A COMPARISON OF XBLOCPLUS AND ROCK ARMOUR ON SUSTAINABILITY, COSTS AND CLIMATE RESILIENCE

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ABSTRACT In this paper rock armour and XblocPlus are compared with regard to costs, carbon emissions and the expected maintenance need. A simplified method is presented to predict damage development during a structure lifetime using a Monte Carlo analysis. This MC analysis is based on a limited number of extreme wave conditions with return periods between 1 year and 1,000 years. Two case studies are presented for which the authors received a design with rock armour and prepared an alternative design with XblocPlus. The maintenance need of the case studies is predicted for two wave climates: 1) the wave climate for 2015 which is seen as current day wave climate and 2) the wave climate that is predicted for the year 2115. The rock armoured structures have a high probability to need maintenance during their 50 years lifetime and increasing wave heights due to climate change increase this probability. The XblocPlus structures have a low probability to need maintenance and a high resilience against increasing waves due to climate change. For the two case studies the XblocPlus structures perform better than the rock armoured structures with regard to cost and carbon emissions.

1. Introduction

Along the UK coastline many man-made coastal protection works can be found. Traditionally they are made of rock amour, sometimes made of local rock , but typically of rock from more distant quarries (e.g. Scotland or Norway). For upgrades of existing structures or for development of new schemes, designers often choose to work with rock armour instead of concrete armour. This choice may be based on 1) the carbon emissions of rock armour which are expected to be lower; 2) the costs of rock armour which is expected to be lower; 3) the natural appearance of rock armour and 4) the fact that rock is the traditional choice.

The paper compares rock armour and concrete armour (in this case XblocPlus, Figure 1) for coastal protection projects on 1) carbon emissions due to material sourcing and construction; 2) construction costs and 3) the expected maintenance need during the lifetime of a structure.

For this purpose two case studies from UK coastal protection schemes are used. For these projects the authors received a rock armour design from clients and prepared an XblocPlus design based on the same design wave conditions and overtopping limits. Due to confidentiality reasons, no project details are presented apart from schematized cross sections, wave climate and design conditions. The wave climate for both sites is based on numerical wave models which were prepared by the client. For both schemes the design conditions are depth limited waves. The future wave climate heights include sea level rise.

Based on the required material quantities for the rock and the XblocPlus design, the construction costs are calculated based on estimated unit prices. Furthermore the carbon emissions are calculated based on CO2 emissions per ton of material including material sourcing, transport and installation. These emissions are based on detailed carbon emission calculations performed by the authors for the Dutch Afsluitdijk project and which have been adjusted for the difference in transport distance from the rock quarries to the project sites.

Finally a Monte Carlo analysis of progressing damage during the structure lifetime is performed in order to compare the maintenance need of the XblocPlus and the rock armour design. The most important limitations of the presented studies are 1) the study focusses on armour stability and excludes toe stability, crest stability and wave overtopping under changing wave and water level conditions; 2) the Monte Carlo is performed for the 2015 data and for the 2115 data, but not for a gradually changing wave climate during the lifetime of the structures; 3) only 1 storm even per year is applied.

The objectives of the paper are 1) to offer designers a simplified method to compare coastal protection projects with regard to carbon, cost and maintenance need; and 2) to show the results of this simplified analysis for the two case studies.

As a natural appearance of coastal protection schemes is important to many designers, it is relevant to note that concrete armour units can be adjusted by texture and colour in order to make a coastal structure blend in better in the surroundings (Figure 1).

Figure 1 A: normal XblocPlus slope and B) adjusted XblocPlus slope to blend in surroundings

(courtesy Levvel)

(courtesy Te Ara Tupua Alliance)

2. Case Studies

2.1 Scheme 1: Seawall protecting an eroding cliff/dune coast

This scheme comprises of a shore protection for an eroding cliff/dune coast. The wave climate is characterised in Figure 2 where the current day wave climate is presented (2015) as well as the predicted wave climate for 2115.

