Proceedings of the 9th International Conference on Physical Modelling in Coastal Engineering (Coastlab24)

Delft, Netherlands, May 13-16, 2024

Conference Paper, DOI: 10.59490/coastlab.2024.689

Coastlab24
13-16 May 2024, Delft University of Technology, NL

TESTING THE HYDRAULIC RESPONSE OF A HIGH PERMEABLE CORE BREAKWATER

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ABSTRACT

Physical modelling tests were conducted in the wave flume of Artelia's hydraulic laboratory to study the hydraulic response/stability of a rubble mound breakwater made with a non-standard core composed of crushed concrete blocks (tetrapod). This design carried out by EDF, is aimed at having high permeability and fits in an eco-design approach, through the reuse of existing materials already on site. Eventually, the hydraulic efficiency of three different sections were tested and compared, all sections having the same armour layer and the same main dimensions but different {core; filter} systems : core only made with crushed tetrapod, core and underlayer made with crushed tetrapod (no filter layers with rocks) and baseline design (quarry run core and rock underlayer). Several responses were studied: armour layer stability, overtopping and transmission of the structure and head loss on both sides of the structure with an inflow/outflow system in the rear side basin set up in the wave flume. This case study illustrates 1) the importance of the physical modelling approach to testing unusual structures, as part of an eco-design approach, where the use of standard design formulas does not allow to verify the hydraulic behaviour of a high permeable breakwater and 2) also shows that unconventional design can lead to satisfactory hydraulic results.

KEYWORDS: Physical modelling, high permeable breakwater, eco-design, stability

1 INTRODUCTION

EDF requested an innovative solution in line with a sustainable development approach, involving the reuse of materials already on site. The innovative nature of the adopted design of the breakwater led to carry out tests on a physical model in a wave flume, to verify its hydraulic response and stability. The physical model was carried out to verify the hydraulic stability of a rubble mound breakwater, with a core composed of recycled materials.

Three sections were tested in the wave flume (see Figure 4):

- an initial section (**SECTION 1**), with a core made with recycled crushed tetrapod blocks, a rock underlayer, and an armour layer made of concrete tetrapod blocks.
- an optimized section (**SECTION 2**), in which the underlayer rockfill was replaced by crushed tetrapod blocks.
- an third section with a conventional core, made with quarry run (**SECTION 3**), modeled at permeability scale according to state-of-the-art rules, and an underlayer rockfill, to compare the hydraulic responses of an eco-designed model with a standard rubble mound breakwater design.

The wave flume was equipped with an inflow/outflow system in the rear side basin to measure the head losses due to lowering/increase of the water level. This design results in a more permeable model than usual, which is also intended to limit head losses on either side of the structure. As part of the eco-design approach, which involves the reuse of existing materials, a carbon impact analysis was carried out to assess the benefits of this solution in comparison with a conventional approach.

2 PHYSICAL MODELLING

2.1 Description of the models in the wave flume

The model tests were performed in one of the wave flumes of the Hydraulic Laboratory of ARTELIA near Grenoble (France). The flume is 1.2m wide, 41.5m long, 1.5m depth and is equipped with a flap-type wave paddle oscillating around a buried transverse horizontal axis driven by a hydraulic jack. Waves up to 0.26m and peak periods ranging between 0.7 and 3.5s can be generated, for a maximum water depth at the generator of 1.4m. The flume is also equipped with the Active Wave Absorption (AWA) system, allowing for the real-time absorption of the waves reflected by the tested structure back to the paddle (Figure 1).

