
D_60_filter	0,28	m	Diameter of which 60% are smaller
D_10_filter	0,18	m	Diameter of which 10% are smaller
ratio	1,56	[-]	d_60_filter/d_10_filter
criterium	OK	[-]	Internal stability criterion

Use wider grading	Use gabions
Undo	Undo

WARNING: If you select a wider grading or gabions, you can undo these steps by clicking on "Undo"
It is however not possible to adjust values of prior steps once one of these buttons is selected.
This is because the values are overwritten by clicking on these buttons, so the formula behind it
is lost.

CORE MATERIAL

W_core	0,0013	t	Unit weight of the core material
Rock size	Coarse	[-]	Rock size of the core material
Grading	45/125	mm or kg	Standard grading of the core material
M_50	3,23	kg	Median rock weight

D_n50	0,11	m	Equivalent cube length of median rock
D_n10	0,07	m	Diameter of which 10% are smaller
D_n15	0,076	m	Diameter of which 15% are smaller
D_n60	0,101	m	Diameter of which 60% are smaller
D_n85	0,196	m	Diameter of which 85% are smaller

Retention criterion			
D_15_filter	0,19	m	Diameter of which 15% are smaller
D_85_found	0,196	m	Diameter of which 85% are smaller
ratio	0,97	[-]	d_15_filter/d_85_foundation
criterium	OK	[-]	Retention criterion (I)

W_50_filter	32	kg	Median rock weight for the filter
W_50_found	3,23	kg	Median rock weight for the foundation
ratio	9,91	[-]	W_50_filter/W_50_foundation
criterium	OK	[-]	Retention criterion (II)

Permeability criterion			
D_15_filter	0,19	m	Diameter of which 15% are smaller
D_15_found	0,076	m	Diameter of which 15% are smaller
ratio	2,5	[-]	d_15_filter/d_15_found
criterium	NOT OK	[-]	Permeability criterion

Internal stability criterion			
D_60_filter	0,101	m	Diameter of which 60% are smaller
D_10_filter	0,07	m	Diameter of which 10% are smaller
ratio	1,44	[-]	d_60_filter/d_10_filter
criterium	OK	[-]	Internal stability criterion

Use wider grading	Use gabions
Undo	Undo

WARNING: If you select a wider grading or gabions, you can undo these steps by clicking on "Undo"
It is however not possible to adjust values of prior steps once one of these buttons is selected.
This is because the values are overwritten by clicking on these buttons, so the formula behind it
is lost.

Final output - seaside

Armour Layer			
Type	Rocks	[-]	Type of armour unit
M_50	5,33	t	Median rock weight
D_50	1,27	m	Equivalent cube length of median rock
r	2,59	m	Thickness of the armour layer

First filter layer			
Type	Rocks	[-]	Type of armour unit
M_50	716	kg	Median rock weight
D_50	0,68	m	Equivalent cube length of median rock
r	1,36	m	Thickness of the first filter layer

Second filter layer			
Type	Rocks	[-]	Type of armour unit
M_50	32	kg	Median rock weight
D_50	0,24	m	Equivalent cube length of median rock
r	0,48	m	Thickness of the second filter layer

Core material			
Type	Rocks	[-]	Type of armour unit
M_50	3,23	kg	Median rock weight
D_50	0,11	m	Equivalent cube length of median rock

Filter layer grading

Core material
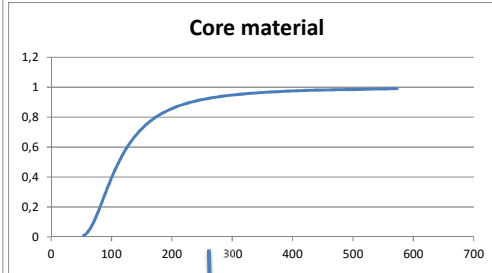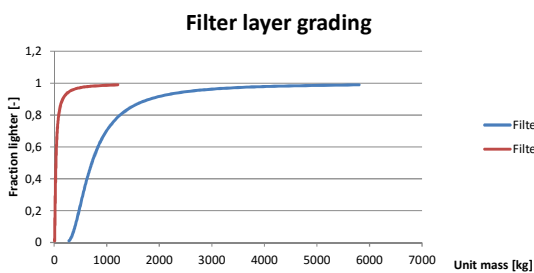
Show values
Hide values

On the y-axis the fraction smaller is shown [-], on the x-axis the diameter [mm] is shown

LEESIDE

For economic reasons it is assumed that the filter layers are the same for the lee- as for the seaside.

Final output - leeside

Armour Layer

Type	Rocks	[-]	Unit weight of the filter layer 1 material
M_50	5,33	t	Median rock weight
D_50	1,27	m	Standard grading of the filter
r	2,54	m	Armour layer thickness

First filter layer

Type	Rocks	[-]	Type of armour unit
M_50	716	kg	Median rock weight
D_50	0,68	m	Equivalent cube length of median rock
r	1,36	m	Thickness of the first filter layer

Second filter layer

Type	Rocks	[-]	Type of armour unit
M_50	32	kg	Median rock weight
D_50	0,24	m	Equivalent cube length of median rock
r	0,48	m	Thickness of the second filter layer

BEDPROTECTION

It is optional to use bedprotection, if it is applied, please fill in the green cells below

Input

ρ_s	1,6	t/m³	The density of the stabilizing sand
h	0,5	m	Height of the layer

Go to the next design step

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Main Menu

See progress

Input of the user is required
Parameters for intermediate results
Parameters which can be selected as final result

You can either manually fill in the final crest width, or use the design formula
For the manual input, the width needs to be larger than 3.D_50=   3,81

Manual input

| B | 5 | m | Crest width | Select |

Design formula

n	3	[-]	Number of units in width-direction **(min 3)**
k_Δ	1,02	[-]	Layer coefficient
W	52,29	kN	Primary armour unit weight
w_a	25,51	kN/m³	Specific weight of armour unit material

| B | 3,89 | m | Crest width | Select |

Final output

| B | 5 | m | Crest width |

| C_r | 0,25 | [-] | Crest width reduction factor |

Note that the crest width reduction factor gives some additional information
It is not used in later parts of the design

Go to the next design step

	Toe protection			Input of the user is required		Main Menu
	Source:	CEM		Parameters for intermediate results		See progress
	Author:	L. De Smet		Parameters which can be selected as final result		

SEASIDE

General input

N_od	0,5	[-]	Nuber of units displaced out of the armour layer within a strip width of D_n50 **(0,5=no damage, 2=acceptable damage)**
b_toe	3	[-]	Number of stones in the width-direction of the toe **(3 to 5)**
h_toe	2	[-]	Number of stones in the height-direction of the toe
H_s	3	m	Design wave height
d	15	m	Water depth
berm	No	[-]	Is there a berm present?
h_s	N/A	m	Water depth at the bottom of the toe berm wrt the SWL
ρ_w	1,025	t/m³	Mass density of the water
Waterdepth	Intermediate water	[-]	Type of water depth
Very shallow	No	[-]	Is the water very shallow or not?

Since the breakwater is constructed in :	Intermediate water
Following materials can be used as toe material:	Rocks or concrete blocks (use the feature below to characterize their dimensions)

Select armour units

Rocks or concrete blocks

Van der Meer

ρ_s	2,68	t/m³	Mass density of the rocks

D_n50	N/A	m	Equivalent cube length of median rock
M_50	N/A	kg	Mean rock weight

Material	N/A	[kg] or [mm]	Standard grading of proposed material	**Select rocks**
M_50	N/A	[kg]	Mean weight of the proposed material	

Same material?	Material not used yet

Burcharth et al.

ρ_s	2,7	t/m³	Mass density of the rocks

D_n50	N/A	m	Equivalent cube length of median rock
M_50	N/A	kg	Mean rock weight

Material	N/A	[kg] or [mm]	Standard grading of proposed material	**Select rocks**
M_50	N/A	[kg]	Mean weight of the proposed material	**Select concrete cubes**

Same material?	Material not used yet

Select a filter layer manually

First filter layer	Material	300 - 1000	[kg]	**Select as toe material**
	M_50	716	[kg]	

Second filter layer	Material	5 - 40	[kg]	**Select as toe material**
	M_50	32	[kg]	

Final output

Material	Rocks	[-]	Type of unit
Grading	300 - 1000	kg	Grading of the units
D_n50	0,68	m	Equivalent cube length of median rock
M_50	716	kg	Median rock weight
ρ_s	2,3	t/m³	Density of the units
H	1,36	m	Height of the toe
B	2,04	m	Width of the toe
Slope	1:1,5	[-]	Slope of the toe (same as for the armour layer)

LEESIDE

General input

You can either insert the same toe as at the seaside or make a seperate design				**Select same toe**

N_od	0,5	[-]	Number of units displaced out of the armour layer within a strip width of D_n50 **(0,5=no damage, 2=acceptable damage)**
b_toe	3	[-]	Number of stones in the toe, when considering the width **(3 to 5)**
h_toe	2	[-]	Number of stones in the toe, when considering the height
H_s	1,2	m	Design wave height
d	15	m	Water depth
berm	No	[-]	Is there a berm present
h_s	N/A	m	Water depth at bottom of the toe berm wrt the SWL
ρ_w	1,025	t/m³	Mass density of the water
Waterdepth	Intermediate water	m	Type of water depth
Very shallow	No	[-]	Denotes whether the water is very shallow or not

Since the breakwater is constructed in :	Intermediate water
Following materials can be used as toe material:	Rocks or concrete blocks (Click on the button below)

Select armour units

Rock or concrete blocks

Van der Meer

ρ_s	2,68	t/m³	Mass density of the rocks

D_n50	N/A	m	Equivalent cube length of median rock
M_50	N/A	kg	Mean rock weight

Material	N/A	[kg] or [mm]	Standard grading of proposed material	Select rocks

| M_50 | N/A | [kg] | Mean weight of the proposed material | Select rocks |

Same material?   Material not used yet

Burcharth et al.

