SOLUCIONES NO TÍPICAS HOLANDESAS PARA MEJORAR LA SEGURIDAD DE LA PRESA DE CIERRE MÁS ANTIGUA DE LOS PAISES BAJOS (AFSLUITDIJK) EN EL MAR DEL NORTE

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RESUMEN

"Afsluitdijk", o Presa de Cierre en castellano, es uno de los principals viaductos en los Países Bajos. Fue construido entre 1927 y 1933 vinculando las ciudades de Den Oever en Wieringen de la provincia de Holanda del Norte con el pueblo de Zurich en la provincia de Frisia. La presa tiene 32 kilometros de extensión y 90 m de ancho, con una altura inicial de +7,25 m NAP ("Normaal Amsterdams Peil", o Nivel Normal de Ámsterdam en castellano) y una pendiente de 1:4 (valor original, ahora 1:3.6) a cada lado (Rijkswaterstaat, 2009).

Después de 80 años de rendimiento exitoso se esperan cambios en las condiciones de borde, y debido al incremento de los requisitos de seguridad para protección de inundaciones, es necesario pensar una adaptación de la estructura para que pueda cumplir su función en el futuro. "Rijkwaterstaat", o el Ministerio de Infraestructura y el Ambiente en castellano, ha decidido chequear una solución resistente al rebase de olas ("overtopping" en inglés), la cual provea la protección requerida hasta el año 2050.

Este proyecto apuntó a definir y proponer nuevas configuraciones del dique con soluciones no típicas holandesas, las cuales tuvieron que cumplir con los Requerimientos del Empleador. Se utilizó una sección existente del "Afsluitdijk" como punto de referencia, se asumió -5.0 m NAP como nivel del lecho del "Waddenzee" (o Mar de Wadden en castellano) intentando adoptar un diseño representativo y comparable para todas las nuevas configuraciones que se presentan. Esta decisión se basó en que la profundidad media del Mar de Wadden está entre -4.0 a -5.0 m NAP.

Se plantearon dos etapas de estudio: Diseño Intermedio y Diseño Final. En primera instancia varias soluciones no típicas holandesas fueron definidas con el objetivo de cubrir un amplio rango de opciones. Durante el Diseño Intermedio, se evaluaron las alternativas listadas a continuación (las pendientes son indicadas de la siguiente forma Vertical:Horizontal; por ej. 2V:3H):

1. Rip-Rap sin berma, pendiente 2:3
2. Rip-Rap sin berma, pendiente 1:2
3. Xbloc®, pendiente 2:3
4. Xbloc®, pendiente 3:4
5. Rompeolas con berma, reconfiguración dinámicamente estable
6. Rip-Rap con berma
7. Acropode™ II, pendiente 3:4 (hasta el límite exterior)
8. Acropode™ II, pendiente 3:4 (pendiente de corte)
9. Cubos de hormigón, pendiente 2:3
10. Rip-Rap sin berma, pendiente 1:3.6, capa adicional sobre la pendiente existente aumentando el ancho de impronta actual del "Afsluitdijk" en el Mar de Wadden, desde ahora referenciado como: invadiendo del Mar de Wadden
11. Xbloc®, pendiente 3:4, invadiendo del Mar de Wadden
12. Rompeolas con berma, reconfiguración dinámicamente estable, invadiendo del Mar de Wadden

Estas alternativas se compararon a través de un análisis multi-criteria, junto con la estimación de costos. Como resultado, las dos alternativas más favorables, 4 y 10 de la lista anterior, fueron seleccionadas.

En el Diseño Final, más estudios fueron realizados para ambas alternativas seleccionadas, las que fueron contrastadas con una de las alternativas propuestas por "Rijkswaterstaat" (llamada "OverTopping resistant solution"). El diseño 10 resultó en la solución más favorable de las soluciones propuestas.

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INTRODUCTION

The starting point is the Afsluitdijk, one of the most important infrastructures in the Netherlands. The Afsluitdijk was built aiming to protect the coast along the Zuiderzee against the North Sea, turning it into a fresh water lake at the same time. The old coastline configuration is shown in Figure 1. It is clearly visible that the Afsluitdijk protects central Netherlands from the effects of the North Sea (Merwe & Bezuidenhout, 2007). As it was mentioned in the Summary, after almost a century of successful performance, changes are expected.