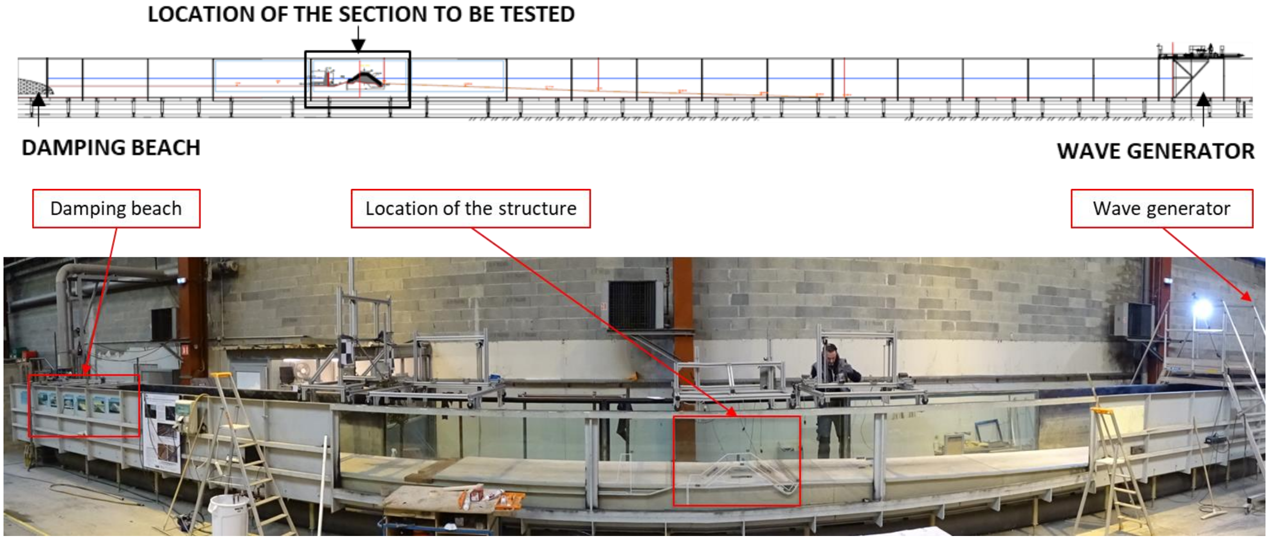

Figure 1. Layout of the model in the wave flume

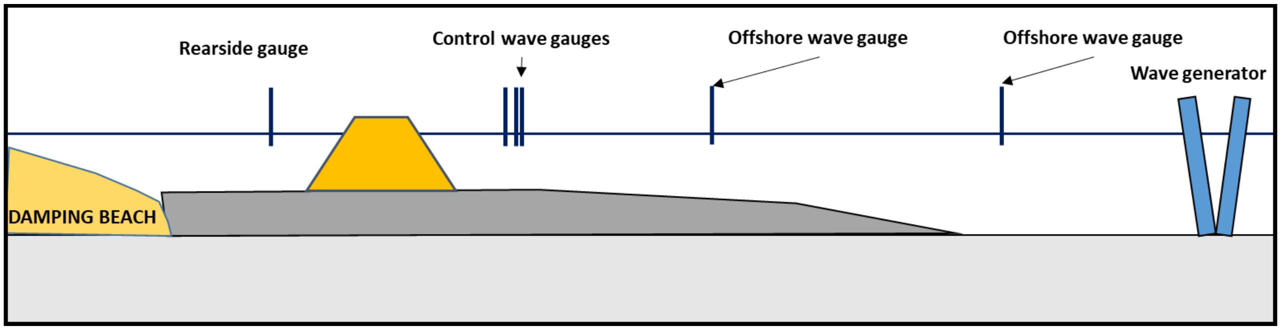

Figure 2. Location of the capacitive gauges in the wave flume

The scale considered is 1:51, based on Froude scaling. A simplified seabed profile was built with a non-erodible plywood surface. Waves in the flume were measured using a total of six (6) capacitive gauges (see Figure 2): one (1) gauge in front of the wave generator, controlling the wave generated at the wave generator before any refraction on the seabed, at depths of around -30 m; one (1) complementary offshore gauge positioned at depths of around -15 m; a set of three (3) control gauges positioned at 0.4 wavelength from the future structure. This set of gauge was used to compare measurements from the calibration phase (without structure) and from the tests with structure. In addition, one (1) gauge was positioned on the rearside of the structure.

The initial design of the structure (**SECTION 1**), in the prototype scale, consisted of the following:

- an 11 m^3 tetrapod double armour layer,
- an 1 - 3 t rockfill underlayer,
- a breakwater core of recycled crushed 4 m^3 tetrapod blocks.

The toe of the structure on the seaward side is a buried "V-shaped" toe, in order to reduce the footprint of the structure as much as possible. The rear side end was equipped with an inflow/outflow system (see Figure 3).

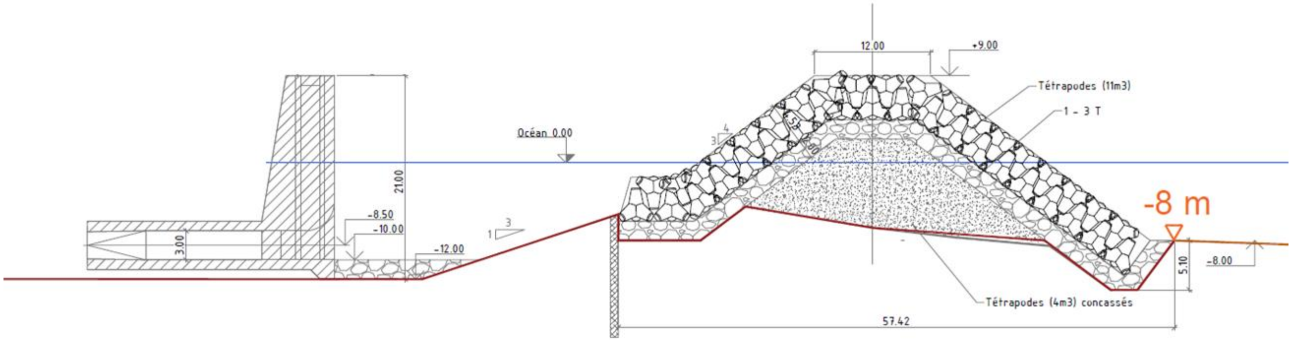

Figure 3. Rubble mound breakwater section + inflow/outflow system in the wave flume – SECTION 1

Figure 4. Sections tested in the wave flume. From left to right, SECTION 1, SECTION 2, SECTION 3.

2.2 Crushed tetrapod - Core modeling

The core of the breakwater, made of recycled crushed tetrapod blocks, was modeled according to the Froude scaling (scaled on the basis of the geometric reduction factor) with a correction to account for the difference in seawater/freshwater densities. The characteristics of the tetrapod blocks used in the model are shown in the following table:

Table 1. Characteristics of the tetrapod blocks used for the core

Size (mm)	Unit volume (cm3)	Unit Weight (g)	Specific gravity (t/m3)	Prototype volume (m3)
48.5	31.9	81.4	2.44	4.23
49	33.3	78.1	2.37	4.42

In the laboratory, the tetrapod blocks were crushed using a hammer. The blocometry obtained consisted of four (4) distinct pieces: “one leg only”, “two attached legs”, a “leg-center” and “center only”. The characteristics of this blocometry is illustrated in

Figure 5. The "one leg only" pieces represented 70% of the core volume.