ρ_s	2,7	t/m³	Mass density of the rocks

D_n50	N/A	m	Equivalent cube length of median rock
M_50	N/A	kg	Mean rock weight

Material	N/A	[kg] or [mm]	Standard grading of proposed material	Select rocks
M_50	N/A	[kg]	Mean weight of the proposed material	Select concrete cubes

Same material?   Material not used yet

Select a filter layer manually

First filter layer	Material	300 - 1000	[kg]	Select as toe material
	M_50	716	[kg]	

Second filter layer	Material	5 - 40	[kg]	Select as toe material
	M_50	32	[kg]	

Final output

Material	Rocks	[-]	Type of unit
Grading	300 - 1000	kg	Grading of the units
D_n50	0,68	m	Equivalent cube length of median rock
M_50	716	kg	Median rock weight
ρ_s	2,3	t/m³	Density of the units
H	1,36	m	Height of the toe
B	2,04	m	Width of the toe
Slope	1:1,5	[-]	Slope of the toe (same as for the armour layer)

Go to the next design step

Roundhead design
Source: CEM
Author: L. De Smet

CE cloud

	Input of the user is required
	Parameters for intermediate results
	Parameters which can be selected as final result

General input

tan(α_rhead)	0,67	[-]	Tangens of the roundhead slope
H_s	3	m	Design wave height
tan(α)	1:1,5	[-]	Tangens of the breakwater slope at the leeside
ξ_m	3,23	[-]	Surf-similarity parameter
Armour	Rocks	[-]	Type of armour layer unit
γ_b_sea	0,2	[-]	Breaker index for the seaside

Roundhead design

The armour layer units used are: Rocks
Select armour for the roundhead section:

Rock	Tetrapod
Dolos	Tribar

By clicking on one of the four buttons, the corresponding roundhead unit will be
calculated automatically in the parts below,

Rock or Dolos

rho_s	2,6	t/m³	Density of the units
Armour units	Rocks	[-]	Type of units
A	0,272	[-]	Parameter
B	-1,749	[-]	Parameter
C_c	4,179	[-]	Parameter
Δ	1,54	[-]	rho_s/rho_w-1
D_n50	1,42	m	Diameter of median rock size
M_50	7,44	t	Median unit weight

Select

Tetrapod of tribar

rho_s	2,6	t/m³	Density of the units
Armour units	Tetrapods	[-]	Type of units
Δ	1,54	[-]	rho_s/rho_w-1
ξ_m	3,23	[-]	Surf-similarity parameter
Waves	Non-breaking	[-]	Breaking waves?
K_D	5,5	[-]	Stability coefficients
D_n50	0,96	m	Diameter of median rock size
M_50	2,3	t	Median unit weight
layers	2	[-]	Amount of layers

Select

Final output

Armour units	Rocks	[-]	Type of armour units
D_n50	1,42	m	Diameter of median rock size
M_50	7,44	t	Median unit weight
r	2,84	m	Thickness of the armour layer

Go to the next design step

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Financial overview
Source:
Author: L. De Smet

Main Menu

See progress

Input of the user is required	
Parameters for intermediate results	
Parameters which can be selected as final result	

For the calculation of the different costs, a cost list is made.
The cost list can always be edited by clicking on the button:

Cost list

Distances			
Armour units	100	km	Transport distance
Filter 1	200	km	Transport distance
Filter 2	200	km	Transport distance
Core	200	km	Transport distance
Toe	100	km	Transport distance
Roundhead armor	100	km	Transport distance

Porosity			
Armour units	0,4	[-]	Porosity of the ALU
Filter 1	0,35	[-]	Porosity of filter 1
Filter 2	0,25	[-]	Porosity of filter 2
Core material	0,2	[-]	Porosity of the core material
Toe material	0,4	[-]	Porosity of the toe material
Roundhead armour	0,4	[-]	Porosity of the roundhead material

Materials

Armour units - seaside			
Type	Rocks	[-]	Type of armour unit
D_n50	1,27	m	Diameter of median rock
M_50	5,33	t	Median unit weight
r	2,59	m	Thickness of the layer
V	51,74	m³/m	Total volume
M	134,52	t/m	Total mass
cost	3833,82	€/m	Total cost

Armour units - leeside			
Type	Rocks	[-]	Type of armour unit
D_n50	1,27	m	Diameter of median rock
M_50	5,33	t	Median unit weight
r	2,54	m	Thickness of the layer
V	19,98	m³/m	Total volume
M	51,95	t/m	Total mass
cost	1480,58	€/m	Total cost

Armour units - crest			
Type	Rocks	[-]	Type of armour unit
D_n50	1,27	m	Diameter of median rock
M_50	5,33	t	Median unit weight
r	2,59	m	Thickness of the layer
V	7,77	m³/m	Total volume
M	20,2	t/m	Total mass
cost	575,7	€/m	Total cost

First filter layer			
Type	Rocks	[-]	Type of filter material
D_n50	0,68	m	Diameter of median rock
M_50	0,72	t	Median unit weight
r	1,36	m	Thickness of the layer
V	55,11	m³/m	Total volume
M	126,75	t/m	Total mass
cost	3422,25	€/m	Total cost

Second filter layer			
Type	Rocks	[-]	Type of filter material
D_n50	0,24	m	Diameter of median rock
M_50	0,03	t	Median unit weight
r	0,48	m	Thickness of the layer
V	20,68	m³/m	Total volume
M	47,56	t/m	Total mass

cost	1046,32	€/m	Total cost

Core material

Type	Rocks	[-]	Type of core material
D_n50	0,11	m	Diameter of median rock
M_50	0,00323	t	Median unit weight
V	293,55	m³/m	Total volume
M	675,17	t/m	Total mass
cost	14853,74	€/m	Total cost

Toe material - seaside

Type	Rocks	[-]	Type of toe material
Amount	1	[-]	Number of toes at seaside
D_n50	0,68	m	Diameter of median rock
M_50	716	kg	Median unit weight
V	1,66	m³/m	Total volume
M	3,82	t/m	Total mass
cost	118,42	€/m	Total cost

Toe material - leeside

Type	Rocks	[-]	Type of toe material
Amount	1	[-]	Number of toes at leeside
D_n50	0,68	m	Diameter of median rock
M_50	716	kg	Median unit weight
V	1,66	m³/m	Total volume
M	3,82	t/m	Total mass
cost	118,42	€/m	Total cost

Roundhead

Type	Rocks	[-]	Type of roundhead material
D_n50	1,42	m	Diameter of median rock
M_50	7,44	kg	Median unit weight
V	47,21	m³/m	Total volume
M	122,75	t/m	Total mass
cost	3805,25	€/m	Total cost

TOTAL BREAKWATER MATERIAL COST

Cost-trunk	25449,25	€/m	Trunk material cost per meter
Cost-head	28678,8	€/m	Head material cost per meter

Transport

Armour unit	11366,85	€/m	Transport cost for armour units
Filter 1	13942,5	€/m	Transport cost for filter 1
Filter 2	5231,6	€/m	Transport cost for filter 2
Core	74268,7	€/m	Transport cost for core material
Toes	420,2	€/m	Transport cost for toe material
Roundhead	6751,25	€/m	Transport cost for the roundhead

TOTAL BREAKWATER TRASPORT COST

Cost-trunk	111981,1	€/m	Trunk transport cost
Cost-head	110870,1	€/m	Head transport cost

Construction

Armour unit	6820,11	€/m	Construction cost for armour units
Filter 1	1818,63	€/m	Construction cost for filter 1
Filter 2	682,44	€/m	Construction cost for filter 2
Core	14853,74	€/m	Construction cost for core material
Toes	252,12	€/m	Construction cost for toe material

There is assumed that the construction cost for a roundhead
is the same as for the trunk sections

TOTAL BREAKWATER CONSTRUCTION COST (trunk and head)

Cost	24427,04	€/m	Total construction cost per meter

TOTAL BREAKWATER COST BREAKDOWN

Armour	24077,06	€/m	Total cost of armour units per meter
Filter 1	19183,38	€/m	Total cost of filter 1 material per meter
Filter 2	6960,36	€/m	Total cost of filter 2 material per meter
Core	103976,18	€/m	Total cost of core material per meter
Toe	790,74	€/m	Total cost of toe material per meter
Roundhead	10556,5	€/m	Total cost of roundhead material per meter

Total-trunk	154987,72	€/m	Total cost of trunk-section per meter
Total-head	156559,09	€/m	Total cost of head-section per meter

Cost of materials

Cost of process steps

Generate final design sheet

CE cloud

Cost List
Source: Tutuarima
Author: L. De Smet

Input of the user is required
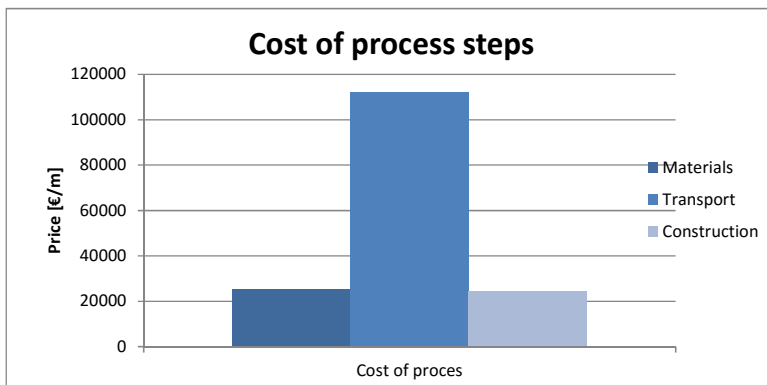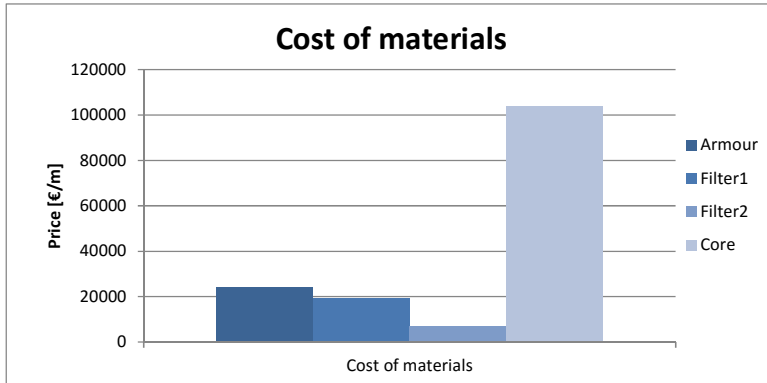
Production

Rocks

2-300	kg	22	€/t
1-3	t	27	€/t
3-6	t	28,5	€/t
6-...	t	31	€/t

Concrete units

Cubes	120	€/m³
Tetrapod	150	€/m³
Accropode	200	€/m³
Dolos	170	€/m³
Tribar	180	€/m³
Core-Loc	200	€/m³
X-bloc	220	€/m³
Foot protection blocks	120	€/m³

Others

Caisson	480	€/m³
Gabion	55	€/m²
Gravel	18	€/t
Coarse sand	10	€/m³

Transport

<=300	kg	0,55	€/t/km
>300	kg	0,88	€/t/km
Caisson		4,5	€/t/km

Construction

Bedprotection	33	€/t
Core	22	€/t
Rock armour	33	€/t
Filter layers	33	€/m³
Cubes	540	€/m³
Tetrapod	745	€/m³
Accropode	960	€/m³
Dolos	850	€/m³
Tribar	870	€/m³
Core-loc	960	€/m³
X-bloc	960	€/m³
Caisson	620	€/m³

Back to cost assessment rubble-mound breakwater

Back to cost assessment caisson breakwater

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Back to cost assessment caisson breakwater

Final design sheet of the rubble-mound breakwater
Source:
Author: L. De Smet

Hydraulic Boundaries

ρ_w	1,025	t/m³
d	15	m

Seaside			Leeside		
H_s	3	m	H_s	1,2	m
T_p	9	s	T_p	7	s
s_m	0,0426	[-]	s_m	0,0254	[-]

