REPAIR OPTIMIZATION AND PERFORMANCE ANALYSIS OF THE ASPHALT PROTECTION LAYER OF THE SOUTHERN BREAKWATER IN FRONT OF THE PORT OF AMSTERDAM

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Breakwaters provide shelter against waves and currents for safe navigation to port entrance by sea vessels. The breakwaters of IJmuiden, in front of the port of Amsterdam, were initially built in the 19th century and extended in the years 1961 – 1967. The extension reaches out into water depth of approximately 15 m and consists of a core with armour stone 300 – 1 000 kg grading. It has a protection layer being a mixture of stones up to 60 kg overfilled with bituminous grout. The thickness of the layer is approximately 2.25 m. The mixture was made on shore. The breakwater is designed for wave heights up to 7.5 m. Since construction the breakwaters were frequently and severely damaged by wave impact and compressed air in the core and have been repaired many times. In order to stabilize the protection layer, concrete cubic blocks were installed in different periods. In the period 2013 – 2022 the performance of the blocks in combination with the asphalt protection layer was closely monitored and, together with the maintenance regime, evaluated in 2023. In conclusion, damage of blocks and the protection layer are tolerable for large stretches of the breakwaters. Only a few blocks disappeared and small parts of the asphalt protection needed to be repaired. The situation at the roundhead of the southern breakwater is different. Multiple times damage occurred in this period. Therefore in 2020 the remains of the blocks at the roundhead were removed and a new protection layer was constructed above the original damaged layer. The slope was smoothened with armour stone and fully grouted with mastic asphalt. This new protection layer at the roundhead of the southern breakwater did not meet the requirements and damages still occurred, many due to erosion of the asphalt. Already after a year the new protection layer needed to be repaired (2021). Repair was difficult due to wave conditions and the application of asphalt around and below the water surface. In addition, the quality of materials and construction method was insufficient. In 2023 and 2024 new repairs took place. The working method and quality of materials were improved during these repairs in order to optimize the reconstruction. The strength increased resulted in less damage than other years, but the construction is still not resistant to its design loads.

Keywords: breakwaters, asphalt, mastic, protection layer, damage, repair, design, failure modes, hydraulic loads

INTRODUCTION

History (1900 – 2012)

On November 1st 1876 a new channel from Amsterdam to the North Sea, including the locks at IJmuiden, was opened by King Willem 3rd. The channel was constructed to provide better access to the port of Amsterdam compared to the existing routes. At the seaside two breakwaters were constructed to provide shelter for incoming vessels. All the construction work was executed by an English contractor. The breakwaters had a symmetrical lay-out, see Figure 1.

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Figure 1. The old breakwaters constructed in the 19th century.

Over the years vessel sizes increased, causing a need to widen and deepen the entrance between the breakwaters. In 1957 research was started for a new design of the entrance area which resulted in a design of two asymmetrical breakwaters, the southern (3 000 m) longer than the northern (2 500 m). The lay-out had two benefits: 1) less sedimentation in the channel and 2) less hindrance of the prevailing wind- and current direction for incoming vessels. The original design consisted of core material covered with armour stone and a top layer of tetrapods. However, before the start of construction the design of the top layer was changed for economic and technical reasons. Also a strong lobby of the asphalt industry played a role. The protection layer changed to a stone asphalt mixture of stones up to 60 kg overfilled with bituminous grout. The extension consists of a core with armour stone grading 300 – 1 000 kg. The thickness of the layer is approximately 2.25 m, see Figure 2. It reaches out into water depth of approximately 15 m. The breakwater is designed for wave heights up to 7.5 m. The stone asphalt mixture was made on shore, kept on temperature and transported to the construction site. The layer was impermeable, although water could still penetrate into the core through the toe construction.

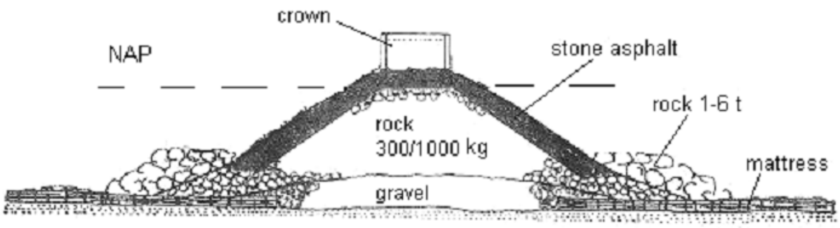

Figure 2. A cross-section of the breakwaters as it was used during construction.

