

# The Extension of the Pointe Noire Breakwater – Congo

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## Summary

The design of the extension of the Pointe Noire breakwater and the optimisation of the crest design by physical model testing are described in this paper. A hybrid construction with interlocking concrete armour units on the slopes in combination with rock armour on the crest was applied for this structure. The model tests demonstrated the advantages of this approach for low crested breakwaters. Following the design of the Pointe-Noire breakwater additional systematic research was conducted based on the stability of Xbloc armour on low crested breakwaters. Based on this research an increase in Xbloc armour unit weight of 50% for structures with relative freeboard of  $R_c/H_s < +1.0$  and of 100% for relative freeboard  $R_c/H_s < +0.5$  is recommended. The results of project specific 3D model tests have been applied successfully to improve the construction methodology of the Pointe Noire breakwater in order to cope with the local conditions including rapid sedimentation of the structure and to manage weather downtime during construction due to the swell conditions.



Figure 1: Site location and completed breakwater extension Pointe-Noire – Congo.

## Introduction

Le Port Autonome de Pointe-Noire is the largest sea port in Congo (Figure 1) and has been operational since the 1930's. The port infrastructure has been developed across various projects over the years and currently several projects are under construction to further upgrade the port facilities. In 2009, a tender was awarded to Royal Boskalis Westminster nv for the extension of the existing breakwater by 300m in order to reduce sediment transport into the port basin.

The original design for the extension consisted of a low crested breakwater with a rock armour layer up to 24 – 30 tonnes. For constructability and economic reasons, an alternative design was developed using Xbloc armour units of  $3\text{m}^3$  and  $4\text{m}^3$  (respectively 7.2 and 9.6 tonnes). The design was fine-tuned during 2D model tests conducted by Delta Marine Consultants (Utrecht, The Netherlands), and using 3D model tests conducted by HR Wallingford (Oxfordshire, UK).

The verification and fine tuning of the design focussed on the cross sectional dimensions and armour stability of the breakwater. The length and orientation of the breakwater did not form part of the assessment. The breakwater extension was constructed in 2011-2012.

This paper describes the design of the breakwater extension and the optimisation of the crest design through the use of physical model testing. The construction of the breakwater, the production, and placement of the Xbloc armour units are also addressed together with the lessons learned during construction

## Design Aspects

### 2D Model Test Results

2D hydraulic model tests were conducted in April 2010 in the laboratory of DMC. The design wave height for the new structure was set at  $H_s=5.25\text{m}$  with a corresponding period of  $T_p=13\text{s}$  and a design water level of  $+2.5\text{m}$  CD. With a crest height of  $+5.0\text{m}$  CD the structure has a low relative freeboard of approximately  $R_f/H_s = 0.5$ . The alternative design consisted of an armour layer of interlocking concrete armour units; Xbloc armour units of size  $3\text{m}^3$  covered the seaward slope, the crest and the rear side of the structure (Figure 2a). The use of  $3\text{m}^3$  Xbloc armour units was based on the design guidelines for Xbloc at that time. No correction factor was taken into account for the low crested design characteristic of the structure. The application of a correction factor for Xbloc armour on low crested structures was later introduced based on the research conducted by Van der Linde (2010).

The initial cross section tested proved to be stable on the lower part of the seaward slope up to the waterline. However, the structure as a whole proved insufficiently stable as there was significant movement of several Xbloc elements in the top rows of the armour layer at the seaward side, and severe rocking of several Xbloc armour units on the crest of the structure was observed. No units were extracted from the armour layer.

The cause for the observed instability on the upper part of the slope and the crest was found in the stability mechanism of Xbloc. The hydraulic stability of Xbloc and other single layer armour units is largely determined by the interlocking, i.e. by the armour unit shape and by the interaction with neighbouring armour units. The best interlocking is achieved on relatively steep slopes, where the armour units are resting primarily on units of the next lower row (and less on the underlayer), and where the retaining forces exerted by units from the next higher row are relatively large. Interlocking therefore relies on both the slope and the gravitational locking support from armour units further upslope.