Layer information

	Armour		Filter 1		Filter 2		Core	Bedprotection	Toe			Round-head	Units
	Sea	Lee	Sea	Lee	Sea	Lee			Sea		Lee		
Type	Rocks	Rocks	Rocks	Rocks	Rocks	Rocks	Rocks	Sand	Rocks		Rocks	Rocks	[-]
Grading	Smooth & rounded	Smooth & rounded	300 - 1000	300 - 1000	5 - 40	5 - 40	45/125	/	300 - 1000		300 - 1000	/	kg
Placement	Randomly	Randomly	/	/	/	/	/	/	/		/	/	[-]
ρ_s	2,6	2,6	2,3	2,3	2,3	2,3	2,3	1,6	2,3		2,3	2,6	t/m³
D_n50	1,27	1,27	0,68	0,68	0,24	0,24	0,11	/	0,68		0,68	1,42	m
M_50	5,33	5,33	716	716	32	32	3,23	/	716		716	7,44	kg/t
r	2,59	2,54	1,36	1,36	0,48	0,48	/	0,5	1,36		1,36	2,84	m
V_tot/m	51,74	19,98	55,11		20,68		293,55	34,25	1,66		1,66	47,21	m³/m
M_tot/m	134,52	51,95	126,75		47,56		675,17	54,8	3,82		3,82	122,75	kg/t/m
€/m	24077,06		19183,38		6960,36		14853,74	0	790,74			156559,1	€/m

Dimensioning

q	0,001	m³/s/m	Berm?	No	
R_c	3,97	m	d_b	N/A	m
h_tot	18,97	m	B	N/A	m
B_tot	68,49	m			

Draw the breakwater — This button will redirect you to the sheet which can generate an Autocad drawing

Costs

Total-trunk	154987,72	€/m
Total-roundhead	156559,09	€/m
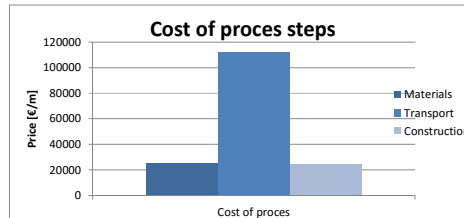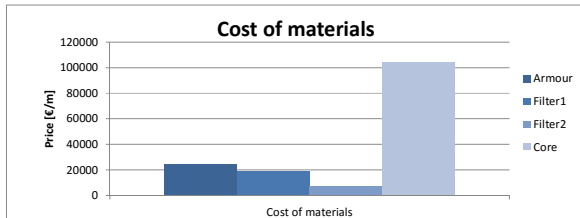
Cost of materials
Price [€/m]

Legend: Armour, Filter1, Filter2, Core

Cost of proces steps
Price [€/m]

Legend: Materials, Transport, Construction

Amount of breakwaters inserted: 0

Set as 1st breakwater section
Set as 2nd breakwater section
Set as 3rd breakwater section
Set as 4th breakwater section
Set as 5th breakwater section

Compare with caisson breakwater

Open cost assessment of the whole breakwater

Design next breakwater section

X	Y
0	0
0	0,5
68,49	0,5
68,49	0
0	0
0	0,5
2	0,5
4,04	1,86
6,08	1,86
6,08	0,5
8,12	0,5
6,08	1,86
31,745	18,97
36,745	18,97
62,41	1,86
62,41	1,86
62,41	0,5
66,49	0,5
64,45	1,86
62,41	1,86
60,37	0,5
62,41	0,5
60,64	0,5
36,745	16,43
36,745	16,38
31,745	16,38
7,925	0,5
6,08	0,5
9,965	0,5
31,745	15,02
36,745	15,02
36,745	15,07
58,6	0,5
62,41	0,5
57,88	0,5
36,745	14,59
36,745	14,54
31,745	14,54
10,685	0,5
0	0,5
0	0
0	0,5
0	15
25,79	15
0	15
0	16,5
28,04	16,5
0	16,5
0	0
68,49	0
68,49	15
42,7	15
68,49	15
68,49	15,6
41,8	15,6
68,49	15,6
68,49	0
0	0
0	0
0	0
0	0
0	0

Autocad tool
Source:
Author: L. De Smet

Draw in Autocad

Write to notepad

Back to final design

0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0

Rubble-mound breakwater design:

Implementation of the boundary conditions

Source: CEM, Goda
Author: L. De Smet

■ (green)	Input of the user is required
■ (orange)	Parameters for intermediate results
■ (yellow)	Parameters which can be selected as final result

Main Menu

See progress

SEASIDE

General input
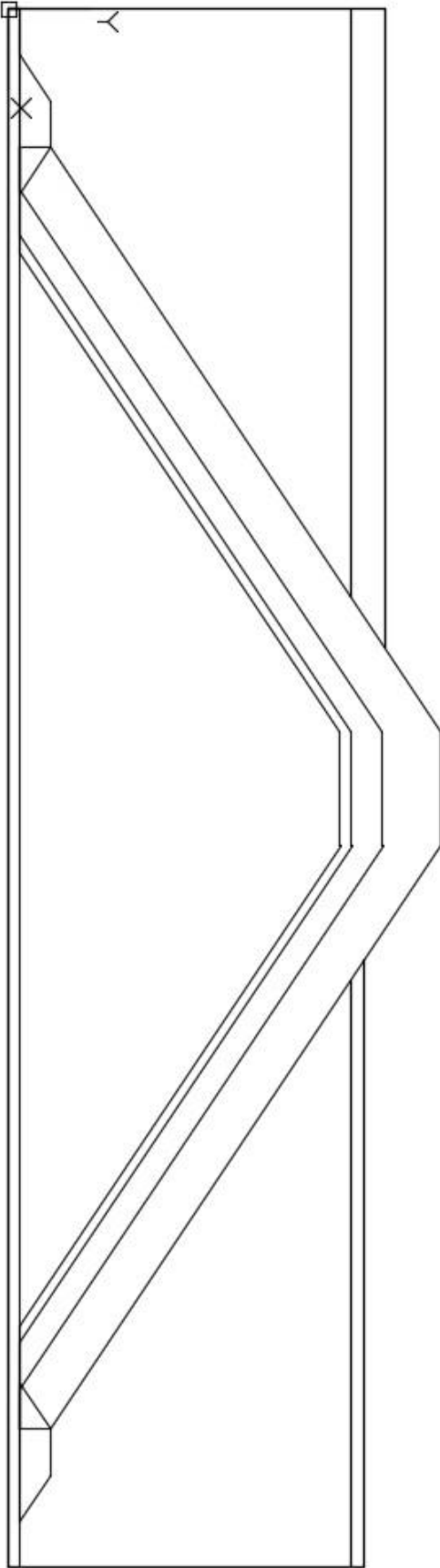
Symbol	Value	Unit	Description
ρ_w	1,025	t/m³	Density of the water
h_s	15	m	Water depth next to the foundation
α	0	°	Bottom slope
β	10	°	Angle of wave incidence (0° is head-on)
T_p/T_m	1,25	[-]	Mean wave period ratio **(default: 1,25)**
$T_p/T_{m-1,0}$	1,1	[-]	Spectral wave period ratio **(default: 1,1)**

Further input

1. Manual input

Symbol	Value	Unit	Description
H_s	3	m	Wave height
T_p	9	s	Peak wave period
T_m	7,2	s	Mean wave period
$T_{m-1,0}$	8,18	s	Spectral wave period
L_{p0}	126,47	m	Wave length in deep water
L_p	95,57	m	Local wave length
	Intermediate water		Type of water
s_{p0}	0,0237	[-]	Deep water wave steepness
s_p	0,0314	[-]	Local wave steepness
L_{m0}	80,94	m	Wave length in deep water
L_m	70,49	m	Local wave length
	Intermediate water		Type of water
s_{m0}	0,0371	[-]	Deep water wave steepness
s_m	0,0426	[-]	Local wave steepness
$L_{m-1,0}$	104,47	m	Wave length in deep water
L_{m-1}	84,3	m	Local wave length
	Intermediate water		Type of water
$s_{m-1,0}$	0,0287	[-]	Deep water wave steepness
s_{m-1}	0,0356	[-]	Local wave steepness

Set as parameters

2. Pierson-Moskowitz spectrum

Symbol	Value	Unit	Description
U_{10}	12	m/s	Wind speed at 10 m above sea level
m_0	0,6542	m²	Total wave energy
H_s	3,24	m	Design wave height based on m_0
T_p	8,99	s	Peak wave period
T_m	7,19	s	Mean wave period
$T_{m-1,0}$	8,17	s	Spectral wave period
L_{p0}	126,19	m	Deep water wave length
L_p	95,44	m	Local wave length
	Intermediate water		Type of water
s_{p0}	0,0257	[-]	Deep water wave steepness
s_p	0,0339	[-]	Local wave steepness
L_{m0}	80,71	m	Wave length in deep water
L_m	70,35	m	Local wave length
	Intermediate water		Type of water
s_{m0}	0,0401	[-]	Deep water wave steepness
s_m	0,0461	[-]	Local wave steepness
$L_{m-1,0}$	104,22	m	Wave length in deep water
L_{m-1}	84,16	m	Local wave length
	Intermediate water		Type of water
$s_{m-1,0}$	0,0311	[-]	Deep water wave steepness
s_{m-1}	0,0385	[-]	Local wave steepness

Set as parameters

3. JONSWAP spectrum

Symbol	Value	Unit	Description
U_{10}	12	m/s	Wind speed at 10 m above sea level
F	250000	m	Length of fetch
gamma	3,3	[-]	Peak enhancement **(between 1 and 3,3)**
m_0	0,6128	m²	Total wave energy
H_s	3,13	m	Design wave height based on m_0
T_p	8,99	s	Peak wave period
T_m	7,19	s	Mean wave period
$T_{m-1,0}$	8,17	s	Spectral wave period
L_{p0}	126,19	m	Deep water wave length
L_p	95,44	m	Local wave length
	Intermediate water		Type of water
s_{p0}	0,0248	[-]	Deep water wave steepness
s_p	0,0328	[-]	Local wave steepness
L_{m0}	80,71	m	Wave length in deep water
L_m	70,35	m	Local wave length
	Intermediate water		Type of water
s_{m0}	0,0388	[-]	Deep water wave steepness
s_m	0,0445	[-]	Local wave steepness
$L_{m-1,0}$	104,22	m	Wave length in deep water
L_{m-1}	84,16	m	Local wave length
	Intermediate water		Type of water
$s_{m-1,0}$	0,03	[-]	Deep water wave steepness
s_{m-1}	0,0372	[-]	Local wave steepness

Set as parameters

PM and JONSWAP spectrum

- Pierson-Moskowitz Spectrum
- JONSWAP spectrum

4. Imported file

Import wave heights and periods by clicking on the "Import data" button

Import data

→ Data are available

Symbol	Value	Unit	Description
$H_{1/3}$	3,63	m	Design wave height according to Goda
$T_{1/3}$	7,77	s	Design wave period according to Goda
T_p	9,71	s	Peak wave period estimation
$T_{m-1,0}$	8,83	s	Spectral wave period
L_{p0}	147,21	m	Deep water wave length
L_p	105,17	m	Local wave length