Figure 2 Extreme wave heights at -2m CD; without climate change (2015) and with climate change (2115)

The 2015 wave climate forms the design basis for the shore protections that are compared in this study. The design conditions are a 100 year wave height of H_s=3m with a wave period of T_p=7s and a design high water level of CD+4m. The life time of the structure is 50 years.

The cross section with the XblocPlus is designed to have the same overtopping volume as the original rock structure (1.4 l/m/s based on EurOtop2018 formula). In order to obtain the same overtopping with XblocPlus, the crest level has been raised by 50cm (γ_F=0.45 compared to γ_F=0.40 for rock armour).

The rock armour is designed with the Van der Meer equation with S=2 and P=0.1. The XblocPlus size is designed with a stability number of $H_s/\Delta D_n$=2.5 and stability factors described in DMC Xbloc & XblocPlus Design Guidelines 2023. A factor of 1.5 has been applied on the block volume because of the impermeable core due to the geotextile underneath the under layer.

The XblocPlus cross section is designed with a 3V:4H slope as steep slopes have a positive effect on the stability of interlocking armour units. The rock structure as the authors received it from the client has a 1V:2H slope. There could be potential to apply rock on a steeper slope but as this would lead to increased rock armour size, this has not been investigated.

The two cross sections are shown in Figure 3. Table 1 shows the material quantities per linear metre of structure.

Figure 3 Cross section with rock (top) and XblocPlus (bottom) for Scheme 1

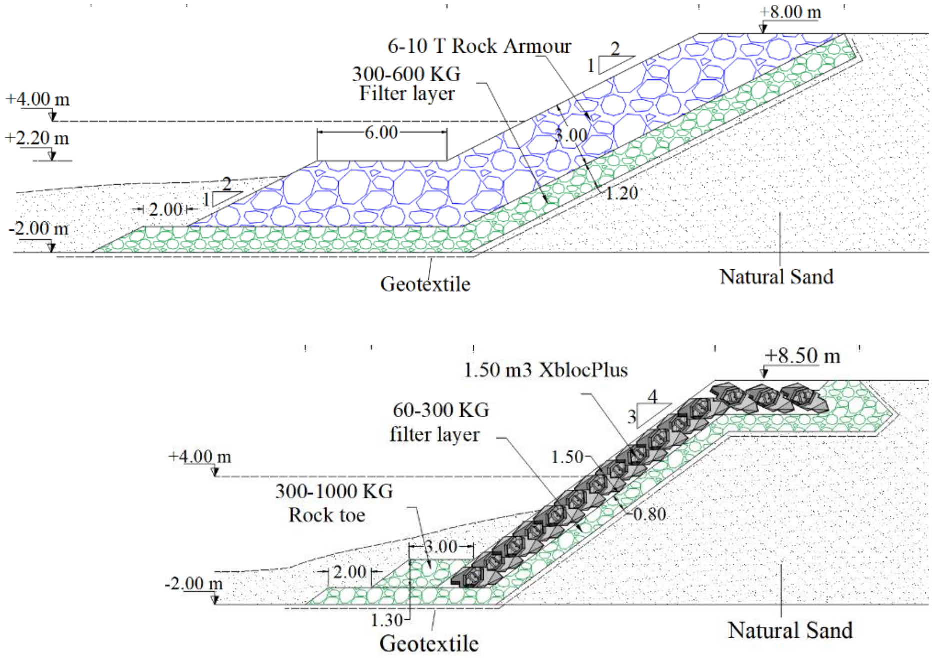


Table 1 Material Quantities (per metre) of the rock and XblocPlus design in Scheme 1