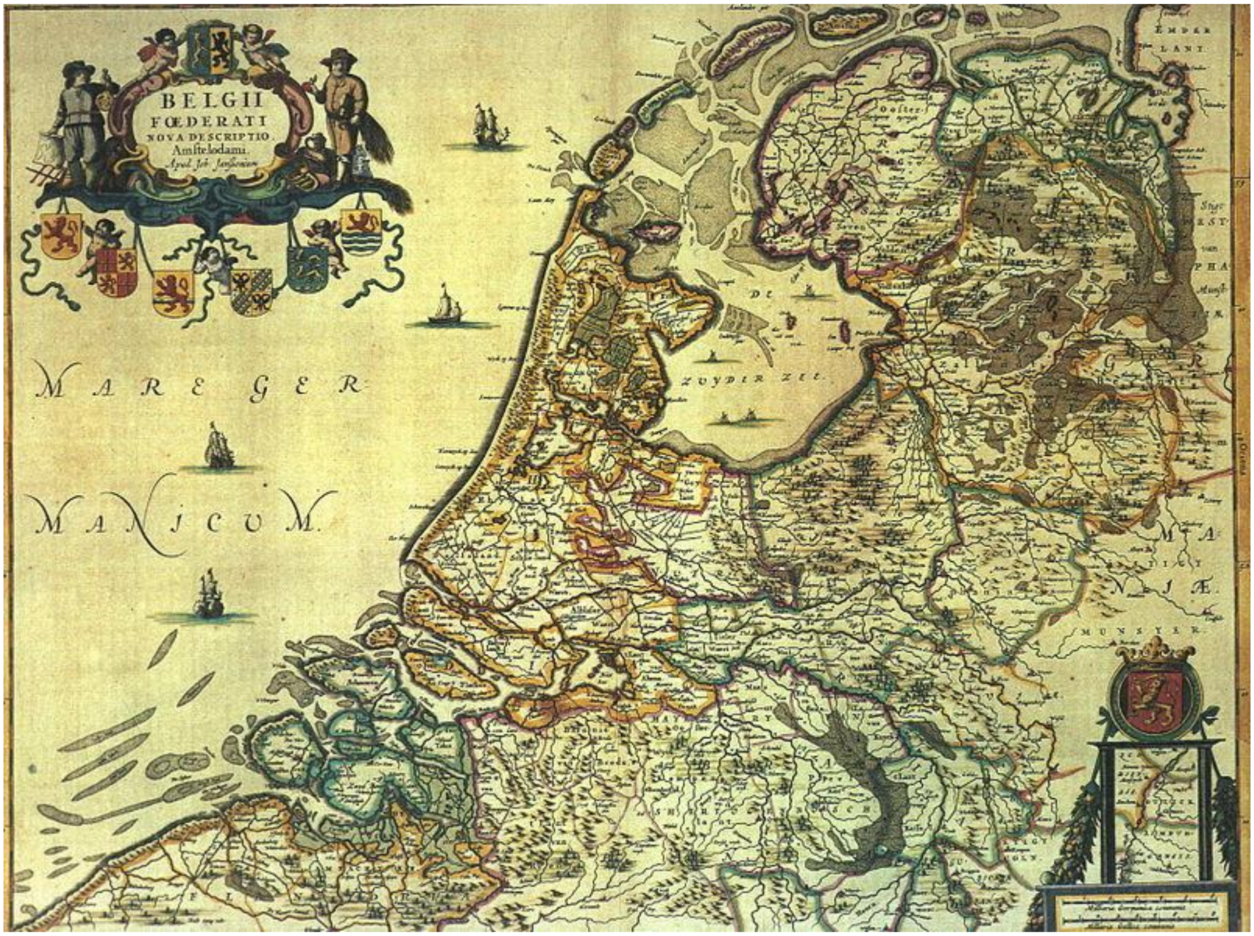

Figure 1 Map of the Netherlands 1658, Source: Janssonius

The task given by Rijkswaterstaat to this Multidisciplinary Team, and the purpose assigned is to define the upgraded cross section for the Afsluitdijk. The developed design had to accomplish several goals:

- Provide the required safety level
- Respect the imposed conditions (keep roads operational while working, and any other requirements from the Client)
- Optimized construction cost (definition of the optimal cross section and construction methods according to the given conditions)

The project focused on the development of a design that fulfils the given conditions, and a substantiation of the advantages of the chosen design. First, several non-typical Dutch solutions have been defined trying to cover a wide range of options. Then, a comparison among them is done by means of a multi-criteria analysis. Finally, the most advantageous solution proposed for the Afsluitdijk is chosen. The studies are also based in a cost estimation analysis.

As background information, it can be mentioned that the Afsluitdijk was built up with boulder clay, clay and sand which were found in the bottom of former Zuiderzee. The dam is erected on top of a smaller closure made of boulder clay which was emplaced previously to separate both water masses. On the Ijsselmeer side of this dam, a wide body of sand which is covered with boulder clay and clay was built. The dam body below the waterline is protected with osier wood and reed mattresses, where Rip-Rap is placed on. Above waterline, the dike is protected with basalt blocks. The crest and inner slope are covered with grass. Furthermore, a motorway stretches out at the top of the dam, enabling road traffic between the provinces of Noord Holland and Friesland.

For the current situation, the dike reaches a level of +7.8 m NAP with an outside slope of 1:3.6 covered with basalt blocks as a revetment. There is also a permeable clay layer on top of the crest covered with grass with an inside slope of around 1:2.7. The total a width of the dike is between 80 m to 100 m. If the current structure faces these severe storm conditions it would mean that a wave overflow of approximately 366 ℓ/s/m will occur, rising Lake Ijssel's water level by 0.5 m over storm duration of 12 hours.

An existing cross section from the Afsluitdijk was used as starting point. Specifically, cross section 10a referred to "Legger Afsluitdijk" document (Rijkswaterstaat, 2009) shown in Figure 2, is chosen as the characteristic cross section and the proposed designs are based on it.

The adopted sea bottom elevation for this cross-section is -5.0 m NAP. This value is used in every proposed new configuration trying to have a representative design for the whole dike length. However, it is important to mention that the actual existing depths at the area where cross section 10a is located are around -10.0 m NAP. In addition, other cross sections are in shallower areas around -2.0 m NAP.

On the following figures details about its layout and cross section can be found.