Intermediate water			Type of water
s_p0	0,0247	[-]	Deep water wave steepness
s_p	0,0345	[-]	Local wave steepness
L_m0	94,26	m	Deep water wave length
L_m	78,57	m	Local wave length
Intermediate water			Type of water
s_m0	0,0385	[-]	Deep water wave steepness
s_m	0,0462	[-]	Local wave steepness
L_m-1,0	121,73	m	Deep water wave length
L_m-1	93,25	m	Local wave length
Intermediate water			Type of water
s_m-1,0	0,0298	[-]	Deep water wave steepness
s_m-1	0,0389	[-]	Local wave steepness

Set as parameters

Final output

Click on one of the "Set a parameter" buttons
to select the appropriate parameters

Delete final values

ρ_w	1,025	t/m³	Density of the water
d	15	m	Water depth
α	0	°	Bottom slope angle
β	10	°	Angle of wave incidence
H_s	3	m	Design wave height
T_p	9	s	Peak wave period
T_m	7,2	s	Mean wave period
T_m-1,0	8,18	s	Spectral wave period
L_p0	126,47	m	Deep water wave length
L_p	95,57	m	Local wave length
s_p0	0,0237	[-]	Deep water wave steepness
s_p	0,0314	[-]	Local wave steepness
L_m0	80,94	m	Deep water wave length
L_m	70,49	m	Local wave length
s_m0	0,0371	[-]	Deep water wave steepness
s_m	0,0426	[-]	Local wave steepness
L_m-1,0	104,47	m	Deep water wave length
L_m-1	84,3	m	Local wave length
s_m-1,0	0,0287	[-]	Deep water wave steepness
s_m-1	0,0356	[-]	Local wave steepness

Go to the next design step

Design water depth at the toe of the caisson
Source: CEM
Author: L. De Smet

▮	Input of the user is required
▮	Parameters for intermediate results
▮	Parameters which can be selected as final result

General input

h_s	15	m	Water depth
T	5	m	Draught of the design ship
d/T_min	1,15	[-]	Miminal depth to draught ratio (default 1,15)
(h-d)_min	1,5	m	Minimal height of the RM foundation (default 1,5 m)
H_m0	3	m	Design wave height
T_m-1,0	8,18	s	Spectral wave period

R_c = crest freeboard
H_{m0} = wave height at the toe of the structure
h_s = water depth at the toe of the structure
d = water depth above the berm of the structure
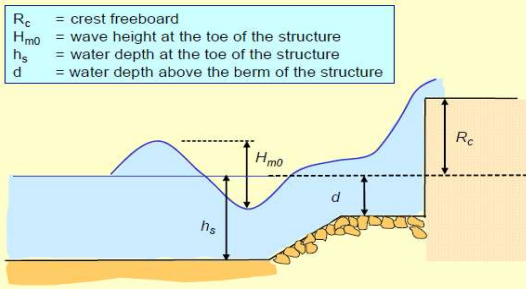
Application ranges

Lower limits of d				Upper limits of d		
1. Draught design ship	5,75	m		4. Min RM thickness	13,5	m
2. Waves on RM	7,5	m				
3. Non-impulsive cond	4,64	m				

7,5	<= d <=	13,5

At this point it is up to the user to select a
design depth within the generated range

d	9	m	Waterdepth at the toe of the caisson

Note that the non-impulsive wave condition is not always achieved when an existing breakwater is calculated.
It is up to the user to select a certain parameter, taking into account the different lower and upper limits (4 requirements)
which are given in the two tables above:

The 1st requirement is met
The 2nd requirement is met
The 3rd requirement is met
The 4th requirement is met

Final output

d	9	m	Water depth at the toe of the caisson
Impulsive?	No	[-]	Are the incoming waves impulsive or not?

Go to the next design step

The value for d is the same at the lee- as at the seaside

Height assessment of the caisson
Source: EurOtop, CEM
Author: L. De Smet

| | Main Menu |
| | See progress |

	Input of the user is required
	Parameters for intermediate results
	Parameters which can be selected as final result

General input

C_r	1	[-]	Overtopping reduction factor
q	0,001	m³/s/m	Mean overtopping discharge
H_s	3	m	Design wave height
β	5	°	Oblique wave angle
Impulsive?	No	[-]	Are the incoming waves impulsive or not?
h_s	15	m	Water depth next to the rubble-mound foundation
d	9	m	Water depth at the toe of the caisson
d*	0,58	[-]	Impulsiveness parameter for a composite wall
h*	0,97	[-]	Impulsiveness parameter for a vertical wall
γ_b	0,2	[-]	Breaker index

EurOtop: Deterministic & probabilistic design

Non-impulsive wave conditions:

Note that for non-impulsive wave conditions, there is no difference in calculation for a vertical wall
or a composite wall

The formulas below can be used since the waves are non-impulsive:

Non-impulsive waves

Deterministic approach
R_c	N/A	m	Crest freeboard		Select

Probabilistic approach - Non-oblique waves
R_c	7,48	m	Crest freeboard		Select

Safety factor
γ	0,97	[-]	Oblique waves reduction factor

Probabilistic approach - Oblique waves
R_c	7,26	m	Crest freeboard		Select

Impulsive wave conditions:

In this section, overtopping formulas for composite breakwaters are used. It is assumed that the
mounds are always moderate.

The waves are non-impulsive, formulas below can not be used!

Impulsive waves

Deterministic approach
R_c	N/A	m	Crest freeboard for a deterministic approach, composite breakwater

| Select |

Probabilistic approach
R_c	N/A	m	Crest freeboard for a probabilistic approach, composite breakwater

| Select |

CEM: Franco and Franco

Safety factors
γ_β	1	[-]	Oblique waves reduction factor
γ_s	1	[-]	Front geometry reduction factor

Franco and Franco (1999)
R_c	7,2	m	Crest freeboard		Select

Configuration of the top cap

It is possible to save concrete by altering the configuration of the top cap as is shown below
Please insert an appropriate concrete top cap reduction factor (0 = full rectangular box)
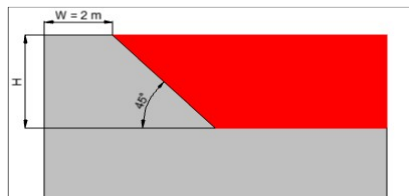
δ_red	0,05	[-]	Amount of concrete which can be removed compared to the total amount in the rectangular caisson box **(default = 0)**

At this stage it is not possible to calculate the specific configuration since the width of the caisson
Is not yet known

Go back to the width assessment:
(Please ignore if you did not design the width yet)

[Go back to the width assessment]

Final output

q	0,001	m³/s/m	Mean overtopping discharge rate
R_c	7,48	m	Crest freeboard
H_caisson	17,48	m	Height of the caisson
γ_red	0,05	[-]	Concrete reduction factor

[Go to the next design step]

CE ≋ cloud

Pressures on the caisson
Source: CEM
Author: L. De Smet

[Main Menu]
[See progress]

🟩	Input of the user is required
🟧	Parameters for intermediate results
🟨	Parameters which can be selected as final result

General input

ρ_w	1,025	t/m³	Water density
H_s	3	m	Design wave height
H_design	5,4	m	Design wave height, Goda approach
α	0	°	Bottom slope
β	10	°	Angle of wave incidence
h_c	7,48	m	See figure b
h_s	15	m	See figure a and b
h_b	15	m	Water depth at a distance of 5.H_s
d	9	m	See figure b
h_w	16,48	m	See figure b
L_m	70,49	m	Local wave length, based on T_m
L_Goda	95,57	m	Wave length at a distance of 5.H_s, based on T_p
Impulsive?	No	[-]	Are the incoming waves impulsive or not?

Figure a:
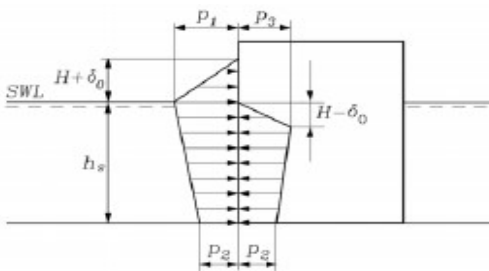
Figure b:
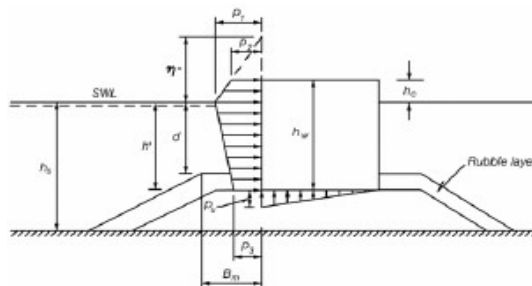
Sainflou pressures - Regular waves

Extra input parameter

δ_0	0,46	m	Vertical shift in the wave crest and wave trough at the wall

Sainflou pressures

p_1	31,05	kN/m²	Wave pressure at SWL, corresponding to the wave crest
p_2	14,82	kN/m²	Wave pressure at the base of the vertical wall
p_3	25,54	kN/m²	Wave pressure at SWL, corresponding to the wave trough

[Select]

Goda pressures - Irregular waves

Extra input parameters

B_m_sea	10	m	Width of the foundation at the seaside **(default 10 m)**
λ_1	1	[-]	Modification factor **(default value = 1)**
λ_2	1	[-]	Modification factor **(default value = 1)**
λ_3	1	[-]	Modification factor **(default value = 1)**
α_1	0,76	[-]	Goda parameter
α_*	0,05	[-]	Goda parameter
α_3	0,79	[-]	Goda parameter
η*	8,04	m	See figure b

[Berm width altered]   By clicking on this button you will be redirected back to the foundation design.

Goda pressures

p_1	43,57	kN/m²	Pressure, see figure b
p_2	3,03	kN/m²	Pressure, see figure b
p_3	34,42	kN/m²	Pressure, see figure b

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p_u	32,35	kN/m²	Pressure, see figure b

Select

Final output

p_1	43,57	kN/m²	Pressure, see figure b
p_2	3,03	kN/m²	Pressure, see figure b
p_3	34,42	kN/m²	Pressure, see figure b
p_u	32,35	kN/m²	Pressure, see figure b

Go to the next design step

Forces and moments on the caisson

Source: CEM
Author: L. De Smet

	Input of the user is required
	Parameters for intermediate results
	Parameters which can be selected as final result

General input

Symbol	Value	Unit	Description
ρ_c	2,1	t/m³	Concrete density **(default 2,1)**
ρ_w	1,025	t/m³	Water density
p_1	43,57	kN/m²	Pressure
p_2	3,03	kN/m²	Pressure
p_3	34,42	kN/m²	Pressure
p_u	32,35	kN/m²	Pressure
h_c	7,48	m	Crest freeboard
h'	9	m	Submerged weight of the wall from the toe to the SWL
h_w	17,48	m	Total height of the caisson

Wave induced forces and moments - Goda & Takahashi

Extra input

Are model tests performed?   ☐ Yes   ☒ No

	Mean	Std.	Parameter	Final value		
	μ_x	σ_x	a	$\mu_x + a \cdot \sigma_x$		
U_FH	0,9	0,25	1	1,15	[-]	Uncertainty of the horizontal force
U_FU	0,77	0,25	1	1,02	[-]	Uncertainty of the uplifting force
U_MH	0,81	0,4	1	1,21	[-]	Uncertainty of the horizontal moment
U_MU	0,72	0,37	1	1,09	[-]	Uncertainty of the uplift moment