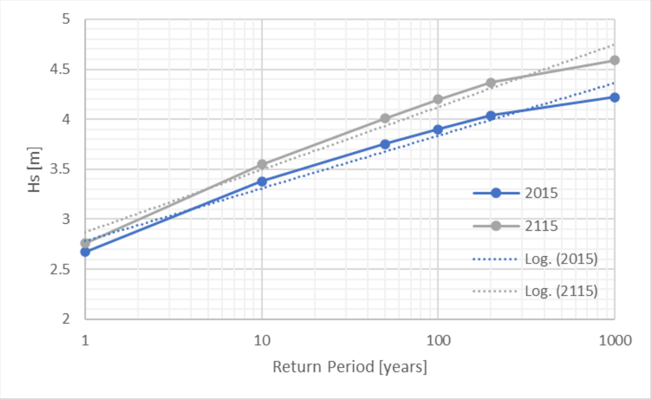
	Rock design	**XblocPlus design**
Geotextile	40.4m^2	33.5m^2
300-1000 kg rock	86.2t	5.2t
60-300 kg rock	-	52.4t
6 – 10 ton rock	154.0t	-
XblocPlus	-	10.8m^3 (25.9t)
Total tons of material per meter (excl geotextile)	240.2	83.5

2.2 Scheme 2: Offshore Breakwater

The 2nd scheme comprises of an offshore breakwater to create a material offloading facility. The wave climate received from the client is summarised in Figure 4. Similar to the approach in the 1st scheme, the 2015 wave climate forms the basis for the design.

The design is based on a 100 year wave height of H_s=3.9m, a wave period of T_p=10s and a design water level of CD+4m. The lifetime is 50 years. Consideration of stability and overtopping is similar to Scheme 1 which results in a 40cm higher crest level for the XblocPlus structure.

Figure 4 Extreme wave heights at -5m CD; without climate change (2015) and with climate change (2115)



The XblocPlus cross section is designed with a 3V:4H slope as steep slopes have a positive effect on the stability of interlocking armour units. The rock structure as the authors received it from the client has a 1V:3H slope. The XblocPlus structure is designed with a core made of 0.3-1t rock for constructability reasons. As a result the XblocPlus structure is expected to result in more wave transmission.

The 2 cross sections are shown in Figure 5 and Table 2 shows the material quantities.

Figure 5 Cross section with rock (top) and XblocPlus (bottom) for Scheme 2

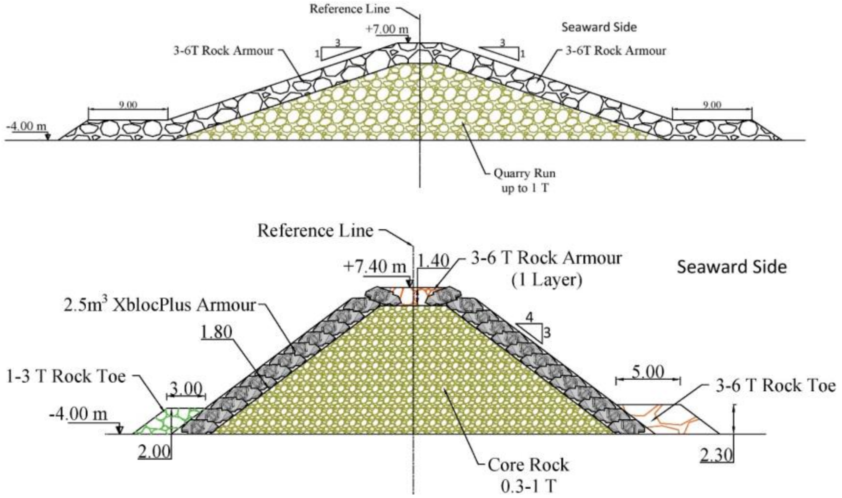


Table 2 Material Quantities (per metre) of the rock and XblocPlus design in Scheme 2

	Rock design	XblocPlus design
Quarry run	475t	247t
300-1000 kg rock	-	84t
1-3 ton rock	-	11t
3-6 ton rock	337t	28t
XblocPlus	-	26.3m^3 (63t)
Total tons of material per metre (excl. geotextile)	812	433