During the years 1960 – 1967 the extension of the breakwaters was constructed. Figure 3 shows a photo of the constructed breakwaters. During the construction, failure of the top layer occurred and resulted in sliding of large pieces of stone asphalt downward the slope. The mixture of stone asphalt was changed several times over the construction period to increase stability. The slope was changed from 1:1.5 to 1:2 (southern breakwater) and even 1:2.5 (northern breakwater). After these changes construction failure still occurred. The roundhead of the southern breakwater was a difficult part to construct due to its forward position and heavy wave loading.

Figure 3. Photo of the breakwaters, on the right the longer southern breakwater, left, the northern breakwater.

One of the failure mechanisms seemed to be the high pressure inside the core of the breakwaters, caused by the open toe-structure. In the 70s a plan was developed to place a large amount of concrete cubic blocks (approximately 22 000, weight varying 22, 30 and 45 ton) on top of the asphalt layer as counterweight for the overpressure during severe storm events, see Figure 4. The concrete blocks were placed direct on the asphalt layer. Due to this impermeable layer the blocks were not stable during storm conditions. Blocks moved or disappeared during storms several times a year. In the 80s and 90s of the 20th century new blocks were placed when this happened. Also new blocks were placed when blocks deteriorated into smaller pieces. Maintenance of the breakwaters became very costly and in 2005 research was performed on how to reconstruct and strengthen the top layer of the stretches that encountered severe wave attack. Several design scenarios were developed and a decision support model with quantitative and qualitative aspects showed that the best option was an overlay construction with single layer of concrete blocks (Dorst 2006), see Figure 5.

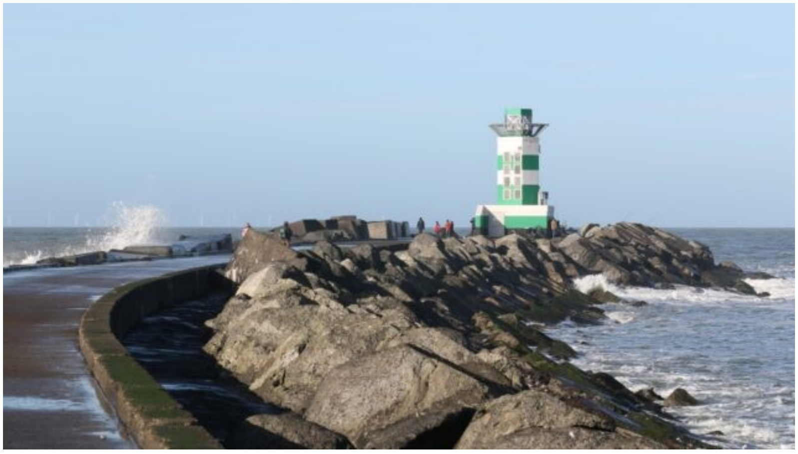

Figure 4. Photo of the breakwater with concrete blocks.

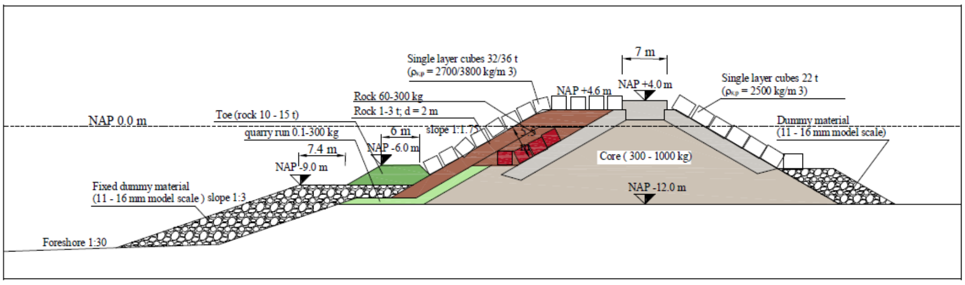

Figure 5. A cross-section of the overlay construction with single layer of concrete blocks (Dorst 2006).

Reconstruction options

In the period 2005 – 2009 studies were done for a reconstruction and a cost benefit analysis showed that short term reconstruction was the best option (Janssen et al. 2009). This study was based on the assumption that the overpressure failure mechanism was predominant. However the monitoring of the internal pressure in the breakwater showed that this pressure was decreasing over the years due to sedimentation along the breakwaters and into the toe structure, preventing wave pressure to enter the dam core. This insight initiated a new strength analysis that was used as input for a risk analysis of the breakwaters. The dominant risk was defined as the unavailability of the harbour entrance by sedimentation due to failure of the breakwater. This analysis showed that this probability was low enough even without the concrete blocks (van Hoven 2013).