Forces

Symbol	Value	Unit	Description
F_H	604,02	kN/m	Horizontal force
F_U/B	16,5	kN/m²	Uplifting force per meter width
F_G/B	269,61	kN/m²	Weight of the caisson per meter width

Moments

Symbol	Value	Unit	Description
M_H	4443,63	kNm/m	Horizontal moment at the heel of the caisson
M_U/B²	11,75	kNm/m³	Vertical moment at the heel of the caisson, divided by B²
M_G/B²	134,8	kNm/m³	Moment due to the weight of the caisson, divided by B²

Final output

Forces

Symbol	Value	Unit	Description
F_H	604,02	kN/m	Horizontal force
F_U/B	16,5	kN/m²	Uplifting force per meter width
F_G/B	269,61	kN/m²	Weight of the caisson per meter width

Moments

Symbol	Value	Unit	Description
M_H	4443,63	kNm/m²	Horizontal moment at the heel of the caisson
M_U/B²	11,75	kNm/m³	Vertical moment at the heel of the caisson, divided by B²
M_G/B²	134,8	kNm/m³	Moment due to the weight of the caisson, divided by B²

Go to the next design step

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Armour layer unit selection

Source: CEM
Author: L. De Smet

Main menu

See progress

   	Input of the user is required	
   	Parameters for intermediate results	
   	Parameters which can be selected as final result	

General input

B_m_lee	5	m	Width of the toe berm at the **leeside** (default = 5m)
B_m_sea	10	m	Width of the toe berm at the **seaside**
ρ_w	1,025	t/m³	Water density
H_s	3	m	Design wave height
h'	10	m	Height of the caisson beneath the SWL
h_s	15	m	Water depth in front of the toe berm
L_p	95,57	m	Local wave length corresponding to T_p
k	0,0657	1/m	Wave number
β	10	°	Wave incidence angle
Quarrystone	☑ Smooth ☐ Rough		Are the stones smooth or rough?
k_Δ	1,02	[-]	Layer coefficient
n	2	[-]	Number of quarrystone layers

Berm width altered

By clicking on this button you will be redirected back to the foundation design.

Stability of the toe berm: Madrigal and Valdés

Extra input

ρ_s	2,6	t/m³	Density of the stones
Δ	1,54	[-]	rho_s/rho_w-1
N_{od}	0,5	[-]	Damage parameter:

0,5	Start of damage
2	Acceptable damage
5	Severe damage

Output

D_{n50}	0,68	m	Median size of equivalent cube
M_{50}	0,82	t	Median weight of equivalent cube

Rock size	Heavy	[-]	Rock size
Grading	300 - 1000	kg	Standard grading
M_{50}	716	kg	Median rock weight of the grading

r	1,33	m	Thickness of the armour layer

Select

Stability of the toe berm: Tanimoto, Yagyu and Goda

Extra input

Δ	1,65	[-]	rho_s/rho_w-1
ρ_s	2,72	t/m³	Density of the rocks
κ_1	0,76	[-]	Parameter
κ_2	0,35	[-]	Parameter
κ	0,266	[-]	Parameter

Output

D_{n50}	0,37	m	Median size of the equivalent cube
M_{50}	0,14	t	Median weight of the equivalent cube

Rock size	Light	[-]	Rock size
Grading	40 - 200	kg	Standard grading
M_{50}	149	kg	Median rock weight of the grading

r	0,77	m	Thickness of the armour layer

Select

Final output

D_{n50}	0,68	m	Median size of the equivalent cube

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Grading	300 - 1000	kg	Standard grading
M_50	716	kg	Median rock weight of the grading
r	1,33	m	Thickness of the armour layer
B_m_sea	10	m	Width of the toe berm at the seaside
ρ_s	2,6	t/m³	Density of the rocks
B_m_lee	5	m	Width of the toe berm at the leeside

Go to the next design step

Note that the same ALU's are used at the leeside!

Foundation details
Source: CEM, Rock Manual
Author: L. De Smet

	Input of the user is required
	Parameters for intermediate results
	Parameters which can be selected as final result

General input

W/W_filter	20	[-]	Weight of the ALU vs weight of the filter material **(default 20)**
W/W_core	100	[-]	Weight of the ALU vs weight of the core material **(default 100)**
Slope_sea	0,33	[-]	Slope of the rubble-mound foundation at seaside **(default 1:3)**
Slope_lee	0,5	[-]	Slope of the rubble-mound foundation at leeside **(default 1:2)**
B_m_sea	10	m	Width of the toe berm at the seaside
D_n50	0,68	m	Median size of the design cube for the armour layer
D_n15	0,2	m	Diameter of which 15% are smaller, armour layer
D_n85	1,16	m	Diameter of which 85% are smaller, armour layer
ρ_s	2,6	t/m³	Density of the rocks
W	716	kg	Median weight of the design armour units
B_m_lee	5	m	Width of the toe berm at the leeside

Filter material selection

n	2	[-]	Number of layers **(default 2)**
Quarrystone	☑ Smooth ☐ Rough		
k_Δ	1,02	[-]	Roughness coefficient

W_filter	35,8	kg	Weight of the core material units
Rock size	Light		Rock size of the filter
Filter grading	5 - 40	kg	Standard filter grading
M_50	32	kg	Median weight of the design cube

D_n50	0,23	m	Equivalent cube length of median rock
D_n10	0,18	m	Diameter of which 10% are smaller
D_n15	0,19	m	Diameter of which 15% are smaller
D_n60	0,28	m	Diameter of which 60% are smaller
D_n85	0,38	m	Diameter of which 85% are smaller

Retention criterion

D_15_filter	0,2	m	Diameter of which 15% are smaller
D_85_found	0,38	m	Diameter of which 85% are smaller
ratio	0,53	[-]	d_15_filter/d_85_foundation
criterium	OK	[-]	Retention criterion (I)

W_50_filter	716	kg	Median rock weight for the filter
W_50_found	32	kg	Median rock weight for the foundation
ratio	22,38	[-]	W_50_filter/W_50_foundation
criterium	NOT OK	[-]	Retention criterion (II)

Permeability criterion

D_15_filter	0,2	m	Diameter of which 15% are smaller
D_15_found	0,19	m	Diameter of which 15% are smaller
ratio	1,05	[-]	d_15_filter/d_15_found
criterium	NOT OK	[-]	Permeability criterion

Internal stability criterion

D_60_filter	0,28	m	Diameter of which 60% are smaller
D_10_filter	0,18	m	Diameter of which 10% are smaller
ratio	1,56	[-]	d_60_filter/d_10_filter
criterium	OK	[-]	Internal stability criterion

Use wider grading   Undo

Core material selection

W_filter	7,16	kg	Weight of the core material units
Rock size	Light		Rock size of the filter
Filter grading	5 - 40	kg	Standard filter grading
M_50	32	kg	Median weight of the design cube

D_n50	0,23	m	Equivalent cube length of median rock
D_n10	0,18	m	Diameter of which 10% are smaller
D_n15	0,19	m	Diameter of which 15% are smaller
D_n60	0,28	m	Diameter of which 60% are smaller
D_n85	0,38	m	Diameter of which 85% are smaller

Retention criterion

D_15_filter	0,19	m	Diameter of which 15% are smaller
D_85_found	0,38	m	Diameter of which 85% are smaller
ratio	0,5	[-]	d_15_filter/d_85_foundation

150

criterium	OK	[-]	Retention criterion (I)

W_50_filter	32	kg	Median rock weight for the filter
W_50_found	32	kg	Median rock weight for the foundation
ratio	1	[-]	W_50_filter/W_50_foundation
criterium	OK	[-]	Retention criterion (II)

Permeability criterion

D_15_filter	0,19	m	Diameter of which 15% are smaller
D_15_found	0,19	m	Diameter of which 15% are smaller
ratio	1	[-]	d_15_filter/d_15_found
criterium	NOT OK	[-]	Permeability criterion

Internal stability criterion

D_60_filter	0,28	m	Diameter of which 60% are smaller
D_10_filter	0,18	m	Diameter of which 10% are smaller
ratio	1,56	[-]	d_60_filter/d_10_filter
criterium	OK	[-]	Internal stability criterion

[Use wider grading]   [Undo]

Bedprotection

ρ	1,6	t/m³	Density of the bedprotection (default 1,6)
h	0,5	m	Height of the layer

Foot protection blocks

#_sea	3	[-]	Amount of foot protection blocks at the seaside
#_lee	1	[-]	Amount of foot protection blocks at the leeside

H_m0	3	m	Design wave height
h_b	9	m	Top of the berm height beneath the SWL
h_s	15	m	Total water depth away from the breakwater

l	2,5	m	Length of the concrete foot protection
b	1,5	m	Width of the concrete foot protection
t'	0,8	m	Height of the concrete foot protection
M_50	6	t	Mass of the concrete foot protection block

Note that the same blocks are used at the lee- as at the seaside

Seaside

The width of the berm amounts:	10 m
The width of the foot protection:	7,5 m

There is no need to alter the toe berm width, so you can ignore the button on the right

[Change berm width]

Leeside

The width of the berm amounts:	5 m
The width of the foot protection:	2,5 m

There is no need to alter the toe berm width, so you can ignore the button on the right

[Change berm width]

Final output

Armour Layer

Type	Rocks	[-]	Type of armour unit
M_50	716	kg	Median rock weight
D_50	0,68	m	Equivalent cube length of median rock
r	1,33	m	Thickness of the armour layer
Grading	300 - 1000	kg	Standard grading

First filter layer

Type	Rocks	[-]	Type of armour unit
M_50	32	kg	Median rock weight
D_50	0,23	m	Equivalent cube length of median rock
r	0,47	m	Thickness of the first filter layer
Grading	5 - 40	kg	Standard filter grading

Core material

Type	Rocks	[-]	Type of armour unit
M_50	32	kg	Median rock weight
D_50	0,23	m	Equivalent cube length of median rock
Grading	5 - 40	kg	Standard core grading

Bedprotection

ρ	1,6	t/m³	Density of the bedprotection
h	0,5	m	Height of the layer

Foot protection blocks

#_sea	3	[-]	Amount of foot protection blocks at the seaside
#_lee	1	[-]	Amount of foot protection blocks at the leeside
l	2,5	m	Length of the concrete foot protection

b	1,5	m	Width of the concrete foot protection
t'	0,8	m	Height of the concrete foot protection
M_50	6	t	Mass of the concrete foot protection block

Go to the next design step

CE cloud	**Caisson width selection and safety assessment**		Main menu
	Source: CEM		See progress
	Author: L. De Smet		

(green)	Input of the user is required
(orange)	Parameters for intermediate results
(yellow)	Parameters which can be selected as final result

General input

In this part, the user can insert a certain width for the caisson, beneath you can directly monitor the different safety factors.
Note that you first have to fill in the green fields in this sheet to be able to calculate the correct values for these factors.