The interlocking and thus the armour layer stability are likely to be reduced in the crest region of a breakwater where the stabilising effect of the slope and neighbouring units further upslope is lacking. The largest wave forces occur typically near the still water line. The crest region of a low crested or submerged breakwater is thus exposed to larger wave loads as compared to a conventional breakwater, while interlocking and hydraulic stability of the armour layer are reduced (Muttray *et al.* 2012).

In order to improve the stability of the Xbloc units in the uppermost part of the slope, and to increase the crest stability without increasing the Xbloc size, it was decided to place 3-6 tonnes rock armour on

the crest (Figure 2b). The rock armour was envisaged to behave as a locking mechanism for the Xblocs in the top rows, while also allowing better accommodation under potential settlement, thereby improving the support of the Xbloc units near the crest. Rock armour gains its stability mainly from its own weight and not by interlocking with neighbouring units. Contrary to stability mechanisms of interlocking units, the stability of rock increases on gentle slopes. The use of rock is therefore believed to be a better solution for crest armoring, especially in cases where the crest is relatively low.

Armour rock of 3-6 tonnes were selected to fulfil this purpose at the time as it was expected to be the largest available grading from the selected quarry. The stability of the rock was however found to be insufficient. The start of damage of the 3-6 tonnes crest armour occurred at 60% of the design wave height. Damage progressed with increasing wave load. Substantial displacement of 3-6 tonnes armour stones from the crest would not be favourable as this may lead to damage of the Xbloc armour units on the rear slope.