There could be potential to apply rock on a steeper slope. This option has not been designed in detail by the authors but the impact on the quantity of armour rock and its carbon footprint has been tentatively estimated as follows. The required armour size on a 1V:1.5H slope would be M_{50}=11.5t with a layer thickness of 3.2m compared to a thickness of 2.4m for the 3-6t armour on a 1V:3H slope. The quantity of heavy armour rock on a 1V:1.5H slope would be approximately 340t/m^1 compared to 337t/m^1 of 3-6t rock for the 1V:3H cross section (reduced slope length compensated by increased layer thickness). The steeper slope will reduce the quantity of core material, but the quantity of heavy armour rock from Norway which has the largest impact on cost - 10-15t rock is also more expensive than 3-6t rock - and CO2 emissions is not substantially reduced.

3. Comparison Maintenance Need

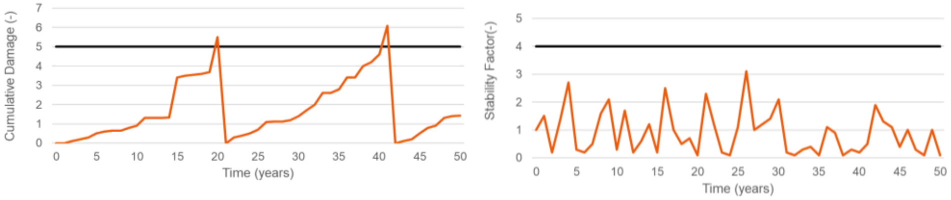
For both schemes, the rock structure and the XblocPlus structure are compared on resilience by a simplified Monte Carlo simulation of damage development during the 50 years lifetime. This simulation is performed for the present day wave climate as well as for the future wave climate as an indication of the vulnerability of the structures to future higher waves.

The simplified MC simulation works as follows:

1. Draw 1 extreme storm per year from the wave climate distribution
2. Determine damage progression for each storm (50 years total)
   a. Rock armour damage progresses with each storm. Repair is needed if threshold level is exceeded.
   b. XblocPlus damage starts if a threshold wave height is exceeded. Repair is needed if damage occurs.
3. Perform this MC simulation over 50 years a thousand times (1000 runs)
4. Simulation gives probability repair and the expected number of repair operations needed in 50 years

Figure 6 shows a single Monte Carlo run in detail. In case of rock structures, progressing damage has been determined for consecutive storms as described by Van der Meer (2011). Maintenance is applied when the accumulative S exceeds a threshold value. When maintenance is applied, full repair is accomplished, meaning that the following year, S is reset to S=0. For the XblocPlus structure $Hs/\Delta D_n$ is determined for each storm, where maintenance will be applied at a threshold value.

Figure 6. Visualisation of one run for rock (left) and XblocPlus design (right); repair threshold in black

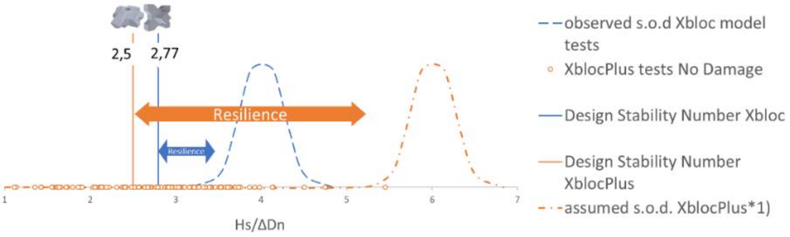


Thresholds for repair

For the rock structure a damage number of S=5 is chosen as threshold for maintenance. A sensitivity analysis showed that applying higher damage levels as threshold for damage leads to an increased risk of failure of the structure at S=8, especially for the future wave climate calculations.