Monitoring and repair: pilot (2013 – 2023)

Based on the previously mentioned risk analysis, it was decided not to reconstruct the breakwaters but to maintain the current situation. The main changes in the monitoring- and maintenance plan for the period 2013 – 2023 were 1) annual monitoring of the condition of the breakwaters, 2) repair if a certain intervention level is reached and 3) in principle no placement of new concrete blocks. The maintenance plan (Rijkswaterstaat 2014) describes the monitoring and repair activities based on different intervention levels defined for e.g. slope, area, depth of profile, movement and loss of concrete blocks. The plan includes a description of the method and materials to be used in case of repair.

MAINTENANCE SINCE 2013

Damage and repair 2019

In the first years after 2013 the concrete blocks and the asphalt layer were observed but no major damage occurred that cut through the intervention levels. The situation at the roundhead of the southern breakwater was different. Based on the trend analysis of 2019 and visual observations, severe damage was observed, characterized by steep slopes and a huge loss of asphalt mass. Also the measured profile cut through the intervention level related to the minimum profile, therefore it was decided to repair the roundhead of the breakwater. Due to the upcoming storm season (in The Netherlands the period from October until April) only the profile above N.A.P. (Dutch average (North)sea level) was repaired. The damage was repaired with armour stone of 10-60 kg that was fully grouted with mastic asphalt. A slope of 1:2.5 was used, the same as the original design. The repair was done with a number of smaller layers. The first layer started at the concrete blocks around N.A.P. that were used as a support structure for the repair.

In February 2020 multiple storms passed the Dutch coast and washed away the repair of 2019. The main cause of the damage was the instability of the supporting concrete blocks. At the northwestern area a steep slope was observed, see Figure 6, and the total area of the damage increased compared to 2019.

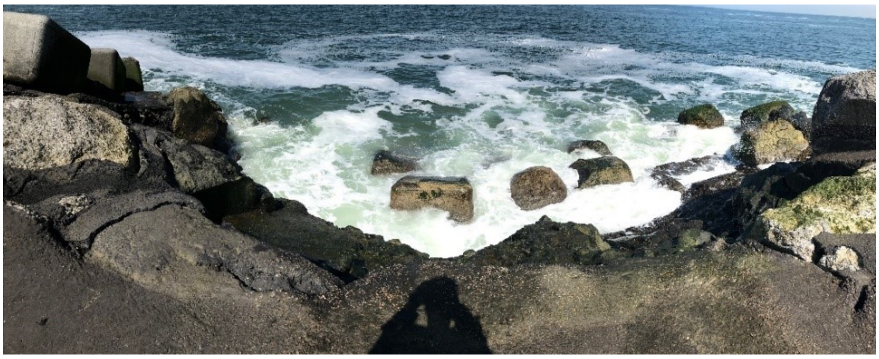

Figure 6. Photo of the damage at the northwestern side of the breakwater roundhead by E. Lee.

Repair 2020 and 2021

In 2020 the breakwater was repaired again. It was decided to make an amendment to the original design.

- The slope was smoothened to 1:3.5 for stability and reduction of wave loads.
- Armour stone of 40-200 kg instead of 10-60 kg was used to improve the stability of the stones during construction and better penetration of the mastic asphalt.
- The penetration with mastic asphalt of the top layer at the toe was increased with 20% extra mastic asphalt and the main area and the transitions to the existing structure with 10% extra. This to create a fully grouted smooth top layer and robust design.
- The construction was built by different layers with a thickness of approximately 1.0 m each. This construction method was chosen from a practical perspective and penetration tests.
- The repair extends to a level of 5 m below N.A.P. An analysis based on historical data over the past ten years demonstrated that material at this level was stable.

Based on the design parameters and the first survey a map was created of the area that needed to be repaired. It was concluded that some concrete blocks and loose parts had to be removed before armour stone and mastic asphalt could be placed. For several cross-sections the design was plotted, one example shown in Figure 7.

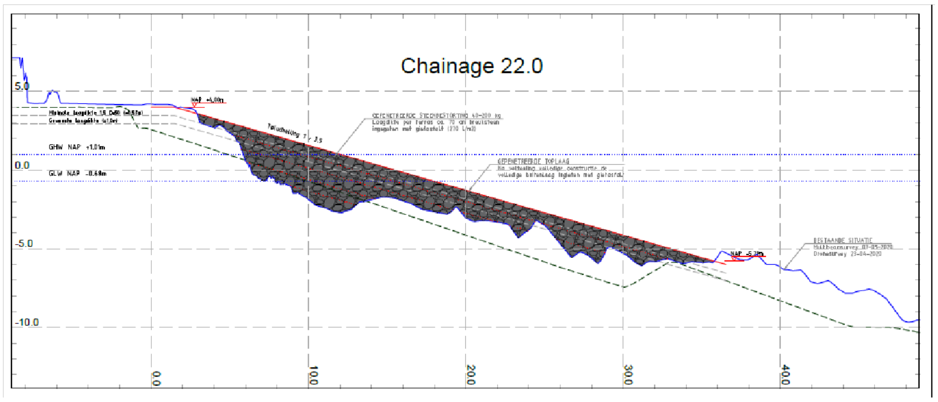

Figure 7. Design of the repair in 2020 for chainage 22.0.