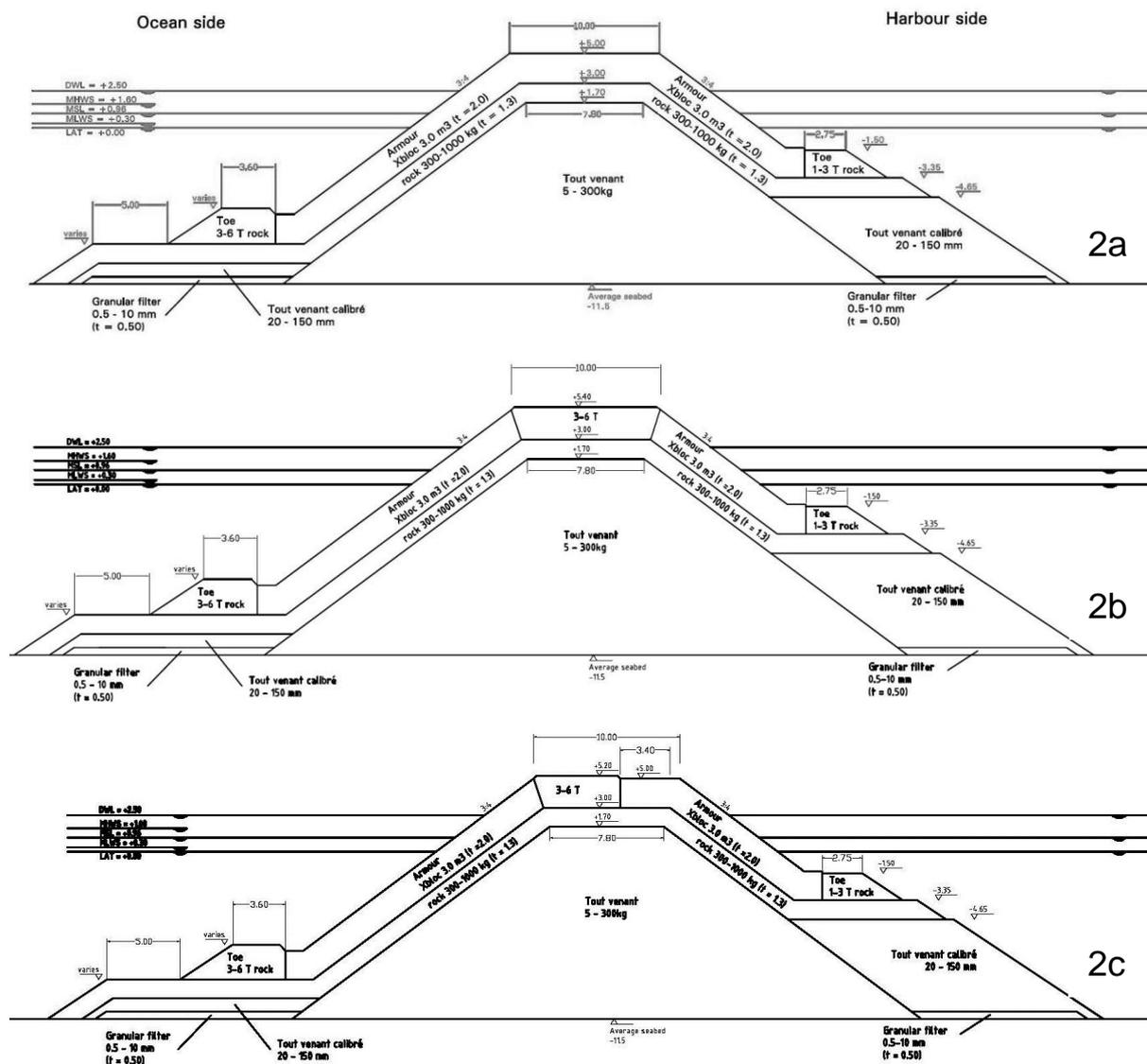


Figure 2: Successively tested cross sections; Initial cross section with Xbloc crest armour (2a); crest with 3-6 tonnes rock armour (2b); crest with 3-6 tonnes rock and Xbloc crest armour (2c).

A stable solution for the breakwater crest was found by placing Xbloc armour on the rear side of the crest resulting in the locking in of the armour rock on the seaward side of the crest (Figure 2c). Two rows of Xblocs were placed on the harbour side (lee) of the crest. The layer thickness of the rock

armour was reduced from 2.4 to 2.2 m and special attention was paid to the installation of the 3-6 tonnes rock on the crest to create a smoother surface in this area.

Previous tests have shown that rough surfaces and thicker armour layers on the crest will result in increased crest exposure and lead to the displacement of the 3-6 ton armour rock in that area.

### Research Low Crested Structures

Partly due to the findings of the 2D model tests for the Pointe-Noire project, additional research was conducted on the stability of low crested and submerged breakwaters with single layer armouring by Van der Linde (2010). The experimental results from Van der Linde (2010) have been re-analysed by Muttray *et al.* (2012) in order to determine the potential reduction in armour layer stability.

Van der Linde (2010) observed significant rocking of armour units in the crest region of low crested breakwaters. The transition from the front slope to the crest armour was found to be most critical for low crested emerged structures. For submerged structures the crest proved to be the most vulnerable section. A relative freeboard of about  $R_d/H_s = 0.4$  was found to be most critical for the total armour layer stability: stability of the seaward slope, crest and rear slope. The stability of the crest was further reduced for a relative freeboard of  $R_d/H_s = 0$  (Muttray *et al.* 2012). This is in line with the findings of the 2D model tests of the alternative design (Figure 2a) for the Pointe-Noire breakwater where Xbloc armour units were placed on the entire crest. The Pointe-Noire breakwater has a relative freeboard of approximately  $R_d/H_s = 0.5$ .