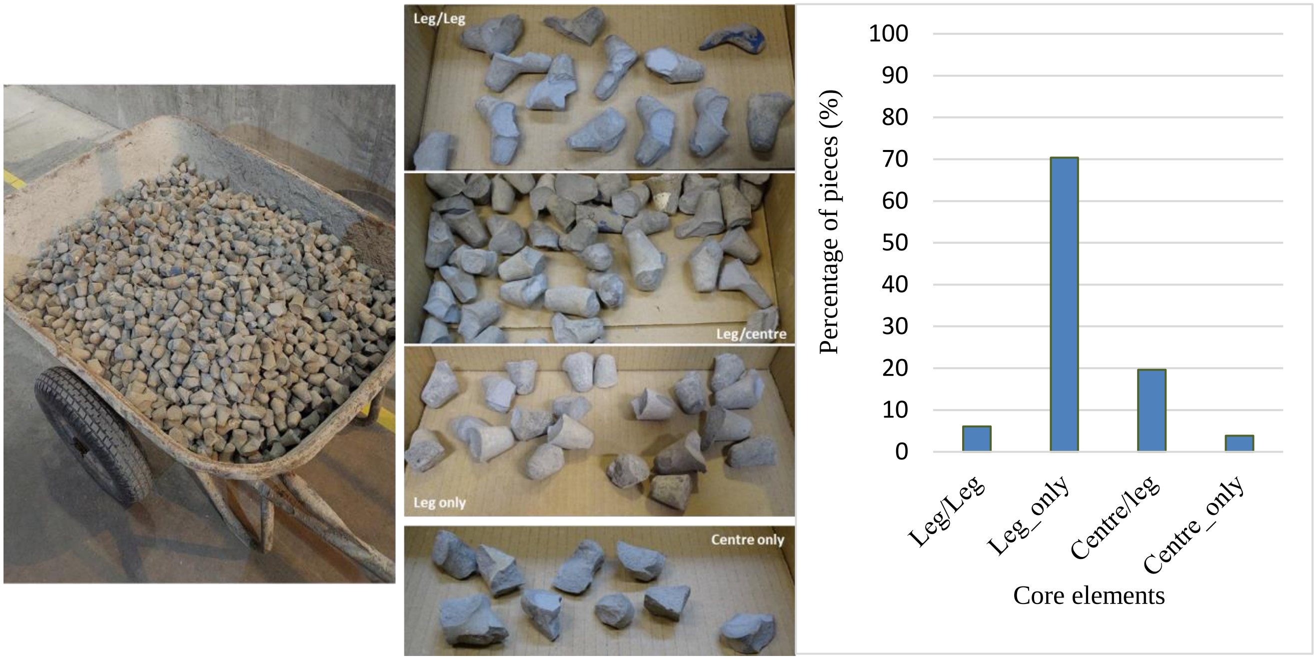

Figure 5. Percentage of the different piece of the core

3 TESTING PROCEDURE

3.1 Wave propagation

For each model, seven (7) stability/hydraulic tests were carried out with the structure subjected to frontal wave action. According to the recommendations of the *Hydralab manual*, the duration of the tests must exceed a minimum number of waves, generally 500 to 3000 waves, satisfied by storms lasting 3 to 6 hours (prototype). For all the tests in the project, the simulation time was 3 hours, except for the overload condition, which lasted 2x3 hours.The tests were conducted considering three values of still water level: -0.2, +1.5 and +1.7 m, corresponding respectively to lower water level, an extreme high level without atmospheric surge and an extreme high level with atmospheric surge.The spectral wave height at the wave generator (- 30 m) ranged 3m to 13.4m. The wave project was 11.2m. Wave periods generated range from 10 to 15.3s.

3.2 Assessment of the stability

Damages were evaluated in terms of the N_{od} damage parameter for the tetrapod armour and the toe. The settlement of the core was analyzed by measuring the evolution of three (3) profiles of the section after each test, with a measuring rod surveying method.

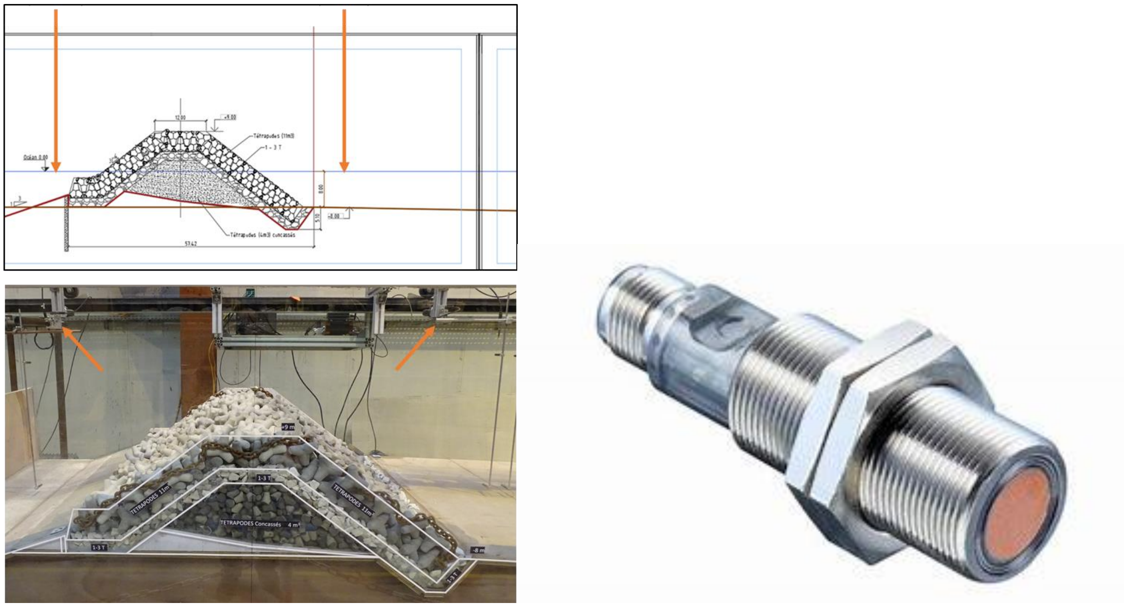

Figure 6. Instrumentation in the wave flume – Head losses measurement

3.3 Assessment of wave transmission and reflection

The transmission of the structure was assessed by measuring wave heights using capacitive gauges located on either side of the structure. The transmission of the structure also includes the overtopping wave. Wave transmission was quantified by the wave transmission coefficient, $K_t=H_t/H_i$, where Ht and Hi are respectively the transmitted and incident wave heights. In the 2D model, incident and reflected wave separation was carried out using the 3 points method of Mansard et al (1980).