During the development of XblocPlus, the design stability number of the unit was chosen as $H_s/\Delta D_n=2.5$. This value was chosen rather conservatively in order to make the system resilient against wave events that significantly exceed the design wave conditions (e.g. as a result of climate change). In Figure 7, test results of Xbloc and XblocPlus are schematised. For Xbloc model tests, start of damage was typically observed between $H_s/\Delta D_n$ = 3.5 and 4.5 and a design stability number is applied of $H_s/\Delta D_n$ = 2.77. For XblocPlus physical model tests, no damage was yet observed as no tests were performed where the wave paddle was able to create sufficiently large waves. The Gauss curve for XblocPlus shown in Figure 7 is therefore an hypothetical Gauss curve. Although it can be seen that damage for XblocPlus starts at higher stability numbers than for Xbloc, DMC has chosen a design stability number of $H_s/\Delta D_n$ = 2.5. This results in a high resilience against waves which exceed the design wave height.

Figure 7 Schematic overview Xbloc and XblocPlus Design Stability Number and physical model test results



For the XblocPlus structures, a threshold for repair has been chosen of $H_s/\Delta D_n=3.5$ for Scheme 1 and $H_s/\Delta D_n=4$ for Scheme 2. The threshold for Scheme 1 is lower in order to take into account the impermeable core due to the geotextile. In the design of Scheme 1, a factor of 1.5 has been applied on the block weight. This translates into a reduction of $H_s/\Delta D_n$ by a factor of $1.5^{1/3}$ which leads to $H_s/\Delta D_n=3.5$.

In Figure 8, the results of the MC runs for the two schemes are shown, both under the current and the future wave climate. These results have been translated into the probability of maintenance need in Figure 9. For the XblocPlus designs no repair is required for both schemes in current and future wave climate. For the rock design maintenance may be expected in the current day wave climate (99% chance of one repair for Scheme 1 and 28% chance of one repair for Scheme 2). For the rock design in the future wave climate, 1 or more repair operations are expected (77% chance of three repairs for Scheme 1 and 89% chance for one repair for Scheme 2). It can be concluded based on the MC analysis that the XblocPlus solution has resilience against the current wave climate and the predicted 2115 wave climate. The rock armoured structures have a high probability to need maintenance during their lifetime and increasing wave heights due to climate change increase this probability.

Figure 8 Results of Monte Carlo simulation for Scheme 1 and 2; rock and XblocPlus option and for 2015 wave climate and 2115 wave climate.