Interlocking concrete armour units may be less stable on the front slope of low crested structures than on conventional breakwaters contrary to rock armour. The armour layer stability on the seaward slope is reduced by about 12% (40% larger armour unit weight required) for low crested structures. For structures with zero freeboard and for submerged structures the stability of the front slope is comparable to conventional, emerged breakwaters. Armour units on the rear slope of low crested structures should be approximately 35% larger than on conventional, high crested breakwaters. The armour layer stability on the crest is reduced by approximately 14% (50% larger armour unit weight required) if the relative freeboard is close to zero. For submerged structures the crest stability rapidly increases with decreasing (negative) freeboard (Muttray *et al.*, 2012).

Larger safety factors are therefore recommended for Xbloc armour on low crested structures. An increase in Xbloc armour unit weight of 50% (for crest levels  $R_d/H_s < +1.0$ ) and of 100% (for crest levels  $R_d/H_s < +0.5$ ) are recommended (DMC, 2011).

Based on the 2D model test for Pointe-Noire and the research on low crest breakwaters with single layer interlocking armour units it appears that extending the armour over the crest is not preferable. For breakwaters with a relative freeboard  $R_d/H_s < 0.8$  it is not advisable at all. Model tests conducted for the Pointe-Noire project showed that a hybrid construction



Figure 3: Setup 3D model (3a); The transition after 3D model testing (3b) and overtopping at the transition during construction (3c).

with interlocking concrete armour units on the slopes in combination with rock armour on the crest is a good solution for low crested breakwaters.

The functioning and interlocking mechanism of Xbloc armour units is similar to other types of interlocking single layer armour units (Coreloc®, Accropode™ etc.). Therefore, the results of this study will most probably apply to other types of single layer armouring.

### **3D Model Test**

3D model tests were conducted in March 2011 in the HR Wallingford laboratory to verify the stability of the breakwater head. The armour on the breakwater head consisted of 4m<sup>3</sup> Xbloc units. Findings of the 2D model tests were incorporated into the design. The Xbloc armour on the crest was partly replaced by a 2.2m thick layer of 3-6 tonnes rock (Figure 2c).

The 3D test showed that the armour rock on the crest was most susceptible to movement in a zone stretching to 100m from the roundhead. This area was subjected to the most severe overtopping, which resulted in crest rock being displaced onto the rear slope of the breakwater more frequently than found elsewhere. It is important to avoid displacement of rock armour in the crest of the structures as such displacement may lead to damage of the Xbloc units.

Although the total number of rocks displaced on the crest was relatively small and did not affect the integrity of the crest, it was decided to increase the weight of the rock grading on the crest to 6-8 tonnes in the zone within 100m of the roundhead. The 2D and the 3D model test results indicated that special attention should be paid to the placement of the armour rock on the crest of the breakwater. The rock armour should be placed tightly on the prototype breakwater to securely lock the Xbloc armouring and further prevent displacement of the armour rock on the crest. Loose exposed rock should be avoided in the crest.

The high overtopping discharges during design and overload conditions resulted in increased disturbance of the 1-3 tonnes toe armour in the rear slopes of the breakwater. It was decided to increase the toe armour to 3-6 tonnes rock in deeper sections. The toe armour in the lee of the roundhead was further extended by 20-30m.

The Xbloc armour layer performed well in all sections except for the rear side of the structure where close to the roundhead some units were found to be rocking, and one 3m<sup>3</sup> unit was extracted from the slope. Extraction of this unit which was located on the crest of the structure occurred during overload conditions. Rocking of units was observed either at the crest of the structure, or within three rows from the top of the slope. It was decided to extend the use of 4m<sup>3</sup> Xbloc armouring on the lee of the structure by 20 – 30 m from the round head towards the shore to increase the stability along this section.

The 3D model test provided further insight into the design of the connection of the existing breakwater to the new breakwater. The transition proved to be on a location where there was wave focussing. As a result this section was frequently overtopped and the 1-3 tonnes rock used in the lee slope armouring was found to be unstable. Ultimately the displacement of armour rock to the lee resulted in undermining of the crest at the transition. The Xbloc armour in the vicinity of the transition was not affected, however, it showed that the design of the transition had to be improved. Figure 3 shows the effect of wave overtopping due to wave focussing along the transition in the 3D model tests and during construction.