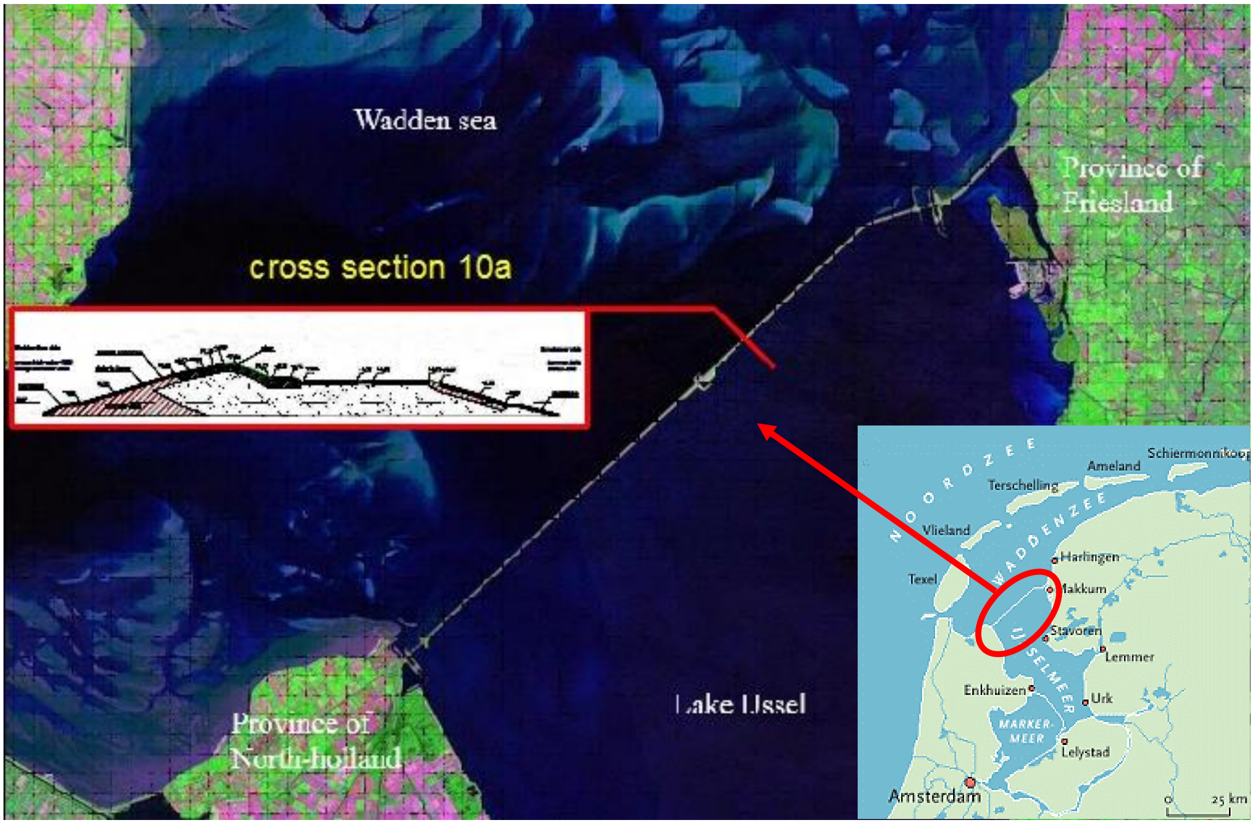

Figure 2 Map of the Northeast part of the Netherlands & general layout of the Afsluitsijk with its cross section 10a

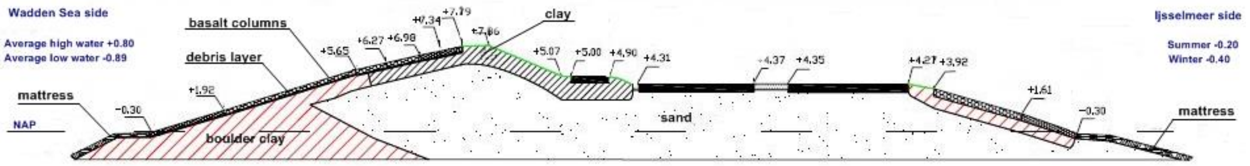

Figure 3 Characteristic Cross Section Afsluitdijk

In addition, it is essential to know and understand Employer's needs in order to design and offer a satisfactory solution. This design complies, not only the explicit requirements, but also other conditions that are not directly requested, but follow the general spirit of Employer's demands. These requirements are introduced in the following statements:

- Define a new armour layer solution and dike configuration, using non-typical Dutch solutions. The new design should be innovative and reliable for Dutch standards.
- Use different values of wave heights and wave periods to perform specific calculations for each proposed cross-section design, i.e. use "Golfklappen betonblokken-info" to compute concrete blocks and Rip-Rap armour units stability; on the other hand use "golfoverslag" values to design crest height for overtopping.
- Limit to the existing boundaries of the current dike situation (no extra space occupied, however some alternatives were developed superseding this constraint due to the fact of special request from the Client; also, keep roads operational while working, et cetera).
- Basalt columns should be reused or sold to the market, if they are removed from the Afsluitdijk. Alternatives without removing the basalt columns are also evaluated under request of the Client assuming there will be no benefit on it.
- The increase in land availability provided by the crown wall is not essential. An optimization of concrete crown wall should be studied.

DESIGN BASIS CRITERIA

In principle, two non-typical Dutch design options are proposed for the armour layer: Rip-Rap and concrete blocks revetment. Within these two possibilities, different variations are studied and calculated in order to see which is more advantageous. While working in the alternatives, special attention is paid to costs. Therefore, material costs and construction procedures are considered in detail as well. By means of this study, the two most favourable alternatives are found. Then, a complete definition of the chosen cross sections is made.

To determine the required armour layer unit size, three calculation approaches are performed. Firstly, the Classical or Deterministic method is used. Then in case it is possible the Partial Safety Coefficients method (consist in a level 1 probabilistic computation) and a Probabilistic Calculation (level 2 probabilistic computation) is applied as well.

The classical or deterministic method can be done using Van der Meer or Hudson formula. Hudson and Van der Meer formulae have different applicability range. For the Afsluitdijk, only Van der Meer formula is applied, due to the limitations that Hudson formula has for non-permeable cores.