3.4 Assessment of head losses

Permeability tests were carried out without wave propagation, but with a gradual increase of the inflow/outflow system capacity. Head losses were evaluated for an initial static level, without waves, by gradually varying the flow rate of the inflow/outflow system. Two ultrasonic sensors were positioned on either side of the structure to measure head losses (measurement accuracy of the order of a millimeter).

4 RESULTS OF THE TESTS

4.1 Hydraulic stability

At the end of each test, the displaced blocks were not replaced, to provide a better representation of the succession of storms in reality. For the three (3) sections tested, the armour layer and the toe ensured a very good stability. For the overload condition, the stability of the sections tested was also satisfactory:

- For the initial section (**SECTION 1**), no blocks were displaced by more than a Dn50 at the end of the test corresponding to the design wave (50-year return period). For the overload test (stability reserve), the seaside and rearside of the armour layer were still strongly stable.
- For the modified section (**SECTION 2**), two blocks were moved/extracted (1 block moved at the end of the 10-year return period and 1 block extracted at the end of the 50-year return period) at the seaward end of the armour slope.
- For the baseline design (**SECTION 3)**, no block is displaced by more than a Dn50 at the end of the test series.

During the tests for the three (3) sections, the blocks of the armour layer showed good interlocking.

For **SECTIONS 3**, no significant settlement of the crest was observed during the test series. Profile variations are of the order of the movements of the block within the armour layer.

For **SECTION 1**, initial settlements of the crest and the upper part of the armour were observed as early as the first test.

For **SECTION 2**, initial settlement of the crest was observed as early as the first test. Then, after each test, further settlement of the armour layer slope (part of the armour stressed by wave) was observed, leading ultimately to vertical settlement of the slope up to 1.35 m, and a horizontal settlement of up to 1.5 m. This progression of settlement, which was not observed in the initial section (**SECTION 1**), confirmed that the settlement of the entire structure is related to the settlement of the core; the presence of a rockfill underlayer in the initial section reduced the stresses on the core and hence its settlement.