Additional tests were conducted for the construction stage to assess the stability of the exposed underlayer and to determine the level of wave overtopping during construction. Based on the model test results the construction platform level of the breakwater was increased from the initially planned +1.7m CD to +3.0m CD which improved the workability significantly during construction.

In the final design, the start point for the Xbloc armour layer was shifted seaward, away from the transition. The rock size of the rear armour was increased from 1-3 tonnes to 3-6 tonnes. The armour layer of the front slope at the transition from the old to the new breakwater was constructed with 6-8 tonnes rock.

## Construction Experience

### Xbloc Production

A total of 2172 Xbloc units of size  $3\text{m}^3$  and 422 Xbloc units of size  $4\text{m}^3$  were produced and installed on the breakwater. The Xblocs were cast on site using 23 steel moulds that were manufactured in The Netherlands and transported to the Congo. The production yard consisted of a concrete production floor at ground level which could accommodate two days of production. The production rate was 1 unit per mould per day. Concrete placement was carried out using either  $1\text{m}^3$  or  $2\text{m}^3$  budgets which were lifted either by crane or forklift. Concrete from the onsite batching plant was transported to the concrete casting area using a truck mixer. Some difficulties were encountered when striking the moulds. Upon investigation it was concluded that the floor on which the moulds were founded should be horizontal and flat to avoid a situation where the mould could not be opened smoothly and demoulding activities may lead to damage of the Xblocs.

During the initial stages of production some crack development was encountered in the lower inside corner of the Xblocs. Depending on the concrete mix design, such cracks may develop near angles in the formwork. In order to reduce the development of cracks, a series of holes were drilled in the formwork around the lower inside corner. By drilling these holes, excess concrete paste and water is able to flow out of the mould and are not trapped in the corner. After drilling of these holes no further cracks were encountered. The holes had a diameter of 6mm and were drilled as shown in Figure 4. It is expected that this solution would also be applicable to crack reduction in corners of similar shaped units.

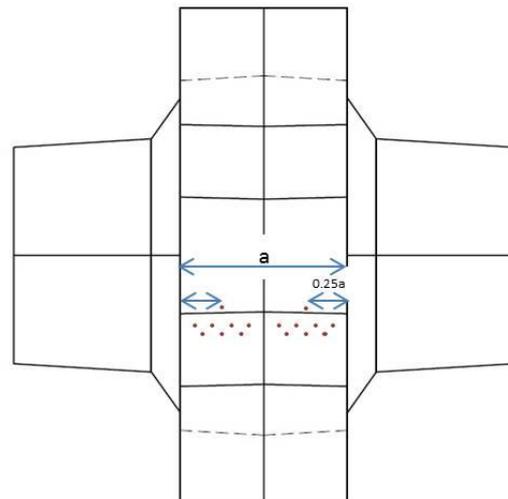


Figure 4: Pattern of holes in the formwork

### Breakwater Construction

#### Quarry Operations

Rock material was required as filter, core and underlayer for the breakwater and as aggregates for the Xbloc production. The rock for the structure and concrete aggregates were mainly supplied from a single quarry identified as Louvoulou (Kouilou). The sand used for the Xbloc production came from Loumé quarry.

The following rock grading's were required:

- filter material 0.5 – 10 mm and 20 – 150 mm
- quarry run, core material 5 – 300 kg
- filter and work layer material 300 – 1000 kg
- armour stone for the toe 1 – 3 tonnes
- armour stone for the toe and the crest 3 – 6 tonnes and 6 – 8 tonnes

The transport of the rock material was carried out by road. New trucks were purchased to transport the rock from the quarry to the project location. The conditions of the road were an important factor

contributing to the wear & tare of the trucks and was found to influence the rock delivery process. Working at night is not advisable in the quarries in Congo as they are not equipped for night work. If required, daily production could be increased by extending the day shifts instead of working night shifts.