The partial safety coefficient method is the one developed by PIANC (PIANC PTC II WG 12, 1992), and it is based on the application of safety coefficients that are added to the Van der Meer design formula. Two safety coefficients are used, one for loads and another for strength.

Using probabilistic computations, the different parameters are treated as stochastic variables, each on them with its own probability distribution function. The equation for calculation of armour unit size is rewritten as a Z-function (reliability function) and then the full probabilistic calculation is carried out.

Furthermore, the toe also needs to be independently studied as it is responsible for withstanding the armour layer. Its stability is related to weight, level and damage level of the toe as it was proposed by Gerding in Toe Structure Stability of Rubble Mound Breakwater (Gerding, 1993) and confirmed latter by L. Docters Van Leeuwen.

Additionally, run up needs to be checked, and it is defined as the vertical distance measured from mean sea level to the highest point reached for a wave in a slope. The EurOtop Manual (Pullen, Allsop, & van der Meer, 2007) recommends make use of $R_{2\%}$, which is the run-up level that is exceeded by 2% of the number of incident waves

Finally, overtopping may be checked as well, because it can arise when run-up exceeds crest height. Its prediction was performed using the guidelines from The EurOtop Manual (Pullen, Allsop, & van der Meer, 2007). The maximum allowed mean discharge is set at 10 l/s/m following the design rules from EurOtop Manual and extensive discussions with the Client.

MULTI-CRITERIA ANALYSIS (MCA)

A Multi-Criteria Analysis is carried on, starting from individual assessment of each team member and the client, to end up with a balanced and consented scoring and weighing for each relevant criterion. The process was iterative and it led to the determination of the most favourable design alternatives. In addition, individual assets from the Client were included.

The analysis made meaningful use of stakeholder engagement; identifying win-win options during the construction process as well as during the dike life cycle. Recommendations from “Multi-Criteria analysis: a manual” (Department for Communities and Local Government, 2009) is addressed. Some of the topics that were weighed are:

- *Technical factors*. This condition is divided in the following topics: Protection from waves, Construction process and Flexibility for future upgrading.
- *Operational factors*. Within this category Resilience and Land availability are considered.
- *Environmental aspects*. Waddenzee protected area invasion, PIANC Working with Nature approach (PIANC EnviCom, 2011), Pollution during construction and Landscape are included.
- *Maintenance*. Essential to know and understand operation’s Client needs in order to design for maintenance simplicity and easy adaptable solutions.
- *Third parties*. Incorporate the ambitions from third parties which can have an interest in developing their activities in the area, i.e. Recreation, Social considerations (economy boost, et cetera).

After the Multi-Criteria Analysis, the decision making stage was addressed, during this process a cost-benefit analysis was carried out in order to choose the most favorable design.

Table 1. Categories and criteria used in comparison of alternatives

TECHNICAL FACTORS	Protection from waves (i.e. wave number)
	Construction Process (duration; phasing; required area & equipment; et cetera)
	Flexibility future upgrading
OPERATIONAL FACTORS	Resilience (i.e. dike width; H_s for N_{od} = failure, et cetera)
	Land availability (possible future road & road safety improvements; new bike lanes; additional service lane; et cetera)

ENVIRONMENT	Incursion in protected area Waddenzee (from identified outer limit)
	Pollution during construction (currents/sedimentology; water turbidity; CO_2 emissions; noise, light and soil pollution; excavation volumes; et cetera)
	Landscape
	PIANC Working with Nature philosophy
MAINTENANCE	Frequency of maintenance and monitoring
	Accessibility for inspection of armour layer
	Accessibility for maintenance tasks (toe; berm; rolling surface for cranes; et cetera)
THIRD PARTIES	Recreation (available area for sightseeing; bike lane; sports; fishing, societal activities inclusion, et cetera)
	Social considerations (Dutch pride; economy boost; et cetera)

Then, a range of scores is chosen. The defined range tries to describe in a simple and accurate way possible states that the performance level of an alternative can reach. The final score scale is:

Table 2.Score range Multi-criteria analysis

EXPECTED PERFORMANCE	**SCORE**
The alternative presents ideal conditions regarding the analysed factor	+4
The alternative presents good conditions, without significant problems	+3
The alternative presents some problems regarding studied factor, but they can be solved	+2
The alternative presents significant problems regarding the analysed factor, difficult to resolve	+1
The alternative presents challenging issues that could proscribe the design	0

Once the range is defined, each alternative design gets a score for each criterion (from Table 2). With the aim of eliminate subjectivity in this report, not a single evaluation but average values are used. The design team has completed the score assignment individually to present an average of the results.

After assigning scores, the next step is to give a relative weight to the different criteria parameters. As the number of relevant factors is significant, the chosen method is to compare the criteria by pairs and choose which one is more important. To this end, when comparing between two factors, a numerical value from each expert is given. One, if the most important is the row parameter and zero, if the most important is the columns factor. Finally, the criterion with higher score turns out to be the most relevant. This step is significantly subjective, as assigning scores. In order to get rid of subjectivity for weighing, experts have also completed the evaluation on their own.