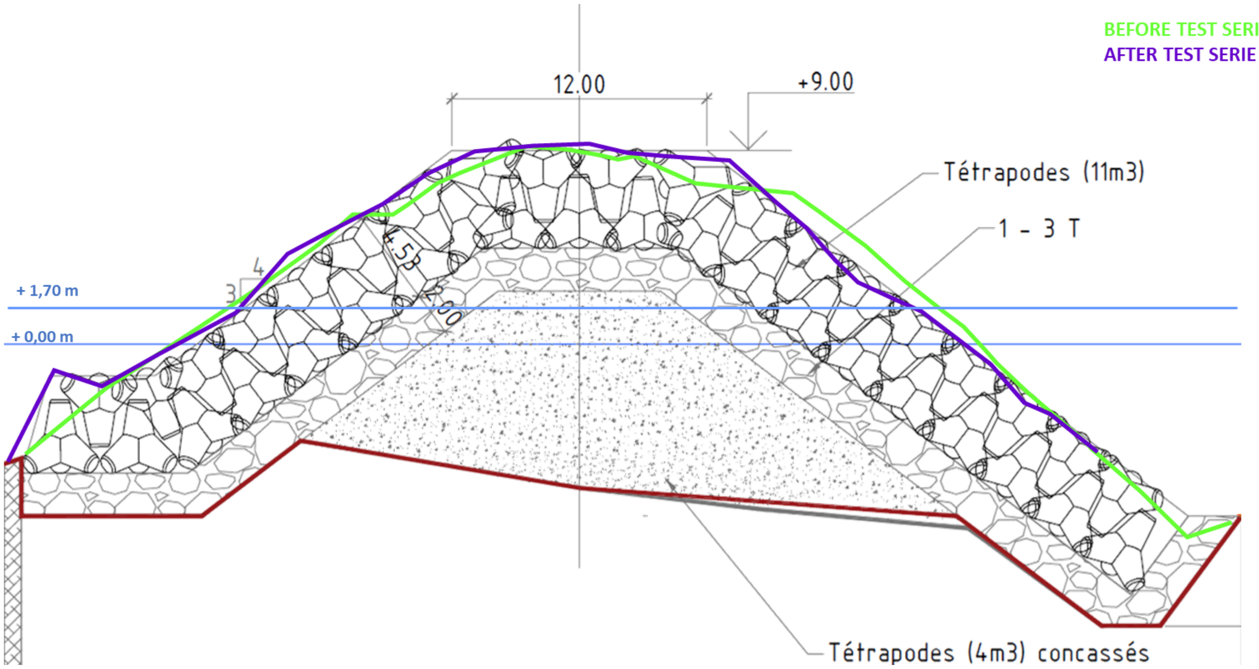

Figure 7. Profile evolution – SECTION 1

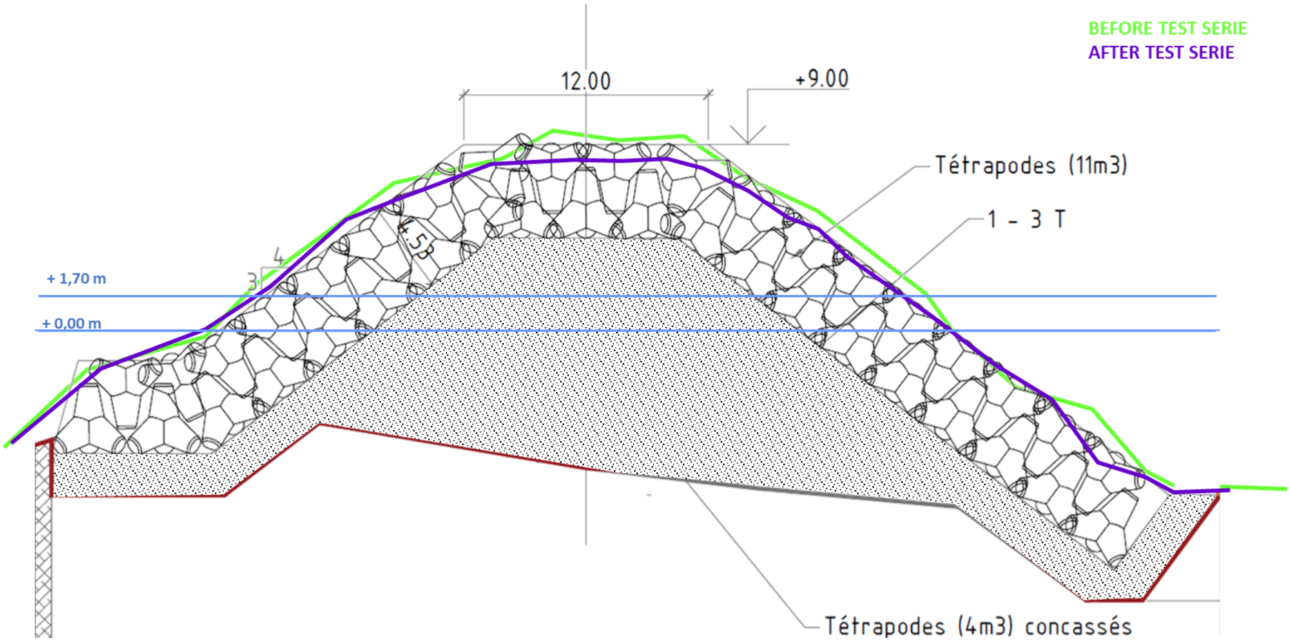

Figure 8. Profile evolution – SECTION 2

4.2 Head losses

With the outflow system in place, a static level of - 0.2 m (lowest water level) and + 1.5 m (highest level) were tested. With the inflow system in place, a static level of + 1.5 m (high level) and + 1.7 m (extreme high level) were tested. The results showed that head losses are influenced by the initial static water level conditions. At low water levels, the wetted area is smaller, so for the same flow rate, flow velocities within the structure are higher, which also increases head losses. High head losses difference were observed for the lowest water level with the outflow system between the baseline design (**SECTION 3**) and the section with crushed tetrapod core (**SECTION 1**) (for example with an outflow of 40 m3/s, the head loss is 3m for the **SECTION 3** and 1 m for the **SECTION 1**), highlighting the porous nature of the breakwater. With the inflow system in place, saturated head losses were also observed, due to the porous nature of the armour layer; high levels are tested (these levels are close to the lower part of the armour layer, so there are few differences in head losses, flow through the breakwater section takes place mainly in the armour layer even if, generally speaking, head losses are greater for the **SECTION 3**.

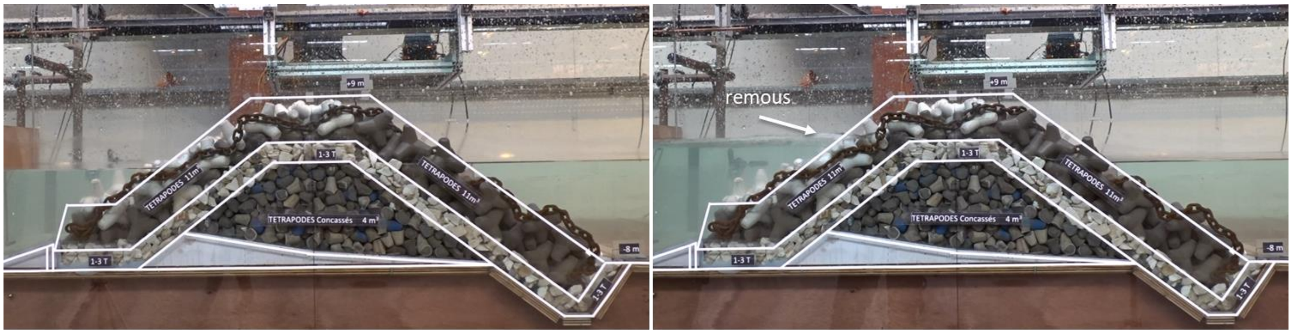

Figure 9. Variation of the water level on either side of the structure – Before the inflow system running (left) and during the maximum inflow discharge tested (right)