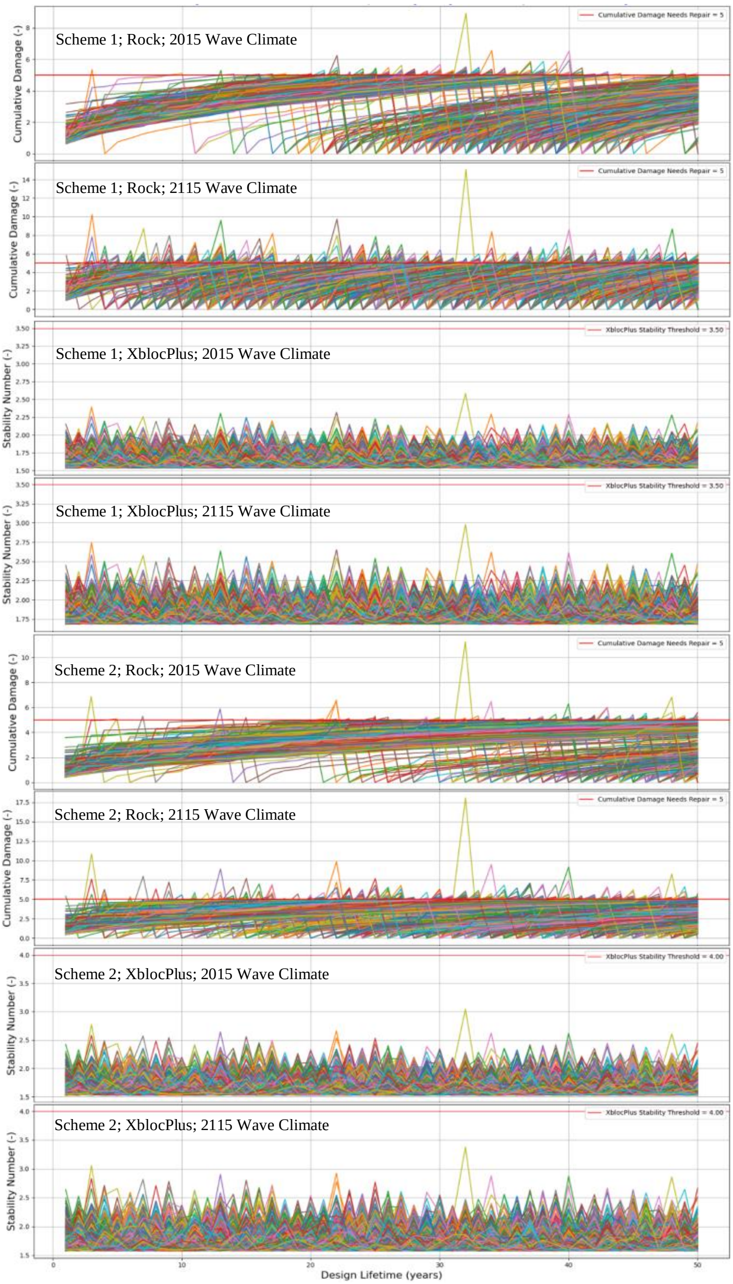
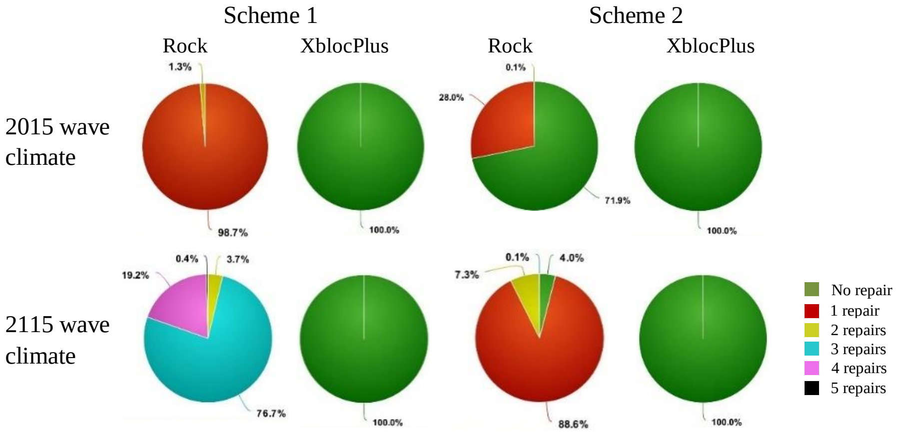


Figure 9 Probability of repairs for all scheme-design combinations considering the 2015 and 2115 wave climate.



4. Comparison on Sustainability

Table 3 shows the CO2 Emissions in kilograms per ton of material for production, transport & installation (EN 15804) of the materials applied in the schemes. These numbers are gained through a life cycle assessment (LCA). LCA is a standardised methodology, used to measure the impacts on the environment associated with the life cycle of a product, process, or service. The environmental impact was determined of the XblocPlus solution and different fractions of quarry stone from cradle to market/assembly.

This research meets the requirements of ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) which are the standards for conducting LCA’s. The LCA calculation was prepared using the SimaPro 9.3.0.3 software. The reference database used is the EcoInvent database 3.6 (2016). As part of a sensitivity analysis, calculations are done also with a 10% higher and lower CO2-eq for rock armour from Norway and for XblocPlus.

Table 3 CO2-eq emissions material production, transport and installations in kg

	CO2-eq [kg]	
Rock from UK quarry	Per ton	14
Rock armour Norway	Per ton	24
XblocPlus concrete	Per m^3	168

4.1 Production

Production is a combination of extraction of the material, transportation from the extraction site to the processing site and processing it into the product.

For rock gradings up to 1-3t, the study is based on rock material from quarries within the UK. For gradings of 3-6t and larger the study is based on basalt sourced from Norway.