B	10,5	m	Width of the caisson

M	366,79	t/m	Total mass of the caisson, filled with sand

Safety factors

	Value	OK/NOT OK?	
SF_1	4,85	OK	Safety factor for sliding of the caisson
SF_2	3,96	OK	Safety factor for overturning of the caisson
SF_3	/	OK	Safety factor for the bearing capacity of the RM foundation

Mass of the caisson

Caisson geometry

t_bottom	0,5	m	Thickness of the bottom slab of the caisson
t_outer	0,5	m	Thickness of the outer walls of the caisson
#_part	2	m	Amount of partition walls within the caisson
t_part	0,5	m	Thickness of the partition walls of the caisson
t_slab	2	m	Thickness of the top slab of the caisson

Densities

ρ_c_dry	2,4	t/m³	Density of the dry concrete
ρ_s_dry	1,6	t/m³	Density of the sand in the caisson
ρ_c_wet	2,6	t/m³	Density of the wet concrete
ρ_s_wet	1,9	t/m³	Density of the wet sand in the caisson

Volumes

V_c_dry	22,78	m³/m	Total volume of dry concrete in the caisson
V_s_dry	55,76	m³/m	Total volume of dry sand in the caisson
V_c_wet	33,43	m³/m	Total volume of wet concrete in the caisson
V_s_wet	71,57	m³/m	Total volume of wet sand in the caisson

Masses

M_c_dry	54,67	t/m	Total mass of dry concrete in the caisson
M_s_dry	89,22	t/m	Total mass of dry sand in the caisson
M_c_wet	86,92	t/m	Total mass of wet concrete in the caisson
M_s_wet	135,98	t/m	Total mass of wet sand in the caisson
M_tot	366,79	t/m	Total mass of the caisson, including Archimedes law

Levelling method

Friction factor considering Morihira, Kihara and Harikawa

Levelling method rough or fine?	☐ Rough ☑ Fine	
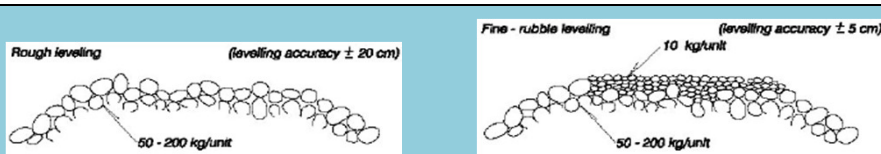
Bottom pattern of the caisson:	☐ Flat ☑ Clog-shaped ☐ Spike	

S	5	cm	Caisson displacement **(5, 10, 20 or 30 cm)**

μ_max	0,925	[-]	Dynamic friction coefficient corresponding to maximum tensile load

Select

Manual friction factor input

μ	0,636	[-]	Friction coefficient between the foundation and caisson **(default 0,636)**

Select		This will automatically generate a rough levelling application	

Safety factors

p_e_max	600	kPa	Max pressure on the foundation **(default 600 kPa)**
M	366,79	t/m	Total mass of the ciasson filled with sand
μ	0,925	[-]	Friction coefficient of the foundation and caisson

Forces			
F_H	604,02	kN/m	Horizontal force per meter
F_U	173,25	kN/m	Uplifting force per meter
F_G	5443,75	kN/m	Weight of the caisson per meter

Moments			
M_H	4443,63	kNm/m	Moment at the heel of the caisson due to horizontal forces, per meter
M_U	1295,44	kNm/m	Moment at the heel of the caisson due to vertical forces, per meter
M_G	14861,7	kNm/m	Moment at the heel due to the weight of the caisson, per meter

Safety against sliding			
SF1	4,85	[-]	Safety factor against sliding

Safety against overturning			
SF2	3,96	[-]	Safety factor against overturning of the caisson

Bearing capacity of the foundation			
p_e_max	600	kPa	Bearing capacity of the foundation
p_e	589,02	kPa	Exerted pressure acting on the foundation
SF3	OK	[-]	Bearing capacity safety

Overview		
SF1	OK	
SF2	OK	Change caisson width
SF3	OK	

Final output

B	10,5	m	Width of the caisson
M	366,79	t/m	Mass of the caisson, filled with sand

Levelling characteristics			
Method	Fine	[-]	Is the levelling method rough or fine?
Bottom	Clog-shaped	[-]	Configuration of the bottom of the caisson
r1	0,8	m	Thickness of the layer with the 50-200 kg rocks (rough and fine configuration)
r2	0,2	m	Thickness of the layer with the 10 kg rocks (only for fine configuration)

Forces & pressure			
F_H	604,02	kN/m	Horizontal force per meter
F_U	173,25	kN/m	Uplifting force per meter
F_G	5443,75	kN/m	Weight of the caisson per meter
p_e	589,02	kPa	Exerted pressure acting on the foundation

Moments			
M_H	4443,63	kNm/m	Moment at the heel of the caisson due to horizontal forces, per meter
M_U	1295,44	kNm/m	Moment at the heel of the caisson due to vertical forces, per meter
M_G	14861,7	kNm/m	Moment at the heel due to the weight of the caisson, per meter

Caisson geometry	
An appropriate design for the crownwall was found	

	Change concrete reduction factor		

H_caisson	17,48	m	Total height of the caisson
B	10,5	m	Total width of the caisson
H	1,16	m	Height of the crownwall
W	2	m	Width of the crownwall **(fixed value)**
t_bottom	0,5	m	Thickness of the bottom slab of the caisson
t_outer	0,5	m	Thickness of the outer walls of the caisson
#_part	2	m	Amount of partition walls within the caisson
t_part	0,5	m	Thickness of the partition walls of the caisson
t_slab	2	m	Thickness of the top cap of the caisson

Go to the next design step	

	Input of the user is required
	Parameters for intermediate results
	Parameters which can be selected as final result

For the calculation of the different costs, a cost list is made.
The cost list can always be edited by clicking on the button:

Cost list

Distances

Armour units	100	km	Transport distance
Filter 1	200	km	Transport distance
Core	200	km	Transport distance
Foot protection	100	km	Transport distance
Caisson	400	km	Transport distance
Sand	200	km	Transport distance

Porosity

Armour units	0,4	[-]	Porosity of the ALU
Filter 1	0,25	[-]	Porosity of filter 1
Core	0,2	[-]	Porosity of the core material
Sand	0,05	[-]	Porosity of the sand

Production

Armour units - seaside

Type	Rocks	[-]	Type of armour units
D_{n50}	0,68	m	Diameter of median rock
M_{50}	716	kg	Median unit weight
r	1,33	m	Thickness of the layer
V	15,16	m³/m	Total volume
M	39,42	t/m	Total mass
Cost	1064,34	€/m	Total cost

Armour units - leeside

Type	Rocks	[-]	Type of armour unit
D_{n50}	0,68	m	Diameter of median rock
M_{50}	716	kg	Median unit weight
r	1,33	m	Thickness of the layer
V	10,77	m³/m	Total volume
M	28	t/m	Total mass
Cost	756	€/m	Total cost

First filter layer

Type	Rocks	[-]	Type of filter material
D_{n50}	0,23	m	Diameter of median rock
M_{50}	32	t	Median unit weight
r	0,47	m	Thickness of the layer
V	16,61	m³/m	Total volume
M	43,19	t/m	Total mass
Cost	950,18	€/m	Total cost

Core material

Type	Rocks	[-]	Type of filter material
D_{n50}	0,23	m	Diameter of median rock
M_{50}	32	t	Median unit weight
V	88,06	m³/m	Total volume
M	228,96	t/m	Total mass
Cost	5037,12	€/m	Total cost

Foot protection blocks

Type	Concrete	[-]	Type of foot protection material

155

l	2,5	m	Length of one foot protection block	
b	1,5	m	Width of one foot protection block	
t'	0,8	m	Thickness of one foot protection block	
V	8	m³/m	Total volume	
M	16	t/m	Total mass	
Cost	1920	€/m	Total cost	

Caisson - concrete

Type	Concrete	[-]	Type of caisson material
V	56,21	m³/m	Total volume of the concrete in the caisson
M	141,59	t/m	Total mass of the concrete in the caisson
Cost	26980,8	€/m	Total cost of the concrete in the caisson per meter

Caisson - sand

Type	Coarse	[-]	Type of sand with which the caisson is filled
V	120,96	m³/m	Total volume of sand in the caisson
M	225,2	t/m	Total mass of sand in the caisson
Cost	1209,6	€/m	Total cost of the sand in the caisson, per meter breakwater

TOTAL BREAKWATER MATERIAL COST

Cost	36967,86	€/m	Material cost per meter

Transport

Armour	3708,1	€/m	Transport costs for the armour units
Filter	1827,1	€/m	Transport costs for the filter material
Core	9686,6	€/m	Transport cost for the core material
Foot protection	880	€/m	Transport cost for the foot protection blocks
Caisson	49839,68	€/m	Transport cost for the caisson
Sand	24772	€/m	Transport cost for the sand in the caisson

TOTAL BREAKWATER TRANSPORT COST

Cost	90713,48	€/m	Trunk transport cost

Construction

Armour unit	855,69	€/m	Construction cost for the armour layer
Filter 1	548,13	€/m	Construction cost of the first filter layer
Core	1937,32	€/m	Construction cost of the core material
Foot protection	264	€/m	Construction cost of the foot protection
Caisson	34850,2	€/m	Construction cost of the caisson (concrete part only)
Sand	2661,12	€/m	Construction cost to fill the caisson with sand

TOTAL BREAKWATER CONSTRUCTION COST

Cost	40568,33	€/m	Total construction cost per meter

TOTAL BREAKWATER COST BREAKDOWN

Armour unit	6384,13	€/m	Total cost of the armour layer
Filter 1	3325,41	€/m	Total cost of the first filter layer
Core	16661,04	€/m	Total cost of the core material
Foot protection	3064	€/m	Total cost of the footprotection
Caisson	111670,7	€/m	Total cost of the caisson
Sand	28642,72	€/m	Total cost of the sand in the caisson

Total cost	186409	€/m	Total cost of trunk-section per meter
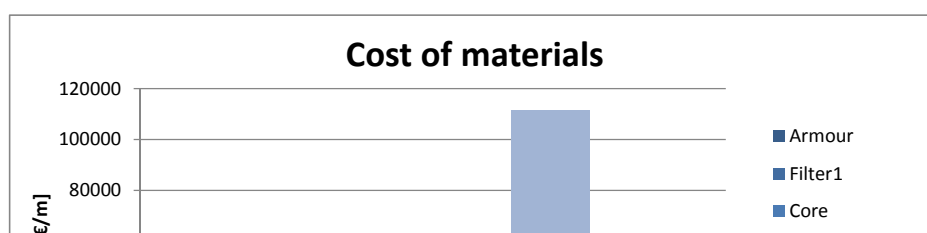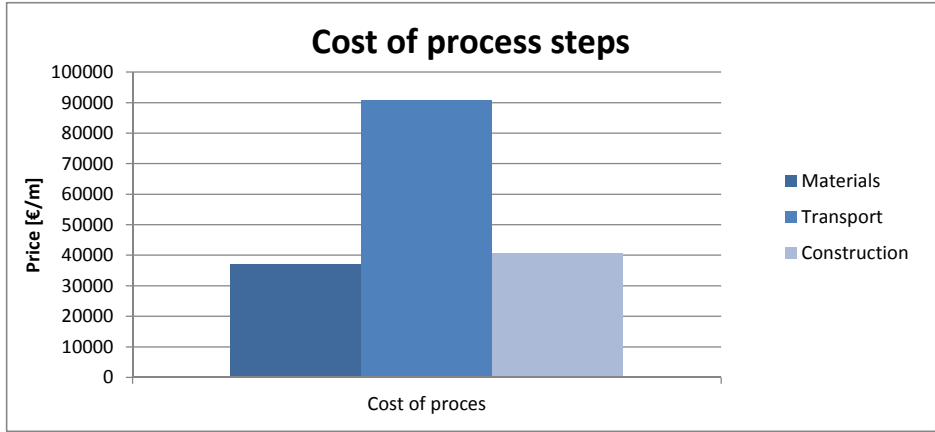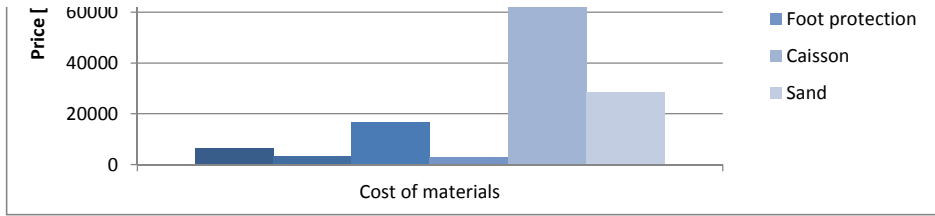
Cost of materials