In 2020 the repair took place from water and land, see Figure 8. During construction in 2020 setbacks were encountered due to bad weather and wave conditions around the head of the breakwater causing severe delay. For example, in 2020 in total 32 workable days were registered, while 39 days the equipment was idle due to wind and wave conditions. Based on the weather and wave conditions in 2020, it was decided to repair in 2021 from land only.

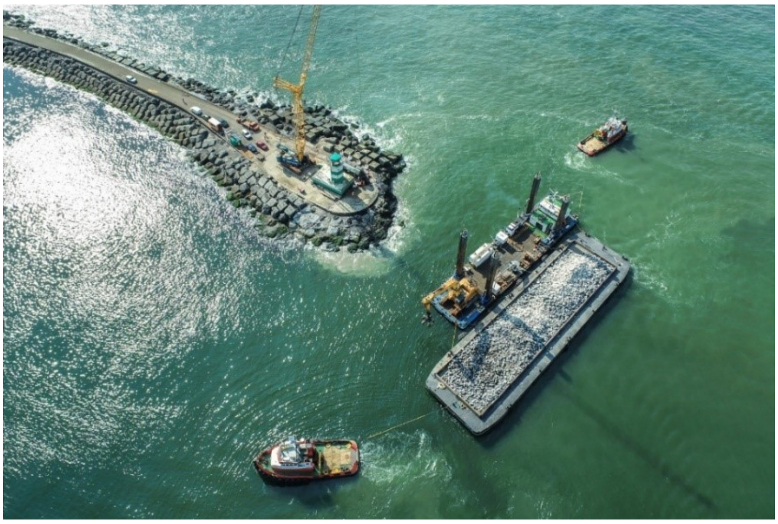

Figure 8. Land-based and sea-going equipment used by Paans Van Oord.

In the repair periods also moderate storms occurred with wave heights over 4 m. In September 2020 a storm caused severe damage. Armour stone that was not yet grouted was moved from the west side to the east side of the roundhead. Also damage was observed at the transitions to the existing construction. It was decided to use 10-20% extra asphalt also for the layers 2 and 3 where it had a connection with the existing slope.

The repair of 2020 required the most material. In a period of ten weeks 9 900 tons of armour stone was placed and 6 000 tons of mastic asphalt was used to penetrate the armour stone. This includes damage by the severe storm in September. For the repair in 2021 less material was used.

In 2020 the area beneath N.A.P. was inspected based on survey-data, but did not show irregularities. Just before the completion of the repair work, waves caused damage in the zone of wave attack reaching till 1.5*H_s below N.A.P. The damage was mainly observed in the range of 0 till -3 m N.A.P. This was only observed in the top layer. Based on the survey of December 2020, which showed an increase of damage at the top layer, it was decided to monitor the repaired work and prepare the repair in the second quarter of 2021.

HYDRAULIC LOADS AND FAILURE MECHANISM

The original breakwaters are designed for wave heights up to 7.5 m. As mentioned the breakwaters experienced many damages in the construction period and operational period, this occurred already with wave heights of approximately 4 m. This led to repairs and alterations of de protection layer. An alteration with great impact was the deployment of concrete blocks from 1968 to 1980. The alterations and the progression of time led to a shift in dominant failure mechanisms. In time the structure experienced settlement and infiltration of sand, which made it more stable and less vulnerable for inside water pressure.

According to wave statistics and measurements, it is very likely that the design wave height has occurred during the lifespan. However, severe damages occurred far more frequently than would be expected given the applied design load. The question is: what failure mechanisms did and do still occur?

In the period 2013 – 2022 the performance of the breakwaters was closely monitored and it was evaluated in 2023 (Rijkswaterstaat 2023). It became clear that this question is difficult to answer. This type of breakwater is uncommon to build, especially not as far into the sea as at IJmuiden where the conditions can be severe. There are no standard design methods or codes for the asphalt protection layer in particular for the harsh conditions at open sea. During the past 30 years a lot of studies have been done and many hypothesis devised. As a result the toe construction and the soil protection in front of the breakwaters where declared stable. The main problem is the asphalt protection layer with concrete blocks and later on without the blocks. The concrete blocks proved to be more or less stable, except at the roundhead of the southern breakwater. At that location the blocks were frequently washed away. Without the blocks wave loads damaged the underlaying asphalt protection layer.