In most cases the production site of the XblocPlus is near the construction site. This means that the individual materials like cement, gravel, sand, basalt and plasticiser is transported to the site by lorry. During the production phase, a steel mould is required and electricity is used to produce the XblocPlus. The concrete mix design is based on the Afsluitdijk project where GGBS (Ground Granulated Blast-furnace Slag) is applied in the concrete mix.

4.2 Transport to site

The rock armour is transported by a powered pontoon to the project site and the XblocPlus by a diesel fuelled excavator. For the large rock gradings from Norway, a transport distance of 1600km is applied. For the smaller gradings coming from UK quarries a distance of 600km by sea is applied.

4.3 Construction

The construction emissions have been based on the detailed calculations that have been performed for the Afsluitdijk Project in The Netherlands as the operations are comparable. Construction of the rock armour is done by crane pontoon and other small processing operations that consume diesel. The XblocPlus construction, like transportation, is carried out by an diesel fuelled excavator.

The most realistic datasets from EcoInvent (2016) were used to calculate the CO2 impact of both rock armour and the XblocPlus. When no dataset was available for the material or process in question, the best comparable dataset was used.

During the construction phase a loss of 3% in materials is considered.

4.4 CO2 Emissions Calculations

Table 4 and Table 5 provide the CO2-eq emissions per linear metre of seawall / breakwater for both the rock design and XblocPlus design for both schemes. In Scheme 1, XblocPlus leads to a reduction of 47%, in Scheme 2 the reduction is 32%.

Table 4 kg of CO2-eq per Linear Metre of Breakwater - Scheme 1

Rock design			XblocPlus design		
Material	Quantity [tons]	CO2-eq [kg]	Material	Quantity	CO2-eq [kg]
Armour	154	3,697	Concrete Armour	10.8m^3	1,809
Filter Rock	86	1,207	Toe Rock	5t	73
-	-	-	Filter Rock	52t	734
	Total	4,904	Total	Total	2,616

Table 5 kg of CO2-eq per Linear Metre of Breakwater - Scheme 2

Rock design			XblocPlus design		
Material	Quantity [tons]	CO2-eq [kg]	Material	Quantity	CO2-eq [kg]
Rock Armour	337	8,078	Concrete Armour	26.3m^3	4,421
Core Rock	475	6,655	Rock Armour	7t	175
-	-	-	Toe Rock	32t	756
			Filter Rock	84t	1,172
			Core Rock	247t	3,458
	Total	14,734		Total	9,982

Table 6 and Table 7 show the results of the sensitivity analysis for Scheme 1 and 2 respectively. Even if the current study overestimates the CO2-eq emissions of rock material by 10% and underestimates the emissions of concrete by 10%, the savings of XblocPlus are still 39% and 26% for Scheme 1 and 2 respectively.

Table 6 Sensitivity analysis Scheme 1 (carbon savings by concrete design, %)

		Concrete (-10%)	Concrete	Concrete (+10%)
	CO2-eq [kg]	2,451	2,616	2,976
Rock (-10%)	4,458	47%	43%	39%
Rock	4,904	50%	47%	43%
Rock (+10%)	5,394	53%	50%	47%

Table 7 Sensitivity analysis scheme 2 (carbon savings by concrete design, %)

		Concrete (-10%)	**Concrete**	**Concrete (+10%)**
	CO2-eq [kg]	9,580	9,982	10,424
Rock (-10%)	13,394	32%	29%	26%
Rock	14,734	35%	32%	29%
Rock (+10%)	16,207	37%	35%	32%

5. Comparison Construction Costs

To quantify the costs involved with the schemes, the material quantities shown in Table 8 and Table 2 are multiplied by unit rates which are summarised in Table 8. This results in the costs shown in Table 9 and Table 10.