INTERMEDIATE DESIGN

As it was mentioned, a wide range of breakwater designs has been studied. To accomplish that, some conditions for the design process have been established:

- Definition of at least one design for each main typology of breakwater (considering different type of materials, one or two-layer concrete armour units, with or without berm, et cetera).
- Definition of different cross section geometries within a defined intervention area, in which the outer end point of the cross section is fixed and it is not invading the Waddenzee. Different slopes, cross section, end point location in the defined intervention area and variation of some other parameters have been studied. However, due to Employer’s Requirements some alternatives invading the Waddenzee were analyzed as well.
- Comparison between available Dutch and foreign technology for concrete armour layer units. This is based in several Reports and Catalogues; i.e. (PIANC MarCom WG 36, 2005).
- For some alternatives, existing basalt columns armour layer are assumed to be removed and new layers are placed on top of the boulder clay core which should be reshaped and protected. In addition, as these basalt columns are kind of unique in Europe, it is recommended to reuse them or at least try to place them into the market. However, after extensive discussions with the Client, it is considered a difficult procedure. Nevertheless, the team still believes those basalt blocks should be saved. Moreover, due to Employer’s Requirements, other alternatives without removing the existing basalt columns armour layer are analyzed.
- It is assumed impermeable core for every proposed alternative, except for dynamically reshaping berm breakwaters where a permeability of P=0.5 was assumed due to the fact of having a sufficient thick armour and underlayers.
- A wave height of 3.72 m is used for the armour layer calculations and a wave height of 3.83 m has been used for the rest of the calculations based on the Employer’s Requirements.

Taking all these considerations into account, the following alternatives have been evaluated (slopes are noted Vertical:Horizontal; i.e. 2V:3H), and in the following paragraphs are briefly described:

1. Rip-Rap without berm, slope 2:3
2. Rip-Rap without berm, slope 1:2
3. Xbloc®, slope 2:3
4. Xbloc®, slope 3:4
5. Berm breakwater, dynamically stable reshaped
6. Rip-Rap with berm
7. Acropode^{TM} II, slope 3:4 (up to the external limit)
8. Acropode^{TM} II, slope 3:4 (cutting slope)
9. Antifer cubes, slope 2:3
10. Rip-Rap without berm, slope 1:3.6, over layer on top of existing slope invading the Waddenzee
11. Xbloc®, slope 3:4, invading the Waddenzee
12. Berm breakwater, dynamically stable reshaped, invading the Waddenzee

RIP-RAP

This design considers typical rubble mound cross section with Rip-Rap. This type of cross section is defined as a breakwater without berm with two layer armour and underlayer (three d_{n50} thicknesses for easiness during construction). Underlayer´s rocks should be the first fraction of quarry yield curve. Two alternatives are presented here. The main difference between them is the armour layer slope. A 2:3 slope and 1:2 slope were studied.

XBLOC®

Two cross section of breakwater with Xbloc® concrete units are studied. This type of cross section is defined as a rubble mound solution with a one-layer armour which is achieved by using interlocking concrete blocks. Xbloc® design is considered of special interest since it is technology fully developed in The Netherlands (and at the time of the study, there were not any Xbloc® breakwater built in the Netherlands). The most significant variation that could be done in this type of design is a change in the armour layer slope. Hence, a 2:3 slope and a 3:4 slope solutions are calculated and implemented on the existing Characteristic dike cross section. For environmental benefits, Eco Xbloc® is a very interesting alternative which can be applied for these designs.

DYNAMICALLY STABLE RESHAPED BERM BREAKWATER

This type of breakwater allows some rock movement (up and down, longshore transport should be restricted) causing the breakwater to reshape until a new reshaped equilibrium profile is achieved. In this report the guidelines “State of the art of designing and constructing berm breakwaters” (Baird, Magoon, & Willis, 1987), “Berm Breakwaters Un-conventional Rubble-Mound” (van Gent, Smith, & van der Werf, 2012) are followed. Berm breakwaters allow an easy construction method making use of only two different rock grading types; one for the armour layer and one for the core. In this type of breakwaters the stability of the armour layer is checked in a different way from rubble mound breakwaters; mainly because rocks are allowed to move up and down. Therefore, the existing profile is reshaped into a new one during storms. Armour layer stability is assured, if in every case there are at least two armour layers on top of the underlayer along the whole profile. In addition, berm breakwaters are less sensitive to scour than a rubble mound breakwater, mainly due to its flexibility. Thus, easy construction methodologies are applied. Those consist in dropping rocks and letting them find their own repose angle. The dynamically reshaping character is one of the main advantages of this type of breakwaters; however, it can become an important disadvantage too; particularly for the imposed boundary conditions of not intruding into the Waddenzee.

BREAKWATER WITH BERM

In practice, introduction of a berm into a sloped breakwater has shown a reduction of the overtopping and an increased stability in the armour layer. This type of breakwater performs in similar manner than rubble mound breakwaters, no motion of rocks is allowed. The main difference appears in the inclusion of a berm. Due to the berm some energy dissipation is expected in the armour layer, reducing the run up and overtopping.

ACCROPODE^{TM} II

The previously described characteristic cross section is designed also with AccropodeTM II. This type of cross section is defined as a rubble mound solution with a 1-layer interlocking concrete armour blocks. The approach is quite similar to Xbloc®; however, its design process is not explicit due to the lack of specialized guidelines. Although, following existing owner bibliography armour layers with Accropode^{TM} II can be designed. Two preliminary alternatives have been studied. Both of them have same armour layer slope (3:4). Therefore, the main introduced difference is the location of the outer armour layer face, one is starting at the actual location of the Afsluitdijk toe with its consequent increasing of available land and the other one is designed maintaining the same existing inner slope and the current land available.

CONCRETE CUBES

First the armour layer is estimated. Concrete and/or Antifer cubes should be displayed in two layers. To determine the required Concrete and/or Antifer Cube size Van der Meer formula is applied. A slope of 2:3 is used. From calculations an antifer cube of 1.50 m side is obtained. The weight of this concrete block is 8.8 ton leading to an amour layer thickness of 3.4 m. This alternative, based on the weight of the each armour unit, can be compared with one of the rubble mound alternatives, however, labour, production facilities (concrete plant, casting yard, et cetera), and consequently, costs are much more important than the rubble mound alternative. Therefore, from explanations previously given can be easily understood that this alternative would not be cost efficient. Hence no further calculations are done following this design. Nevertheless, some of the major breakwaters under construction in the world are designed with concrete cubes.