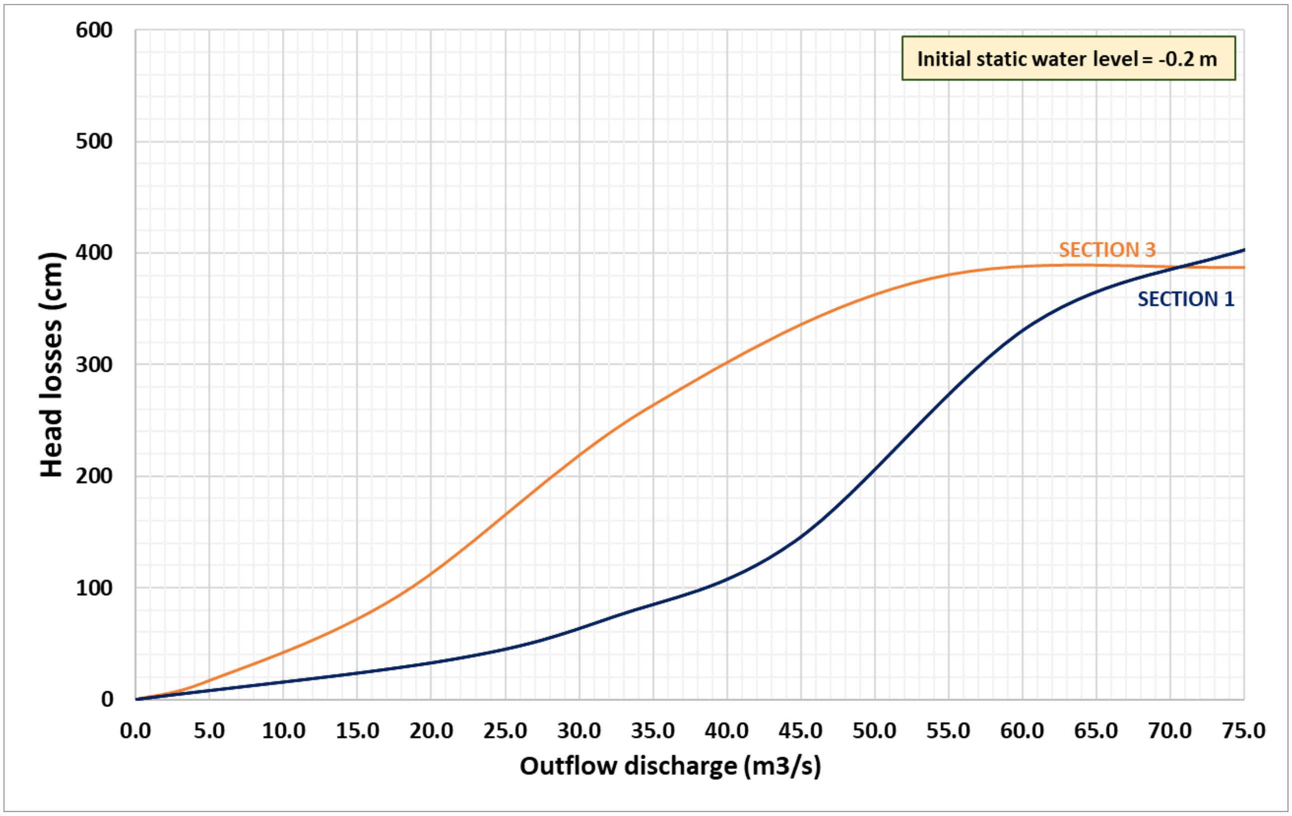

Figure 10. Evolution of head losses with a gradual outflow (prototype units) - Comparison of head losses measured for the initial section (SECTION 1) and a standard design (SECTION 3)

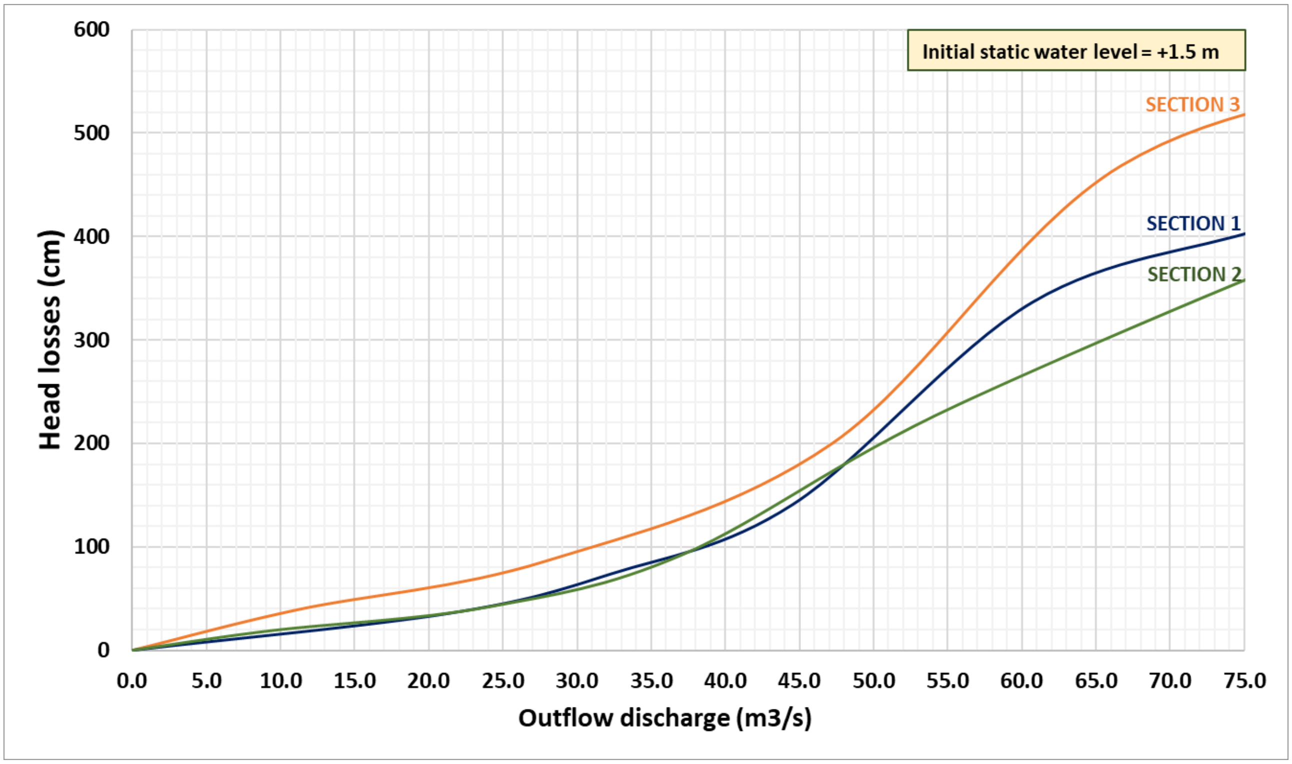

Figure 11. Evolution of head losses with a gradual outflow (prototype units) - Comparison of head losses measured for the initial section (SECTION 1) and a standard design (SECTION 3)