Model studies (W.L. 1971) show that the blocks become theoretically unstable at a stability parameter of 1.2. This is a very low stability parameter, due to the relative small weight of the blocks and the impermeable asphalt layer underneath which does not absorb wave energy. Figure 9 shows the stability parameter for the concrete blocks for the storms in 2013 to 2020 and the conclusion is that during all (relative small) storms the concrete blocks are expected to become unstable. In reality this did not occur in each of those storms and when it did occur, mostly only at the southern roundhead. A reason is that the distance between blocks differ, so some blocks are more exposed than others. Also the blocks were molded in with extra asphalt, which gives more stability. Most damages to the blocks occurred at the southern roundhead, where the blocks experience waves loads from all wind directions.

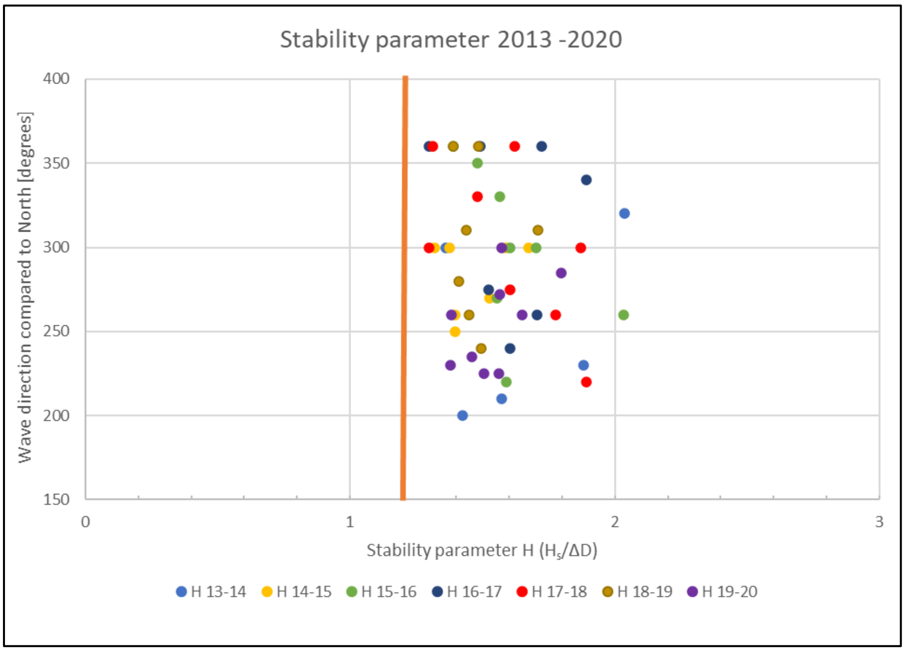

Figure 9. Stability of concrete blocks during storms between 2013 – 2020. Orange line is the stability number for the concrete blocks, derived in model studies (W.L. 1971). The stability numbers of every winter period (H13-14 until H19-20) are plotted in different colors. For example H 13-14 contains the data of the winter period of 2013 – 2014.

With the repair in 2020 the blocks where removed at the southern roundhead. After removal the asphalt protection layer experienced many severe damages each year till now, resulting in different repairs. These damages occur at wave heights above approximately 4 m, far less than the design wave of 7.5 m for the original asphalt protection layer (1960). Analysis shows that the incoming waves during these storms are ‘plunging’ waves (Iribarren number 1.2 – 1.4), resulting in high impact loads on the protection layer. Different hypotheses were studied, leading to the conclusion that erosion of asphalt starts the process, subsequently exposing the stones in the protection layer. Eventually the stones are pulled out by incoming waves. Figure 10 shows damage of this failure mechanism before the repair in 2023.

Figure 10. Photo of damage at the roundhead of the southern breakwater in 2022.

Figure 11 shows the asphalt protection layer directly after the repair in 2023. Details of the repair are discussed in the next chapter. The result is a smooth surface in order to avoid points of impact for local water pressures due to plunging. Figure 12 shows the damage after the first (mild) storm in 2023. First asphalt is peeled off and stones become visible. Then stones are pulled out and the protection layer becomes even more vulnerable for plunging waves, as the surface becomes less smooth. At some parts stones and asphalt are completely gone. This process or failure mechanism is labeled as 'erosion of the asphalt protection layer' (consisting of asphalt and stones). The repairs are made in layers of 1 meter and the attachment between layers seems critical for the strength of the repair. At multiple locations the erosion first propagates to the surface between two layers, before the next layer is damaged. The overfilled and smooth top layer could not prevent this failure mechanism.

Figure 11. Photo of the repair in 2023 with the smooth asphalt top.

Figure 12. Photo of the erosion of the protection layer in 2023. Upward left: stage 1 - peeling of asphalt, downward left: stage 2 - pulled out stones, right: stage 3 – stones and asphalt are washed away.