RIP-RAP OVERLAYER INVADING WADDENZEE

A design based on a layer of Rip-Rap over the existing dike has been studied as a possible solution. This type of cross-section is considered of interest since it requires minimal intervention (no demolition or excavations and fewer materials). For this design, it is considered that basalt columns will not be removed. Therefore, a filter layer is not necessary to keep the core material in place, as this condition is already guaranteed by existing armour layer. The upgrading consists on executing a Rip-Rap cover on the existing outer slope. Since crest elevation is increased around 1.2 m height, no large modifications need to be done at the top of the dike. Of course, the main problem of this alternative is the invasion of the Waddenzee; however, this incursion is around 10.0 m.

XBLOC® INVADING WADDENZEE

An Xbloc® cross-section is studied too. In this case, the possibility of occupying an extra surface of the Waddenzee is considered. This would avoid excavations in order to place the toe inside the limits of the existing cross-section. As the existing dike remains untouched, there is no need to place a filter protection below the underlayer to retain core material. The only modification with regard to preceding designs is the change of position of the armour layer (moving towards the Waddenzee) which does not have any influence in the calculations, as boundary conditions remain the same.

BERM BREAKWATER INVADING WADDENZEE

Following the criterion of introducing alternatives invading the Waddenzee, two more proposals for berm breakwater were analysed. The difference between both alternatives relies on different proposed slopes. An important difference is the reduced amount of materials and extra works needed for this alternative in comparison with the Berm Breakwater alternative without invading the Waddenzee.

RESULTS BASED ON MCA

The aim of this analysis is to make a first selection and rule out the most unfavourable options. According to the obtained results, the goal is to keep at least one concrete units design and one Rip-Rap design.

The alternatives that score better are, as it is shown in Table 3:

1. Xbloc® slope 3:4
2. Accropode™ II (up to the outer limit)
3. Xbloc® slope 2:3
4. Rip-Rap without berm, slope 1:2
5. Xbloc® slope 2:3, invading Waddenzee
6. Rip-Rap without berm, slope 2:3
7. Berm breakwater
8. Breakwater with berm
9. Accropode™ II (cutting slope)
10. Antifer cubes
11. Berm breakwater invading Waddenzee
12. Rip-Rap overlayer, slope 1:3.6

It is important to point out that the majority of the proposed alternatives are focused not only on the improvement of the armour layer, but also on strengthening the dike for long term scenarios. The main concept shared among the team members is to think of robust solutions, flexibility and adaptability for the upgraded Afsluitdijk.

Table 3. Multi-Criteria Analysis results

Criteria	**Rel. weight [%]**	**WEIGHED SCORES for each Alternative**											
		1	2	3	4	5	6	7	8	9	10	11	12
Protection from waves	13,66	55	55	55	55	55	55	55	55	55	55	55	55
Construction Process	3,57	6	11	7	7	10	9	7	7	5	11	11	13
Flexibility future upgrading	11,35	26	26	31	31	37	20	31	20	17	14	31	28
Resilience	5,81	12	12	9	12	19	12	10	9	17	12	16	16
Land availability	5,54	15	15	17	22	13	7	22	11	14	7	22	14
Incursion in Waddenzee	10,42	36	36	36	36	21	36	36	36	34	13	10	8
Pollution during construction	5,34	17	17	12	12	17	17	12	12	7	19	12	19
Landscape	2,02	6	6	5	6	6	7	5	5	5	6	6	5
PIANC WwN	9,07	25	25	27	27	20	27	30	27	25	23	23	23
Frequency maintenance & monitoring	8,52	28	28	30	30	19	26	30	30	32	21	30	19
Accessibility inspection armour layer	7,00	19	19	19	19	19	19	19	19	21	21	18	19
Accessibility maintenance tasks	9,59	29	26	31	31	31	26	31	26	24	19	31	26
Recreation	2,26	7	7	7	7	7	7	8	7	6	5	9	7
Social considerations	5,86	15	15	23	23	17	13	13	13	15	15	23	15
TOTAL	**100**	**295**	**298**	**310**	**319**	**291**	**281**	**310**	**278**	**276**	**239**	**296**	**267**

COST ANALYSIS

Most expensive alternatives are Xbloc® designs, both of them with almost same cost (~20,000 €/m). Their principal items are manufacturing and placement of the concrete units, which represents 40% of the direct cost. The amount of units per meter only differs in one extra unit in the alternative invading the Waddenzee. Excavation is almost the same in both cases. One main difference is the amount of stones, for the alternative invading the Waddenzee more material is needed to cover the bigger intervention area. The need for a geotextile in order to separate the underlayer from clay, which can fulfill filter functions, increase the cost for the alternative invading the Waddenzee, taking in consideration the removal of the basalt columns. This extra cost almost equates with the extra cost for stone material in the alternative not invading the Waddenzee, making both options equal regarding costs.

More economical designs result to be the ones using random placing rocks. These solutions are more economical compared with options that make uses of prefabricated concrete elements, due to the lowest material, production and placement cost. From these alternatives the most economical is the “Rip-Rap Overlayer”, owing the minimum amount of material to be used per meter length. Its cost is almost half of the cost of berm breakwater alternatives. This makes it the most economical alternative of all.