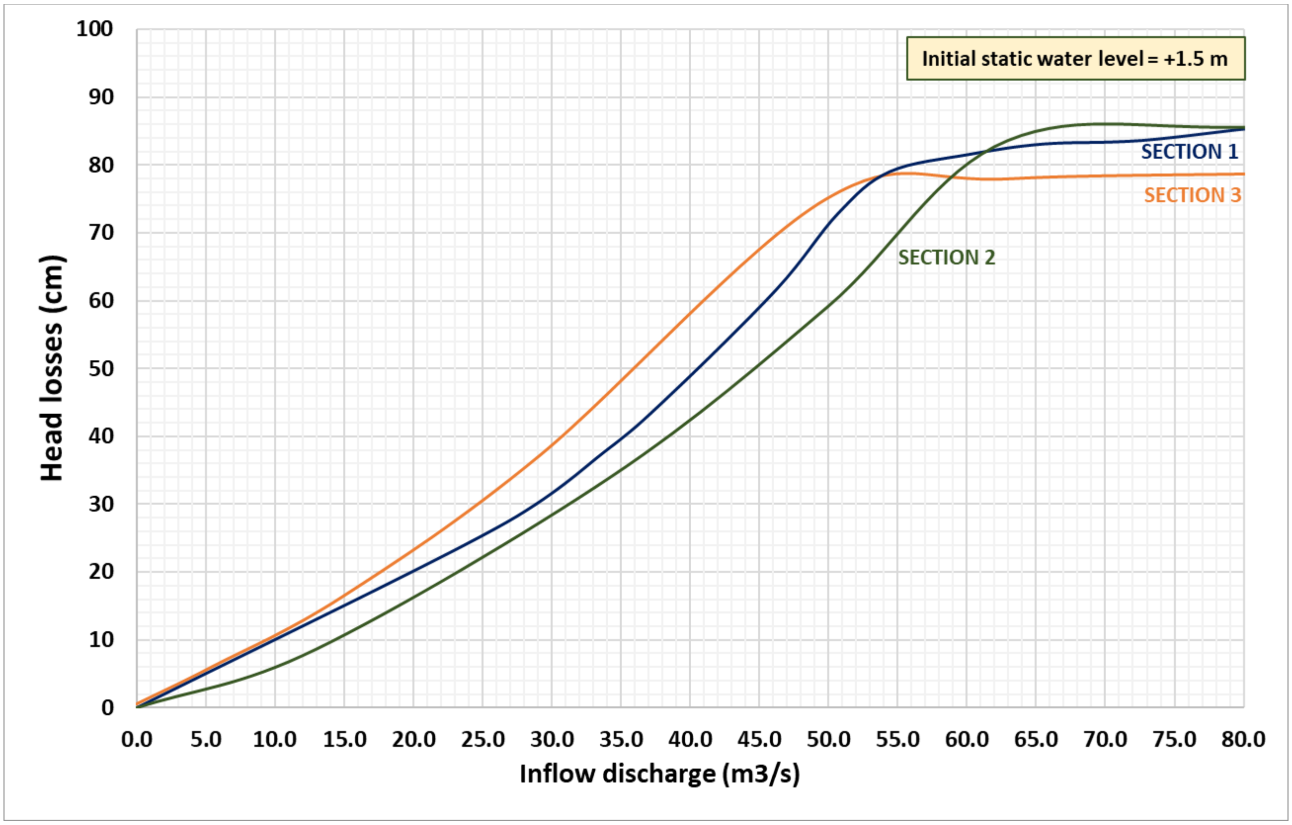

Figure 12. Evolution of head losses with a gradual inflow (prototype units) - Comparison of head losses measured for the initial section (SECTION 1) and a standard design (SECTION 3)