Cost of materials

Cost of process steps

Cost of proces

Generate final design sheet

Final design sheet of the caisson breakwater
Source:
Author: L. De Smet

Hydraulic Boundaries

ρ_w	1,025	t/m³
h_s	15	m
Seaside		
H_s	3	m
T_p	9	s
s_m	0,0426	[-]

Layer information

	Armour		Filter 1		Core	Bedprotection	Footprotection blocks		Caisson concrete	Caisson sand	Units
	Sea	Lee	Sea	Lee			Sea	Lee			
Type	Rocks	Rocks	Rocks	Rocks	Rocks	Sand	Concrete	Concrete	Concrete	Sand	[-]
Grading	300 - 1000	300 - 1000	5 - 40	5 - 40	5 - 40	/	/		/	/	kg
Placement	/	/	/	/	/	/	/		/	/	[-]
ρ_s	2,6	2,6	2,6	2,6	2,6	1,6	2		2,4	1,6	t/m³
D_n50	0,68	0,68	0,23	0,47	0,23	/	/		/	/	m
M_50	716	716	32	32	32	/	6		/	/	kg or t
r	1,33	1,33	0,47	0,47	/	0,5	0,8		/	/	m
V_tot/m	15,16	10,77	16,61		88,06	/	6	2	56,21	120,96	m³/m
M_tot/m	39,42	28	43,19		228,96	/	12	4	141,59	225,2	kg/m or t/m
€/m	1820,34		950,18		5037,12	/	1920		26980,8	1209,6	€/m

Dimensioning

General dimensions				Foot protection blocks			Caisson dimensions		
					Sea	Lee			
q	0,001	m³/s/m		#	3	1	h	17,48	
R_c	7,48	m		l		2,5	B	10,5	
h_tot	22,48	m		b		1,5	t_bottom	0,5	
B_tot	53	m		t'		0,8	t_slab	2	
h_s	9	m					t_outer	0,5	
							#_part	2	
							t_part	0,5	

Draw the breakwater

Costs

Total cost `186409,02` €/m

Cost of materials

(Bar chart — Price [€/m] vs Cost of materials)
Legend: Armour, Filter1, Core, Foot protection, Caisson, Sand

Cost of proces steps

(Bar chart — Price [€/m] vs Cost of proces)
Legend: Materials, Transport, Construction

Amount of breakwaters inserted: 0

Set as 1st breakwater section
Set as 2nd breakwater section
Set as 3rd breakwater section
Set as 4th breakwater section
Set as 5th breakwater section

Compare with RM breakwater

Open cost assessment of the whole breakwater

Design next breakwater section

0	0
0	0,5
57	0,5
57	0
0	0
0	0,5
2	0,5
18,5	6
21	6
21	4,67
18,5	4,67
5,99	0,5
7,4	0,5
18,5	4,2
28,5	4,2
28,5	4,67
21	4,67
21	5,47
28,5	5,47
28,5	4,67
28,5	22,48
30,5	22,48
31,66	21,32
39	21,32
39	4,67
38,8	4,47
38,6	4,47
38,4	4,67
29,1	4,67
28,9	4,47
28,7	4,47
28,5	4,67
28,5	4,47
39	4,47
39	4,67
39	4,2
41	4,2
39	3,67
28,5	3,67
26,5	4,2
28,5	4,2
28,5	4,67
28,5	22,48
30,5	22,48
30,5	22,48
31,66	21,32
39	21,32
39	4,67
39	5,47
41,5	5,47
41,5	4,67
39	4,67
39	4,2
44	4,2
51,4	0,5
52,34	0,5
44	4,67
41,5	4,67
41,5	6
44	6
55	0,5
57	0,5
57	15
39	15
57	15

Autocad tool

Source: CEM, 2007; Goda
Author: L. De Smet

Main menu

Draw in Autocad

Write to notepad

Back to final design

57	0
0	0
0	16,5
28,5	16,5
0	16,5
0	15
28,5	15
0	15
0	0
0	0
0	0
0	0
0	0

Caisson breakwater:
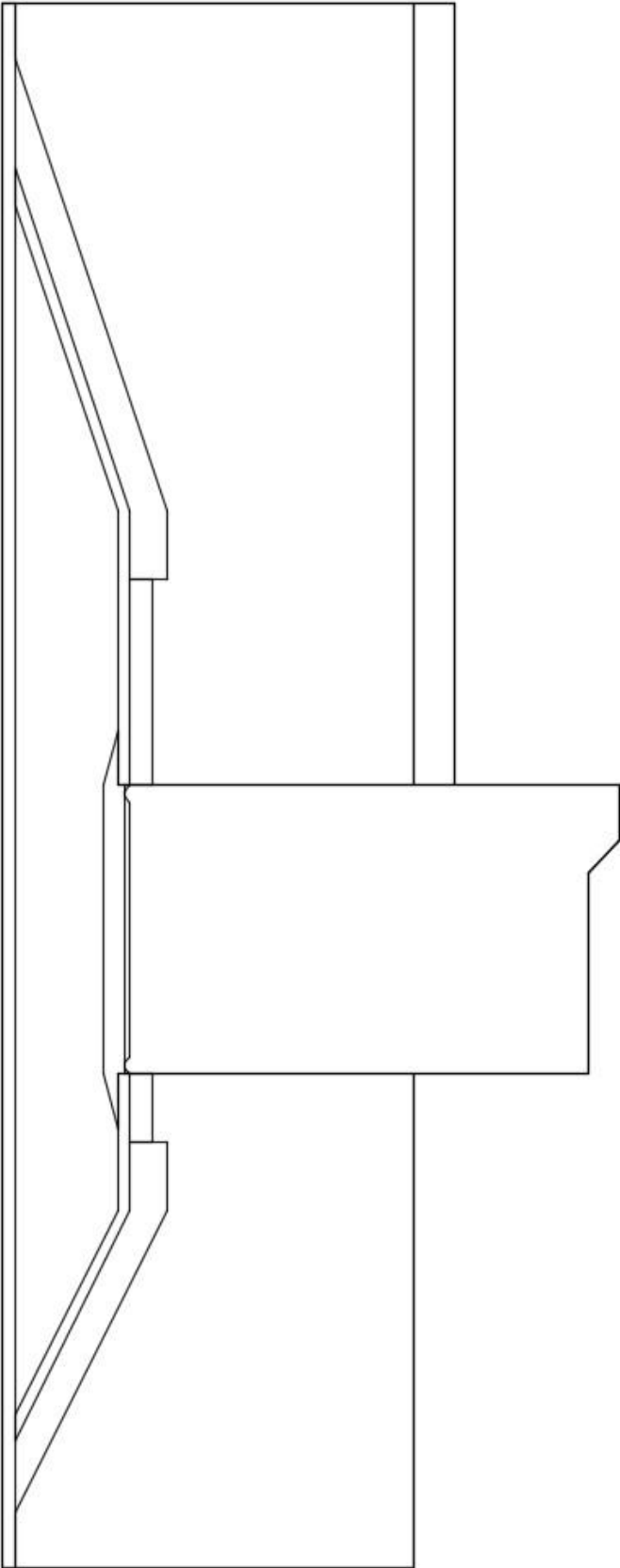
Rubble-mound and caisson breakwater together:

CE cloud

Total cost breakdown of the whole breakwater
Source:
Author: L. De Smet

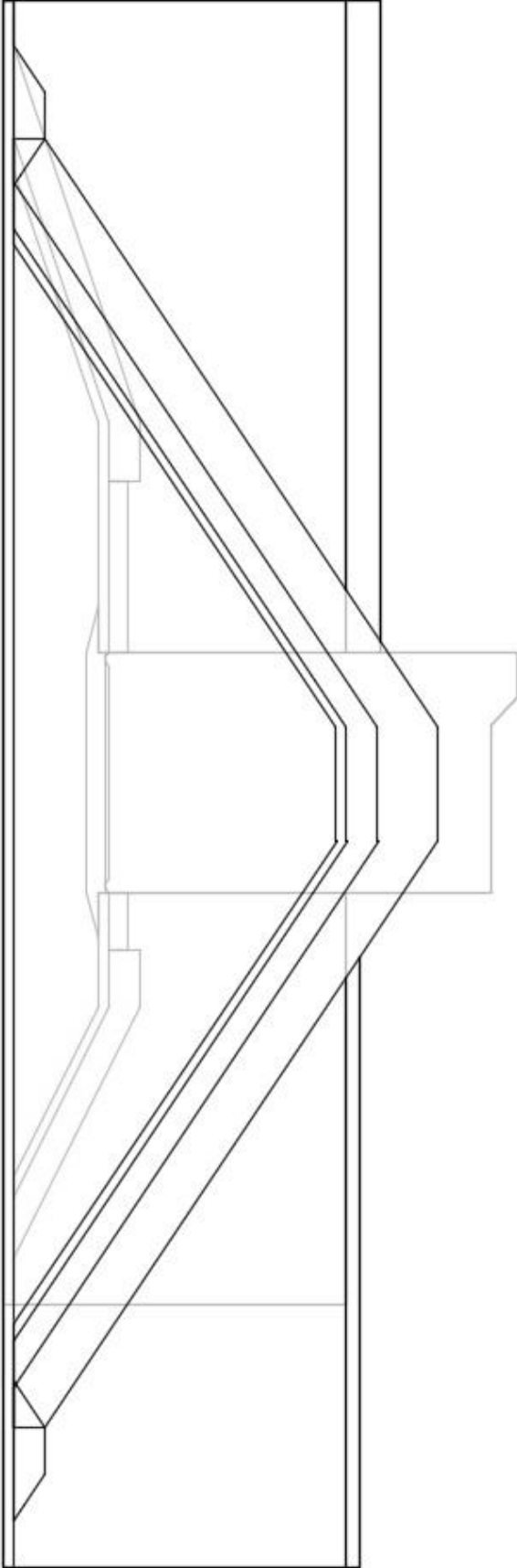|	Input of the user is required
	Parameters for intermediate results
	Parameters which can be selected as final result