Figure 5: Quarry operations

### Construction Sequence

The project site is directly exposed to the sea and swell conditions from the Southern Atlantic Ocean. Construction of the breakwater could only be carried out during the summer months of the Southern Hemisphere. During the summer months significant swell heights up to  $H_s$  of 2m may occur with obvious impact on the construction operations. The breakwater extension was required to reduce sediment transport into the harbour basin by trapping the sediment. During construction rapid sedimentation occurred along the partly constructed sections of the breakwater extension. The accretion was so rapid that construction could not keep up. A solution had to be found to keep ahead of the sand deposition in order to enable construction of the filter layers and toe at the required design depth.

The construction methodology was adjusted to cope with the sediment accretion by first constructing the toe on the seaward side of the structure, followed by the main breakwater body. The toe construction included all filter layers up to the 300-1000 kg underlayer and a part of the 3-6 / 6-8 tonnes berm situated in front of the Xbloc armour layer. The toe structure acted as an underwater reef keeping the upcoming sand away from the temporary breakwater head and allowing the construction of the core and the underlayer.

After installation of the core and underlayer the first rows of Xbloc were installed immediately up to the water line before the accretion of sand reached the top of the toe line. The Xbloc armour in the upper part of the slope was installed at a later stage.

In this way the construction could be built in stages of 10-20m at the time. The contractor was able to apply this construction method using a CAT 385 long boom excavator (Rockbuster) which was able

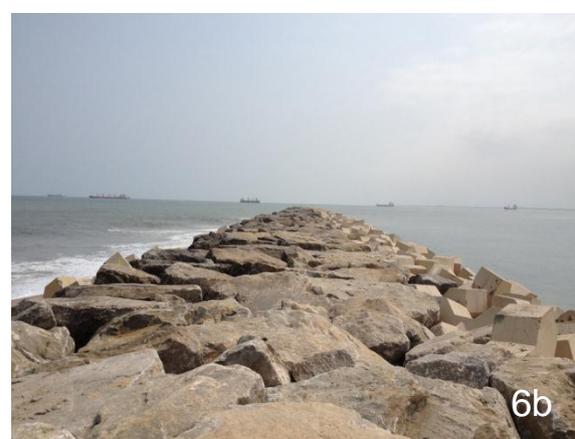


Figure 6: The Rockbuster at work (6a); completed breakwater crest (6b)

to lift 7 tonnes at a reach of 35m. The excavator was customised for the project to place the 3-6 tonnes rock toe and 9.6 tonnes Xbloc units in water depths up to 12m. The rock armour was lifted using a sling inserted into the rock which allowed the operator to place rock armour accurately along the toe. Due to the availability of the customised long boom excavator it was possible to construct the toe 20m ahead of the breakwater core and to keep clear of progressing sand (Figure 6a).

During the construction period the construction had to be stopped several times due to high swell conditions. The downtime due to the swell was about 9%, i.e. 2 weeks of the 22 week construction period. When the work had to be stopped the exposed core and the edge of the Xbloc armour were covered with large rocks to prevent damage to the partly completed structure. Higher swell waves overtopped the structure regularly. As seen during the 3D modelling especially the transition between the existing and new breakwater, where the waves focussed, significant overtopping was experienced (Figure 3c). Following heavy weather periods the temporary stone protection was removed and the structure had to be cleared of sand which was deposited on and over the crest.

### Xbloc and Crest Armour Installation

Xbloc placement rates were mostly determined by the progress of the core and the underlayer installation and profiling. The maximum production per shift of 12hrs was 116 units (10 units/hrs). The production rate for the installation of Xbloc on the crest was 30 units/shift. This production rate was initially constrained by the delivery of Xblobs from the storage to the excavator rather than by the installation itself. The number of units installed was 2594 (both 3m<sup>3</sup> and 4m<sup>3</sup>), which was 7units more than the theoretical number of blocks specified on the placement drawings by DMC. The achieved as built placement density of the installed Xbloc units was 100% to 103% of the theoretical packing density for the sea ward sections of the breakwater, and 98% to 102% of the theoretical packing density for the sections on the lee side of the breakwater.