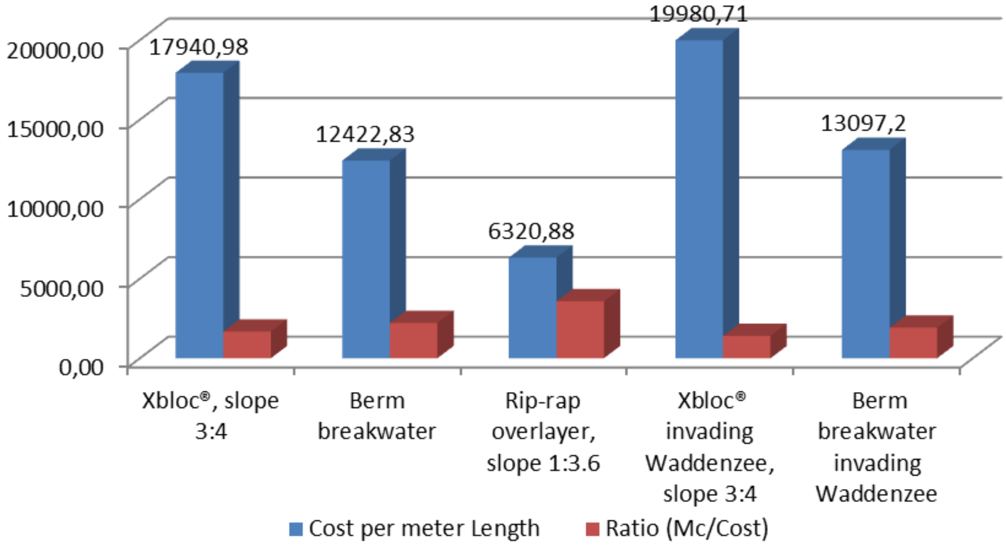

Figure 4 Cost estimation of alternatives per meter length of the dike (excluding geotextile and crown wall)

After the analysis carried out for the proposed alternatives for this Intermediate Design, two alternatives are selected as the best options, one based on concrete units and one based on a Rip-Rap solution. This decision is based on selecting the best alternative for each typology of armour layer solution. Hence, according to the Multi-Criteria Analysis and cost estimation, two final alternatives have been selected:

1. Xbloc®, slope 3:4
2. Rip-Rap overlayer, invading the Waddenzee

For these two alternatives together with one of the possible solutions provided by Rikswaterstaat (an OverTopping resistant pavement alternative), a more comprehensive study is carried on for the Final Design. Cross sections are defined more in detail and other aspects, such as the optimization of the design or the construction process, are covered. Cost estimations are also adapted and together with a Final Multi-Criteria Analysis, are used for the final decision-making process.

FINAL DESIGN

The same criteria and weighing factors are used as which have been done in the intermediate design. The results, taking the average between the Employer's scoring and the group's, are shown as follows.

Table 4. Cross Section alternatives studied within Final Multi-Criteria Analysis

Design 1	Xbloc® 3:4
Design 2	Rip-Rap overlayer
Design 3	OverTopping pavement

As it can be appreciated in Table 5, the Xbloc® design gets the highest score, followed by the Rip-Rap over layer and the OverTopping resistant pavement alternative. The Xbloc® gets highest in "Flexibility future upgrading" that means the equipment can be positioned on it, and it is needed only conventional equipment. Also more space is created in the Xbloc® design. In addition, the Xbloc® does not invade the Waddenzee, which leads to much higher grade in "Incursion in Waddenzee". The OverTopping resistant pavement alternative has the best accessibility for inspecting armour layer, due to its gentle slope so workers can easily walk on it.

Table 5. Final Multi-Criteria Analysis results

CRITERIA			**Relative weights** [%]	**WEIGHED SCORES**		
				1	2	3
TECHNICAL FACTORS	1	Protection from waves	13.85	55	55	24
	2	Construction Process	5.27	11	16	11
	3	Flexibility future upgrading	10.11	26	16	18
OPERATIONAL FACTORS	4	Resilience	6.59	12	15	7
	5	Land availability	6.15	25	9	8
ENVIRONMENT	6	Incursion in Waddenzee	9.45	30	13	24
	7	Pollution during construction	7.25	16	23	18
	8	Landscape	3.30	8	9	8
	9	PIANC Working with Nature	7.91	22	19	8
MAINTENANCE	10	Frequency maintenance & monitoring	8.57	29	22	21
	11	Accessibility inspection armour layer	6.81	18	19	26
	12	Accessibility for maintenance tasks	8.57	24	15	28
THIRD PARTIES	13	Recreation	1.76	5	4	3
	14	Social considerations	4.40	17	11	9
TOTAL			100	299	246	211

FINAL COST ANALYSIS

From the cost estimation analysis, it can be seen that the OverTopping resistant pavement alternative is the cheapest, even though it does score last on the Multi-Criteria Analysis, its MCA/€ ratio is the highest as it can be seen in Figure 5.