Distances

Length between 1 & 2	20	m
Lenght between 2 & 3	4	m
Length between 3 & 4	30	m
Length between 4 & 5	0	m

You can insert the distance between the different selected breakwater sections. It is possible to insert up to 5 (or less) different cross-sections

Visualize cost-breakdown

You can generate the different costs of the trunk-sections by clicking on the button below:

Analyze cost-breakdown

Costs

	1st	2nd	3rd	4th	5th
Production	€/m	€/m	€/m	€/m	€/m
Armour	5890,1	5890,1	5026,83	5026,83	0
1st filter	3422,25	3422,25	2828,79	2828,79	0
2nd filter	1046,32	1046,32	849,64	849,64	0
Core	14853,74	14853,74	9668,56	9668,56	0
Toes	236,84	236,84	236,84	236,84	0
Roundhead	3805,25	3805,25	3186,8	3186,8	0
Foot protection	0	0	0	0	0
Caisson concrete	0	0	0	0	0
Caisson sand	0	0	0	0	0
Total	25449,25	25449,25	18610,66	18610,66	0
Transport					
Armour	11366,85	11366,85	9700,9	9700,9	0
1st filter	13942,5	13942,5	11524,7	11524,7	0
2nd filter	5231,6	5231,6	4248,2	4248,2	0
Core	74268,7	74268,7	48342,8	48342,8	0
Toes	420,2	420,2	420,2	420,2	0
Roundhead	6751,25	6751,25	5654	5654	0
Foot protection	0	0	0	0	0
Caisson concrete	0	0	0	0	0
Caisson sand	0	0	0	0	0
Total	111981,1	111981,1	79890,8	79890,8	0
Construction					
Armour	6820,11	6820,11	5820,54	5820,54	0
Filter 1	1818,63	1818,63	1503,15	1503,15	0
Filter 2	682,44	682,44	554,07	554,07	0
Core	14853,74	14853,74	9668,56	9668,56	0
Toes	252,12	252,12	252,12	252,12	0
Foot protection	0	0	0	0	0
Caisson concrete	0	0	0	0	0
Caisson sand	0	0	0	0	0
Total	24427,04	24427,04	17798,44	17798,44	0
Total costs					
Armour	24077,06	24077,06	20548,27	20548,27	0
1st filter	19183,38	19183,38	15856,64	15856,64	0
2nd filter	6960,36	6960,36	5651,91	5651,91	0
Core	103976,18	103976,18	67679,92	67679,92	0
Toes	909,16	909,16	909,16	909,16	0
Roundhead	10556,5	10556,5	8840,8	8840,8	0
Foot protection	0	0	0	0	0
Caisson concrete	0	0	0	0	0
Caisson sand	0	0	0	0	0
Total costs	165662,64	155106,14	110645,9	119486,7	0

	1-2	2-3	3-4	4-5	
Production	€	€	€	€	
Armour	117802	21833,86	150804,9	0	
1st filter	68445	12502,08	84863,7	0	
2nd filter	20926,4	3791,92	25489,2	0	
Core	297074,8	49044,6	290056,8	0	
Toe	4736,8	947,36	7105,2	0	
Roundhead	76105	13984,1	95604	0	
Foot protection	0	0	0	0	
Caisson concrete	0	0	0	0	
Caisson sand	0	0	0	0	
Total	508985	88119,82	558319,8	0	
Transport					
Armour	227337	42135,5	291027	0	
1st filter	278850	50934,4	345741	0	
2nd filter	104632	18959,6	127446	0	
Core	1485374	245223	1450284	0	
Toes	8404	1680,8	12606	0	
Roundhead	135025	24810,5	169620	0	
Foot protection	0	0	0	0	
Caisson concrete	0	0	0	0	
Caisson sand	0	0	0	0	
Total	2239622	383743,8	2396724	0	
Construction					
Armour	136402,2	25281,3	174616,2	0	
Filter 1	36372,6	6643,56	45094,5	0	
Filter 2	13648,8	2473,02	16622,1	0	
Core	297074,8	49044,6	290056,8	0	
Toes	5042,4	1008,48	7563,6	0	
Foot protection	0	0	0	0	
Caisson	0	0	0	0	
Sand	0	0	0	0	
Total	488540,8	84450,96	533953,2	0	
Total costs					
Armour	481541,2	89250,66	616448,1	0	
1st filter	383667,6	70080,04	475699,2	0	
2nd filter	139207,2	25224,54	169557,3	0	
Core	2079523,6	343312,2	2030397,6	0	
Toes	18183,2	3636,64	27274,8	0	
Roundhead	211130	38794,6	265224	0	
Foot protection	0	0	0	0	
Caisson concrete	0	0	0	0	
Caisson sand	0	0	0	0	Total
Total costs	3313252,8	570298,68	3584601	0	7468152,48 €

Materials

		1st		2nd		3rd		4th		5th	
		Material	t/m	Material	t/m	Material	t/m	Material	t/m	Material	t/m
Armour	sea	Rocks	154,72	Rocks	154,72	Rocks	132,88	Rocks	132,88	/	0
	lee	Rocks	51,95	Rocks	51,95	Rocks	43,5	Rocks	43,5	/	0
1st filter		Rocks	126,75	Rocks	126,75	Rocks	104,77	Rocks	104,77	/	0
2nd filter		Rocks	47,56	Rocks	47,56	Rocks	38,62	Rocks	38,62	/	0
Core		Rocks	675,17	Rocks	675,17	Rocks	439,48	Rocks	439,48	/	0
Toe	sea	Rocks	3,82	Rocks	3,82	Rocks	3,82	Rocks	3,82	/	0
	lee	Rocks	3,82	Rocks	3,82	Rocks	3,82	Rocks	3,82	/	0
Roundhead		Rocks	122,75	Rocks	122,75	Rocks	102,8	Rocks	102,8	/	0
Foot protection		/	0	/	0	/	0	/	0	/	0
Caisson concrete		0	0	/	0	/	0	/	0	/	0
Caisson sand		0	0	/	0	/	0	/	0	/	0

		1-2		2-3		3-4		4-5	
		Material	t	Material	t	Material	t	Material	t
Armour	sea	Rocks	3094,4	Rocks	575,2	Rocks	3986,4	Rocks	0
	lee	Rocks	1039	Rocks	190,9	Rocks	1305	Rocks	0
1st filter		Rocks	2535	Rocks	463,04	Rocks	3143,1	Rocks	0
2nd filter		Rocks	951,2	Rocks	172,36	Rocks	1158,6	Rocks	0
Core		Rocks	13503,4	Rocks	2229,3	Rocks	13184,4	Rocks	0
Toe	sea	Rocks	76,4	Rocks	15,28	Rocks	114,6	Rocks	0
	lee	Rocks	76,4	Rocks	15,28	Rocks	114,6	Rocks	0
Roundhead		Rocks	2455	Rocks	451,1	Rocks	3084	Rocks	0
Foot protection		/	0	/	0	/	0	/	0
Caisson concrete		0	0	/	0	/	0	/	0
Caisson sand		0	0	/	0	/	0	/	0

Main Menu
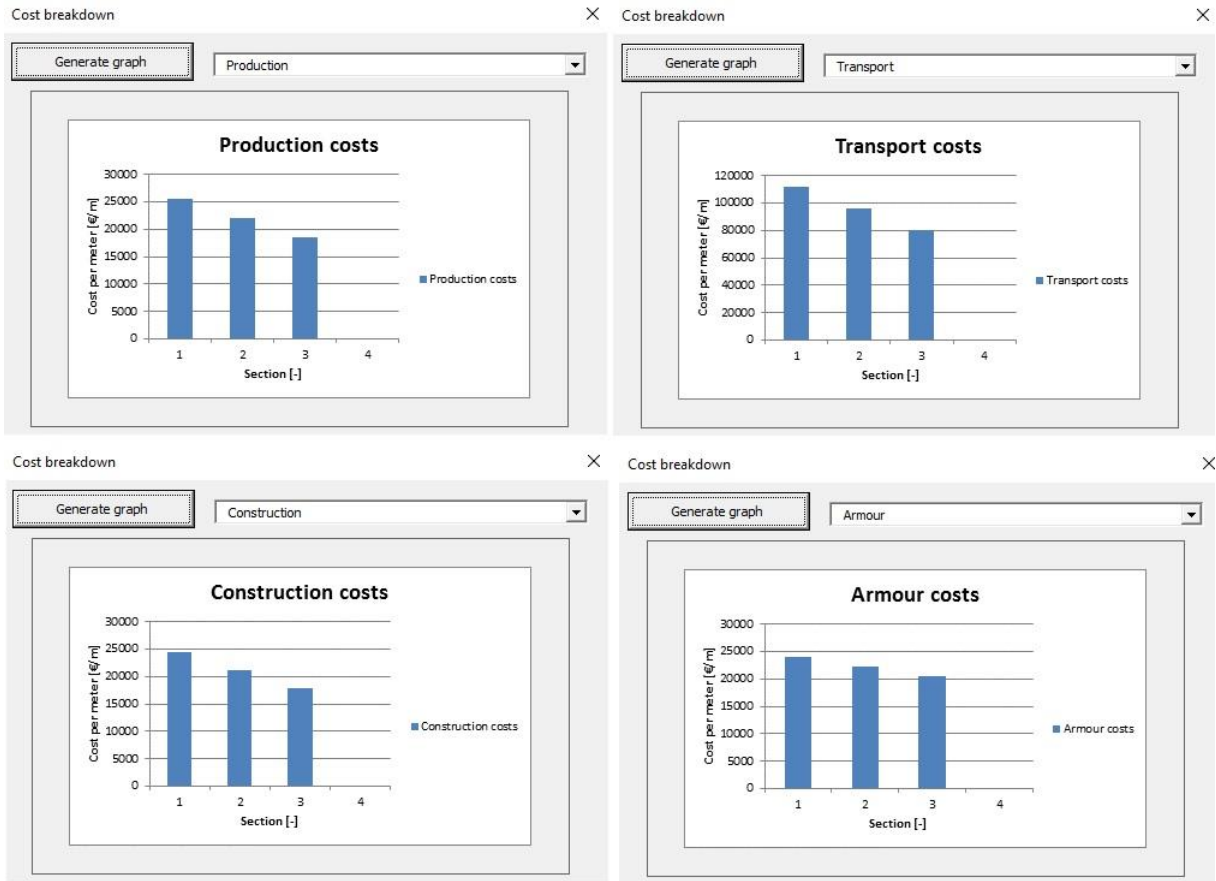
Cost breakdown in 1st filter, 2nd filter, core, toes, roundhead, foot protection, caisson concrete and caisson sand is also available.

Excel-based design tool for the assessment of
rubble-mound and caisson breakwaters

Laurens De Smet

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Counsellor: David Gallach Sanchez

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Civil Engineering

Department of Civil Engineering
Chair: Prof. dr. ir. Peter Troch
Faculty of Engineering and Architecture
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