REPAIR OF THE SOUTHERN ROUNDHEAD IN 2023 AND 2024

After the storm season of 2022/2023 the damage was larger than the defined intervention levels, so the stability of the breakwater was no longer guaranteed and did not meet the requirements.

The repair of 2021 (described in earlier chapter) was executed with the method of armour stone fully grouted with mastic asphalt. For the design of this type of revetment on dikes and dams pressure in the under layer is mostly the dominant failure mechanism which determines the thickness of the layer (Rijkswaterstaat 2015). It is not clear until which wave load this type of revetment is stable, but it is clear that in this case it did not withstand waves with a significant wave height higher than 4 m.

Original repair armour stone fully grouted with asphalt

Armour stone fully grouted with mastic asphalt is a common method to reinforce dikes and dams in The Netherlands. This type of revetment consists of armour stone, often with a grading of 5 – 40 kg or 10 – 60 kg, with a layer thickness of minimal 1.5*D_{n50}, which is grouted with mastic asphalt, see Figure 13.

Figure 13. Typical application of asphalt grouted armour stone on a dike.

Full grouting of the armour stone with mastic asphalt is called ‘vol-en-zat’, which means that the pores in the bottom of the layer are totally filled and the pores in the top are partially filled with mastic asphalt, see Figure 14. For this type of reinforcement the quality of the armour stone is important. Blockage of the pores due to dust or fine fractions will have an impact on the penetration of asphalt through the armour stones, resulting in an insufficiently filled bottom layer, which results in a lower resistance against hydraulic loads. (Rijkswaterstaat 2015)

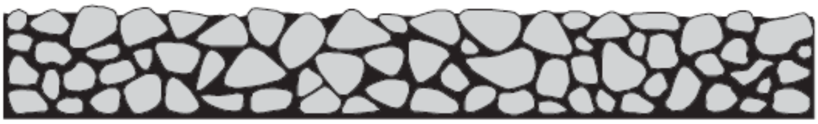

Figure 14. Typical example of ‘vol-en-zat’ (TAW 2002).

Design optimizations

As mentioned before the repair of 2021 was not stable and did not meet the requirements for the breakwater. In 2023 it was necessary to execute a repair again, but the working method and quality of materials were improved, to optimize the quality of the reconstruction. Different kind of optimizations were researched. The focus was on improving the adhesion between the armour stone and asphalt and a more refined construction method.

Because of the harsh hydraulic conditions at the roundhead of the breakwater, loose armour stone can flush away during high wave conditions before it is grouted with mastic asphalt. That is why the initial armour stone with a density of 2 650 kg/m^3 was replaced by armour stone with a density of 3 000 kg/m^3. This improvement should have a positive impact on the stability of the loose armour stone before grouting with mastic asphalt.

The adhesion between stone and asphalt was improved by choosing an armour stone type with a rough surface, because this will lead to more contact surface and so a higher adhesion. Another optimization was the pretreating of the armour stone by removing small particles (so blockage of the asphalt was no issue), removing dust and applying a bitumen layer on the armour stone (which consists of emulsion of modified bitumen and will act as a kind of glue between the asphalt and the stones). As a final touch, the rough surface of the protection layer was finished with a top layer of mastic asphalt to create a smooth surface on which waves will have less impact.

Model tests

All of these optimizations should lead to a higher strength of the protection layer. But before this was applied on the repair of 2023, it was first tested in small model tests and afterwards on full scale to verify this hypothesis.

The small model test was done by the Queensland Test, described in detail in "proef 106" of the "Standaard RAW Bepalingen" (CROW 2020). This test is a common test to check the adhesion between stones and asphalt. A batch of small stones was placed in a plate with mastic asphalt. The variables in the test were:

- Different rock types (to check what the influence of contact surface is on the strength)
- 'Clean' armour stone and armour stone pretreated with a bitumen layer (to check what the influence is of applying a bitumen layer on the strength)
- Plate with stones grouted under water and without water (to check what the influence is of execution above and under water)

Figure 15. Queensland test with left above the pretreated armour stone and right under the 'clean' armour stone.

The adhesion was quantified by the amount of mastic asphalt that is left at the individual stones after pulling the stones out of the plate. Each stone is quantified by the number of '0', '1' and '2', which respectively means that there is no mastic asphalt left, around 50% of the mastic asphalt is left and most of the mastic asphalt is left on the stone. This number for all tested stones is summed up and gives a number that indicates whether the adhesion is good, relatively compared to each other. The conclusion of the test was (Rijkswaterstaat 2023):

- Armour stone with a rough contact surface does have a better adhesion
- Applying a bitumen layer will have a positive impact on the adhesion
- The adhesion above water is better than under water.