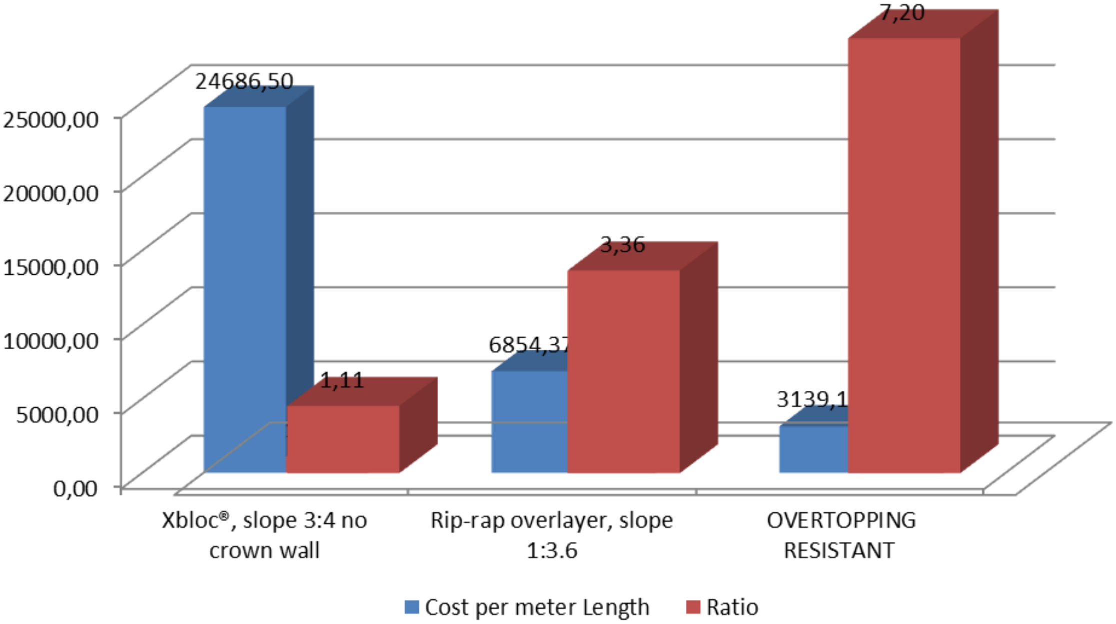

Figure 5 Cost per meter for three selected alternatives

CONCLUSIONS

Consequently, after an extensive analysis of the Final Design alternatives the following results are achieved:

- Best ratio solution: **Rip-Rap overlayer**.
- Among every proposed solution, Rip-Rap overlayer resulted the cheapest one.
- Safety level requirements are achieved.
- Rip-Rap overlayer solution is reducing run-up, consequently overtopping, compared to existing situation due to fact of increasing roughness on the armour layer.
- Minor invasion of the Waddenzee; however, measures, within the Rip-Rap overlayer design, are carried on to enhance the environment (i.e. tidal pools).
- No extra land on top of the dike is added for Rip-Rap overlayer design.
- Rip-Rap overlayer alternative has limited flexibility for future upgrading.
- Basalt columns are preserved on the proposed solution.
- Rip-Rap overlayer is a very simple design, hence special attention should be paid when constructing the toe over the Waddenzee bottom.
- Geotextiles at the interface between the toe and the Waddenzee bottom are required.
- Construction methodology is not a key decision-making factor.
- Small traffic disruptions during construction.
- Maintenance accessibility is reduced compared to current situation.
- Crown wall for Rip-Rap overlayer alternative is not required.

Although under a purely economic point of view the OverTopping resistant pavement alternative is the most convenient, when considering the future performance of the dike it is not that favourable. It does not reduce run-up and overtopping, nor does it increase the dike crest height. It only provides more resistance to the slopes of the dike (asphalt over exiting basalt columns and inner slope).

On the other hand, being Rip-Rap overlayer the proposed alternative (within this report) which, according to MCA; it faces more inconveniences for future upgrading; it is worth to think in a different way to improve this alternative. Nevertheless, Rip-Rap overlayer is still better regarding dike upgrading because it would make the upgrading of the dike easier and less expensive along the life cycle of the structure.

For current cross-section configuration and for the hydraulic boundary conditions of the year 2050, the OverTopping resistant pavement alternative has to cope with an overtopping of around 350l/m/s (Liu, Huang, Rayo, & Lim, 2012). Meanwhile, for the same situation, Rip-Rap overlayer proposed alternative reduces overtopping up to 10 l/m/s.

In addition, for the hydraulic boundary conditions of the year 2100, overtopping amounts will be around 700 l/m/s for OverTopping resistant pavement alternative and approximately 50 l/m/s for Rip-Rap overlayer.

Therefore, Rip-Rap overlayer solution would withstand hydraulic conditions of the year 2100 with minor interventions. These measures could be paving the inner slope, when required in the upcoming future. This would also allow to have a phased construction process, however to accomplish this, a monitoring program and planned adaptation are a must.

In contrary, the OverTopping resistant pavement alternative will not facilitate an upgrading because the slopes are covered in asphalt. Hence, a larger increase in crest height or implementing one of the proposed alternatives would be needed to reach the same level of protection.

To sum up this comparison between the OverTopping resistant pavement alternative and Rip-Rap overlayer alternative, the first one would be more expensive than second concerning life cycle costs, mainly due to the fact of the need to implement major overtopping preventive measures after 2050.

However, it is important to point out that current politics´ dominant way of thinking is directly influencing Rijkswaterstaat standards and procedures. Consequently, possible solutions should be the less expensive ones.

Therefore, as a major conclusion, this project ended up with the proposal to Rijkswaterstaat for keep pushing politicians to think over the whole life cycle of infrastructures. This could lead to introduce more flexibility and adaptability into the designs (robust designs including future planned adaptation). Finally, it can be said that is up to the Dutch politicians and the Ministry of Infrastructure and the Environment to decide whether providing advantages to future generations is worth a larger investment or not.

The full report summarized in this paper can be found on TU Delft Repository http://repository.tudelft.nl/ under the title *Afsluitdijk upgrading, non-typical Dutch solutions*

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MARCAS REGISTRADAS

El uso de marcas registradas en este trabajo no implica ningún respaldo o desaprobación de este producto por los autores o sus empleadores.

Las siguientes marcas registradas usadas en este informe son reconocidas:

Accropode	Sogreah Consultants, France
Core-Loc	US Army Corps of Engineers, USA
Xbloc	Delta Marine Consultants, Netherlands