Table 8 Unit prices for materials including installation

Geotextile	euro/m^2	13
Quarry run	euro/ton	60
60-300kg rock	euro/ton	60
300-1000kg rock	euro/ton	60
1-3ton rock	euro/ton	62
3-6ton & 6-10ton rock	euro/ton	63
XblocPlus	euro/m^3	250

Table 9 Cost estimation Scheme 1

Material	Rock design		XblocPlus design	
	Quantity	Price [€/m]	Quantity	Price [€/m]
Geotextile	40.4m^2	525	33.5m^2	436
60-300 kg rock	-	-	52.4t	3,146
300-1000 kg rock	86.2t	5,172	5.2t	312
6-10 ton rock	154.0t	9,705	-	-
XblocPlus	-	-	10.8m^3	2,691
	Total	15,401	Total	6,585

Table 10 Cost estimation Scheme 2

Material	Rock design		XblocPlus design	
	Quantity	Price [€/m]	Quantity	Price [€/m]
Quarry run	475t	28,523	247t	14,820
300-1000 kg rock	-	-	84t	5,022
1-3 ton rock	-	-	11t	670
3-6 ton rock	337t	21,206	28t	1,765
XblocPlus	-	-	26.3m^3	6,579
	Total	49,729	Total	28,855

Based on Table 9 and Table 10 it can be concluded that the concrete design leads to savings of 57% for Scheme 1 and 42% for Scheme 2. The unit rates applied are assumed market rates dating back to the year 2018.

The authors realise that prices have been fluctuating significantly since 2018 but expect that both concrete and armour rock have become more expensive. To check the sensitivity to price fluctuations, the costs have been compared for a concrete price which is 50% higher and rock prices which are 50% lower. With these prices XblocPlus is still more economic for both schemes (22% cheaper for Scheme 1 and 16% for Scheme 2).

6. Conclusions

This paper presents a simplified method to predict damage development to rock armoured and concrete armoured coastal structures during their lifetime on the basis of a Monte Carlo analysis with a limited number of extreme wave conditions with return periods between 1 year and 1,000 years.

Two case studies are presented for which the authors received a design with rock armour and prepared an alternative design with XblocPlus. The rock armoured and XblocPlus options are compared with regard to costs, carbon emissions and the expected maintenance need.

For the case studies presented it can be concluded that the XblocPlus design leads to lower costs (57% and 42%) and carbon emissions (47% and 32%).

The maintenance need of the case studies is predicted for two wave climates: 1) the current day wave climate and 2) the wave climate that is predicted for the year 2115.

The rock armoured structures have a substantial chance to require one repair operation (99% chance for Scheme 1 and 28% chance for Scheme 2) during their 50 years lifetime based on the current day wave climate. Based on the future wave climate one to multiple repair operations are expected (77% chance of 3 repair operations for Scheme 1 and 89% chance of one repair operation for Scheme 2).

Based on the MC analysis, the XblocPlus structures don’t need maintenance both under the current and the future wave climate.

7. Acknowledgements

The authors like to thank BAM Nuttall for the background information for the 2 case studies presented in this paper.

Furthermore the authors express their gratitude to the Te Ara Tupua Alliance from New Zealand for the joint development of the architectural XblocPlus units shown in Figure 1 which create a natural looking seawall in Wellington Harbour with the advantages of a concrete armoured structure.

8. References

DMC (2023) “Guidelines for Xbloc Concept Design”. Available at: https://www.xbloc.com/design

NEN (2012) NEN-EN 15804: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.

EurOtop (2018) “EurOtop Manual on wave overtopping of sea defences and related structures” Second Edition 2018.

ISO (International Standards Organisation) (2006a), ISO 14040:2006 Environmental management – life cycle assessment – principles and framework, ISO, Geneva

ISO (International Standards Organisation) (2006b), ISO 14044:2006 Environmental management – life cycle assessment – Requirements and guidelines, ISO, Geneva

Van der Meer (2011) Design aspects of breakwaters and sea defences. *Procedings of 5th International Short Conference on Applied Coastal Research*

Reedijk (2018) Hydraulic stability and overtopping performance of a new type of regular placed armour unit. Coastal Engineering Proceedings.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: http://link.springer.com/10.1007/s11367-016-1087-8 [Accessed 25 08 2022].