Based on these conclusions the decision was made to apply armour stone with a rough contact surface (Hyperit) and pretreat it with a bitumen layer before construction. These optimizations were also verified in a full scale model pulling test with the same variables as in the small model test. The test was executed in a large container. The different types of armour stone were placed in the container and the mastic asphalt was applied afterwards. This resulted in the best full scale copy of the situation at the roundhead of the breakwater.

Figure 16. Full scale pulling test with pretreated and not pretreated stones.

The adhesion was quantified by the force that was needed to pull out the stones. The forces needed were relatively compared to each other, to get more insight in the adhesion. The forces needed to pull out clean armour stone was around 15 kN under water and 20 kN above water. For the pretreated stones this was 20 kN under water and 25 kN above water. These are average values of the force, but it is good to mention that for some pretreated stones it was not possible to pull them out, so the mentioned values are a rough estimation, to get an idea of the quality of the adhesion. Results showed that pretreating of armour stone had a positive impact on the adhesion. Another result was that grouting of dry armour stone with mastic asphalt above water led to a better adhesion then grouting wet armour stone under water, probably because a thin water layer is trapped between the asphalt and stone which has an negative influence on the adhesion. Based on the results, the verification was positive and application for execution on the roundhead of the breakwater was verified.

Construction

During construction the conclusions of the model tests were applied and other optimizations in construction method were introduced, which should lead to a higher strength of the protection layer. The first step was to filter out the fine fractions (fragments) from the batch armour stone, because the fine fractions could lead to hindrance of the asphalt flowing into the armour stone.

Figure 17. Process of filtering out the fine fractions of the armour stone.

After filtering out the fine fraction, dust was removed from the armour stone by a stone washing installation. This resulted in clean stones without dust, which improved the adhesion and strength of the protection layer.

Figure 18. Set up for washing of stones which removed dust from the armour stone.

The clean armour stone was then pretreated with a bitumen layer. This was done by immersing the armour stone in a container with liquid bitumen. The result was a batch of armour stone, covered with bitumen.

Figure 19. Pretreated armour stone with a bitumen layer.

Not only the armour stone was pretreated. Also the construction area above water was pretreated by removing algae and dust and then covered by bitumen. So the conditions for a good adhesion between the construction area and the new protection layer were improved, which should lead to a higher strength of the whole construction.

Figure 20. Pretreating the construction area by removing algae.

After pretreating of the stones and the construction area, the stones and mastic asphalt were applied from land as in 2021, in layers with a thickness of 1.0 m. The last finishing touch was to apply a finishing layer, which resulted in a smooth slope surface, shown in Figure 11. The idea was that waves should have less impact on a smooth slope, which should lead to a higher strength of the protection layer and less or no erosion.

RESULTS AFTER STORM

After finishing the work in the summer of 2023, in September of that year new damage occurred. During this storm the significant wave height was more than 4 m. The damage is shown in Figure 21, by the dark blue area. This was part of the recent repaired area, but it is not clear why only this part of the slope was damaged and the other parts were still intact. A positive note is that the damage area was much less than earlier years, when a significant wave height of 4 m with same duration appeared.

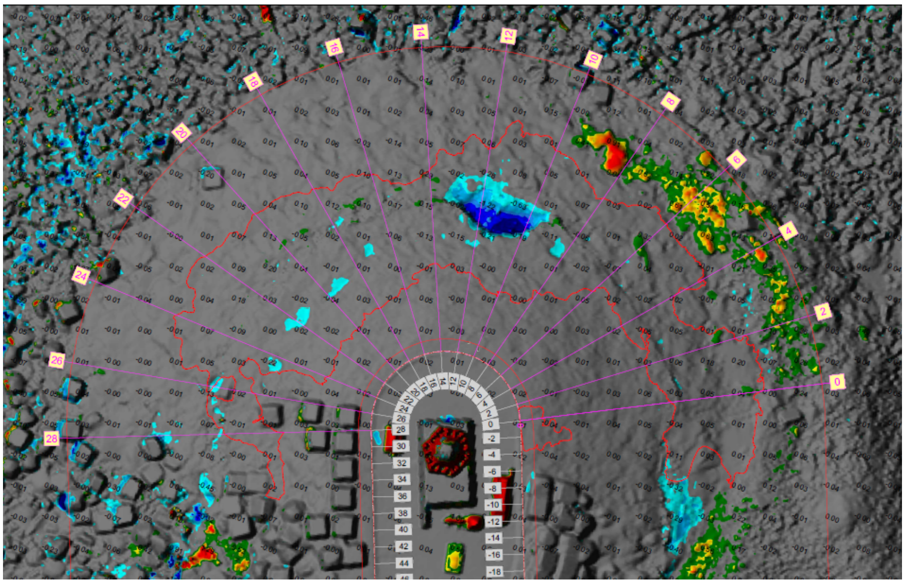

Figure 21. Damage after the storm in September 2023. The dark blue area represents the damage.