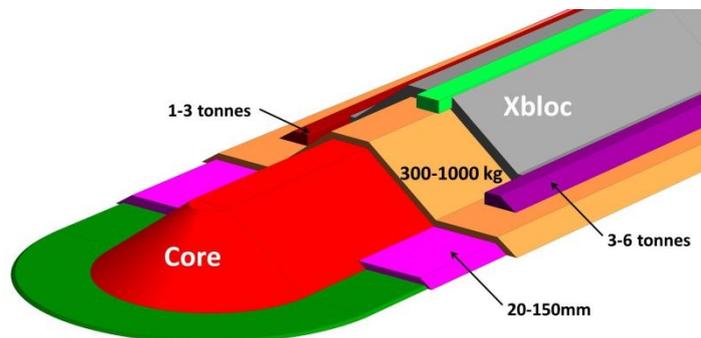


Figure 7: Breakwater model

As demonstrated in the model test the installation of rock armour on the crest is of great importance. According to the design 6-8 tonnes rock had to be installed from KP 175 – 300 and 3-6 tonnes rock to KP175. During the execution of the works the local quarry had difficulties to produce the required grading of 3-6 and 6-8 tonnes. The produced grading was significantly larger and was accepted as such in order to prevent delays and allow completion of the structure before the next winter period. So doing, a crest armour of 6-10 tonnes was applied along the entire breakwater extension. Which increased the stability of the crest armour.

During installation the layer thickness had to be limited to 2.2m to prevent exposure of individual rocks to overtopping waves. Smaller rocks were installed in the bottom and larger rocks were subsequently installed on the top. Each rock was individually pitched and placed to ensure good interlocking and to assure a smooth crest. By careful selection and installation of each rock the layer thickness could be achieved and sufficient locking in of the Xbloc armouring was achieved in the crest. A placement production rate of 150-250 tonnes/shift was achieved. The construction of the breakwater extension was completed in June 2012. Figure 6b shows the completed breakwater crest.

## Conclusion

Physical model testing is inevitable when designing coastal structures. Both the 2D and 3D physical model tests contributed to a functional, cost efficient, constructible and stable design of the breakwater crest, head and transition from the old breakwater to the extension of the breakwater of Pointe-Noire.

The 2D model test showed the reduced stability of single layer armour units on low crested structures. Partly based on the experiences of the model test for the Pointe-Noire project additional systematic research was conducted. For emerged structures the transition from the seaward slope to the crest is

the most vulnerable section as was also shown in the 2D model test for Pointe Noire. An increase in Xbloc armour unit weight of 50% (for crest levels  $R_d/H_s < +1.0$ ) and of 100% (for crest levels  $R_d/H_s < +0.5$ ) is there for recommended (DMC, 2011).

The model tests for the Pointe-Noire project showed that a hybrid construction of interlocking concrete armour units on the slopes in combination with rock armour on the crest is a good solution for low crested breakwaters. This solution is expected to apply also for other types of single layer armouring.

The construction was effected by rapid accretion of sediments along the breakwater extension and by large swell. The construction methodology has been successively adjusted to cope with the sediment accretion. The downtime due to the swell conditions could be managed by increasing the work platform level for the breakwater from the initially planned +1.7m CD to +3.0m CD.

## Acknowledgements

The successful completion of this project would not have been possible without the efforts and support of HR Wallingford, Royal Boskalis Westminster nv, Delta Marine Consultants and the team on site. Our thanks go to all who were involved and provided valuable input, from the execution of the model test to the construction on site.

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