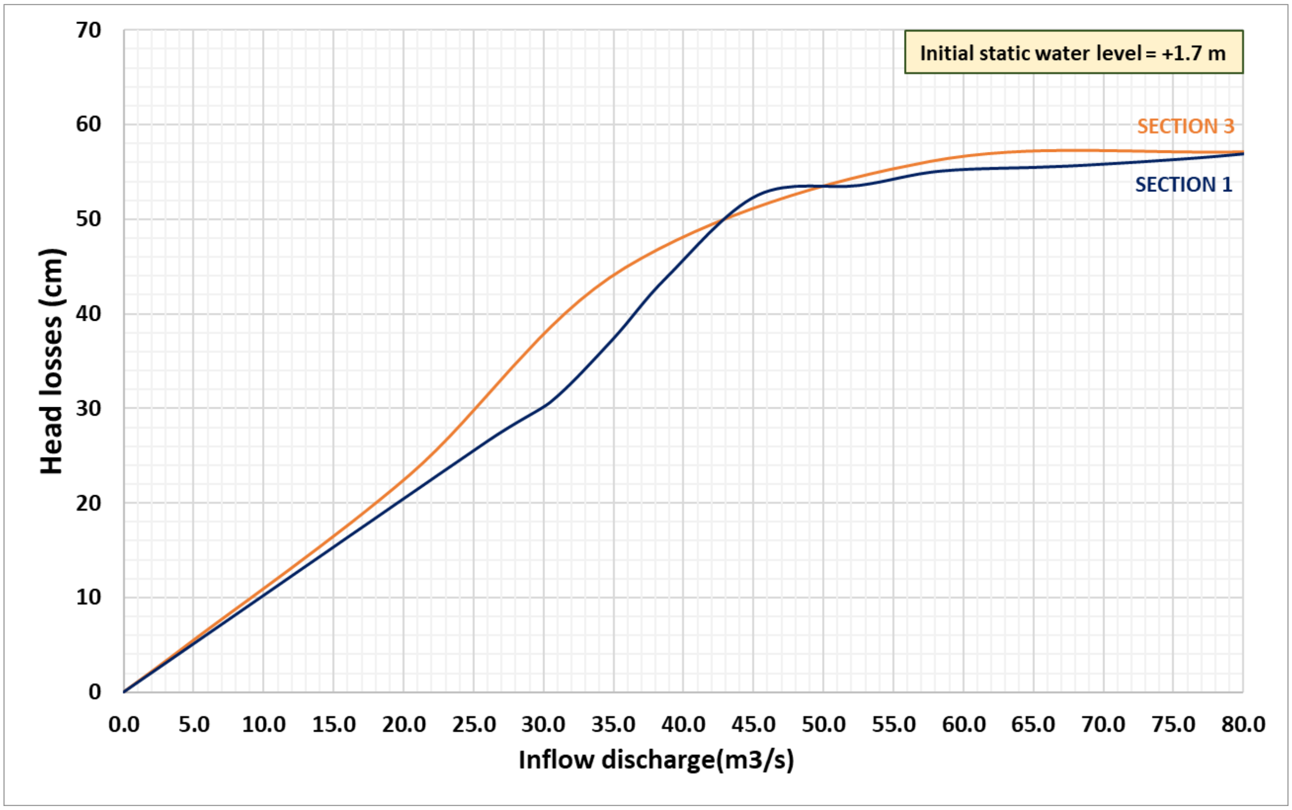

Figure 13. Evolution of head losses with a gradual inflow (prototype units) - Comparison of head losses measured for the initial section (SECTION 1) and a standard design (SECTION 3)

4.3 Wave transmission and reflection

For the three sections tested the 2D reflection coefficients were estimated to be Cr = 0.39 – 0.56 for $H_{mo\ total}$ = 3.3 – 8.24 m at toe of the structure. The coefficients measured on three sections remained homogeneous and did not lead to consider **SECTION 1** and **2** as less reflective structures.

Table 2. Reflection coefficient (Cr) assessment for different return period waves

		SECTION 1	SECTION 2	SECTION 3
Return period	Water level (m)	Reflection coefficient Cr (%)		
5	1.5	39%	39%	39%
10	1.5	53%	52%	51%
25	1.7	55%	54%	54%
50	-0.2	56%	55%	56%
50	1.7	56%	56%	56%

Analysis of the transmission of the structure in the three configurations tested showed **SECTION 1** and **2** were slightly more transmissible than **SECTION 3** (Table 3).

Table 3. Transmission coefficient (Kt) assessment for different return period waves

		SECTION 1	SECTION 2	SECTION 3
Return period	Water level (m)	Transmission coefficient Kt (%)		
5	1.5	12%	15%	10%
10	1.5	19%	21%	18%

25	1.7	24%	26%	27%
50	-0.2	15%	18%	18%
50	1.7	29%	30%	17%

Hydraulic tests carried out on a physical model showed satisfactory hydraulic results for an unconventional design in terms of stability and the reduction of head losses (for low water levels). Slightly difference were observed in terms of the reflection and transmission of the structure in comparison to a standard design. Further these positive conclusion on the hydraulic stability of the innovative solution, the objective was to move forward and to qualify the different solutions in regard of the carbon footprint.

5 CARBON IMPACT OF THE ECO-DESIGN APPROACH

This innovative solution consists of an eco-design approach with the reuse of existing materials. This approach has the advantage of extending the lifespan of products, reducing the production and consumption of materials and reducing the generation of waste materials. As well as having a positive impact on reducing the depletion of local resources, this solution also has a positive impact on the carbon footprint: a carbon impact assessment was carried out, limited to the eco-designed part of the structure only (core). The assessment aim to compare the embodied carbon of two solutions: the baseline solution with the core made with the quarry run (**SECTION 3**) and the eco-designed solution with the core made with recycled crushed tetrapod blocks (**SECTION 2**). As the sections are similar, most materials and construction activities are considered identical. For this reason, and to emphasize the net gain of the eco-designed solution, only materials, transport and core construction were taken into account.

Data on quantities of materials, transport of materials and construction were associated with carbon emission factors using an in-house carbon calculation tool named “Carbon Eval” (developed by Artelia). For the baseline solution, the emissions associated with the materials are calculated by multiplying the rate of Embodied Carbon (EC) per material quantity (e.g. $kgCO_2e$/tonne) and the estimated total quantity of quarry run in the project. Similarly, the emissions associated with the transport of materials are calculated by multiplying an EC rate per amount of material by the distance travelled. A distance of 100km is considered between the quarry and the site. Additionally, we considered the hypothesis that all tetrapod blocks are taken to an inert waste center. Finally, the emissions related to construction equipment are defined as $kgCO_2e$ per energy use ($kgCO_2e$/kWh). The implementation time for the core considered in the project schedule has been taken into account.

For the eco-designed solution, we consider the hypothesis that all recovered blocks are in good condition for reuse. The emissions associated with the supply and transport of materials are zero. The emissions related to construction equipment are the same as in the baseline solution. In addition, the fuel consumption of the hydraulic rock breaker used to crush the blocks was also taken into account in the construction stage of the eco-designed solution.Error! Reference source not found.Results show that the emissions associated with the baseline solution are more than double those of the eco-designed solution. For the baseline solution, 32% of the emissions come from materials, 53% from materials and waste transport and 15% from construction. On the other hand, the emissions of the eco-designed solutions are associated only with the construction stage. These results confirm the benefits of using an eco-designed approach based on the circular economy.

6 CONCLUSION

This case study focused on the use of a physical model to verify the hydraulic stability of a structure based on innovative design. Hydraulic tests carried out on a 2D physical model showed satisfactory hydraulic results in terms of stability and the reduction of head losses (for low water levels). Slightly difference were observed in terms of the reflection and transmission of the structure in comparison to a baseline design. In this case, the physical model gives us an indication of the hydraulic solicitations of the structure but does not allow us to know the tiredness and resistance of the materials (integrity of the concrete of the recycled tetrapod) on a long-term time scale. From an eco-design and carbon impact reduction point of view, in addition to having a positive impact on reducing the depletion of local resources, the core design with the reuse of existing materials has less than half the embodied carbon of the baseline solution. This case study illustrates the importance of the physical modelling to test of hydraulic responses of unconventional designs, which leads to satisfactory results. This case study also highlights innovative solutions to reduce carbon footprint.

ACKNOWLEDGEMENT

Artelia would like to thank EDF for accepting the publication of this article. The authors would also like to thank the Artelia’s laboratory team for their involvement throughout the study.

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