As earlier described the damage area of 2023 was repaired in 2024, to ensure the stability of the roundhead of the breakwater. In November of 2024 new storms with significant wave heights of 4 m appeared, but this time the protection layer was still intact after the storm. Only small parts of the finishing layer disappeared, shown in Figure 22.

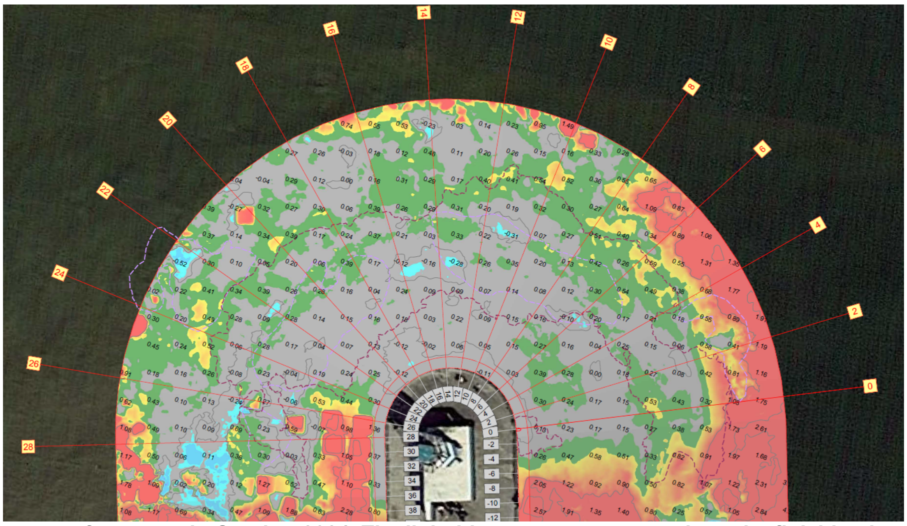

Figure 22. Damage after storm in October 2024. The light blue spots are areas where the finishing layer is partly damaged.

DISCUSSION

It can be concluded that this type of protection layer is not suitable for mild and extreme weather and wave conditions. Eventually it was also concluded that the dominant failure mechanism is erosion of the mastic asphalt which hold the stones together. When a small gap in the mastic asphalt has formed, it provides a gripping point for the next waves to tear more mastic asphalt from the layer and eventually stones as well. It is hard to qualify clear conclusions from monitoring data of the improved repair of the protection layer. A clear conclusion is that the protection layer does still not meet the design requirements (design wave height is 7.5 m), despite optimizations that were done. Another cautious conclusion is that pretreating of armour stone will have a positive impact on the strength of the protection layer, based on the small and large scale test and based on monitoring data of the repair in 2023 and 2024.

CONCLUSION

Since the construction of the breakwaters, a considerable amount of damages occurred on the asphalt protection layer. Due to all the reparations a lot of knowledge is gained on this type of protection layer. During the evaluation of 2023 lessons are learned (Rijkswaterstaat 2023). In this article a summary is given.

The roundhead of the southern breakwater in IJmuiden was repaired in 2023 and 2024 with armour stone fully grouted with mastic asphalt and an improved construction method, which was an utmost effort to realize a protection layer of armour stone fully grouted with mastic asphalt that can withstand large wave loads.

- Pretreating of armour stone will improve the adhesion between armour stone and mastic asphalt, which results in a stronger protection layer of armour stone fully grouted with mastic asphalt.
- Harsh and difficult repair conditions make it almost impossible to correctly penetrate amour stone with mastic asphalt. Mastic asphalt will be flushed away due to waves and the strong current. Perfect application is only possible at moments of still water, which do not frequently occur.
- Armour stone fully grouted with mastic asphalt is not suitable for this location (design wave height 7.5 m). This is based on the recent damage, that was the result of waves up to 4 m, and the utmost effort in the last repair to gain as much strength as possible.
- It is difficult to determine the exact cause of damage. Based on monitoring data, erosion of the protection layer appears to be the main cause.

This project has given new insights about the functionality of mastic asphalt as a protection layer. The utmost effort is done to optimize armour stone fully grouted with mastic asphalt. For design wave heights over 4 m this type of protection layer is incompatible, however other locations with lower wave heights benefit from the lessons learned from this project. Taken everything into account a renovation study of the southern roundhead will start with the use of a more typical protection layer, for example, concrete elements on an open filter.

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