ELASTOCOAST PILOTS IN THE NETHERLANDS
STORM SEASON 2007/2008

ELASTOGRAN GMBH

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ARCADIS

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CHAPTER 1 Introduction

1.1 THE ELASTOCOAST SYSTEM

Elastocoast is a new type of revetment system that can be applied in the wave attack-zone, run-up-zone or inner slope of dikes. It consists of granular material fixed together with a two-component polyurethane adhesive. In the Elastocoast system each individual rock is covered with a thin film of polyurethane. When cured this film bonds the rocks together only on their contact points, retaining a highly permeable, open structure.

The chemical components of the Elastocoast system are produced by the German company Elastogran, which is a subsidiary of BASF. From 2004 to 2007 several pilot tests were performed along the North-Sea islands in the most northern part of Germany. The first commercial project has also been constructed in this area in September 2007, comprising a revetment with an area of 1.500 m^2.

Also in 2007 Elastocoast is introduced to the Dutch market. ARCADIS and Delft University of Technology have been involved to do further research. ARCADIS supervised the construction and monitoring of two pilot tests in the Netherlands (see also figure 1.1a):
- The head of beach groyne no. 20.9 near the Pettemer Zeewering along the North Sea coast, 385 m^2 on a horizontal bed;
- Part of a rudimentary sea dike called 'Zuidbout' near Ouwerkerk in the Eastern Scheldt, 490 m^2 on a 1:3-1:4 slope (figure 1.1b).

These pilot tests were constructed in September and October and are subject to monitoring during the storm season of 2007-2008, running from October 2007 to April 2008.

Figure 1.1
a) Locations of Dutch Pilot tests[1];
b) Pilot location 'Zuidbout'.

1.2 STRUCTURE OF THIS REPORT

In this report the entire process starting with the construction of the two pilots to the monitoring and data analysis of the storm season 2007/2008 is described. The core of this report is divided in three parts; two separate analyses of the pilot locations and a combined discussion of monitoring results from these locations.

In chapter 2, the pilot location Zuidbout is introduced. First, the site location, construction period, availability of data and monitoring are discussed. Then a data analysis is made of the storm season 2007/2008, from which the hydraulic effects at the structure are obtained and loading on the structure can be analyzed.

The same is done for the pilot location Petten in chapter 3. The structure characteristics and loading conditions are different from the pilot location Zuidbout. Therefore a separate analysis is performed.

The monitoring method and results from both pilots are presented and discussed in chapter 4. From the differences as well as from the similarities between the observations conclusions are drawn with regard to the performance of the Elastocoast system during extreme conditions in general.

Finally in chapter 5 a recapitulation is given of the main conclusions that can be drawn and lessons that can be learned from the construction and performance of the Dutch pilot locations.

CHAPTER 2 Pilot location Zuidbout

2.1 LOCATION AND BATHYMETRY

The Zuidbout is located in the Oosterschelde (Eastern Scheldt) estuary on the south bank of the island Schouwen-Duivenland (fig 2.1). The storm surge barrier at the inlet of the estuary is only closed during extreme conditions, so the tidal movement in the estuary normally follows that of the North Sea. This tide is semidiurnal, with one high and one low water every 12 hours. Average water level is NAP+0.03 m and the average tidal variation ranges from NAP-1.39 m to NAP+1.58 m. An example of the astronomical tide at the nearby city of Stavenisse is shown in figure 2.2.

Figure 2.1
The Zuidbout is located in the Eastern Scheldt estuary[2].

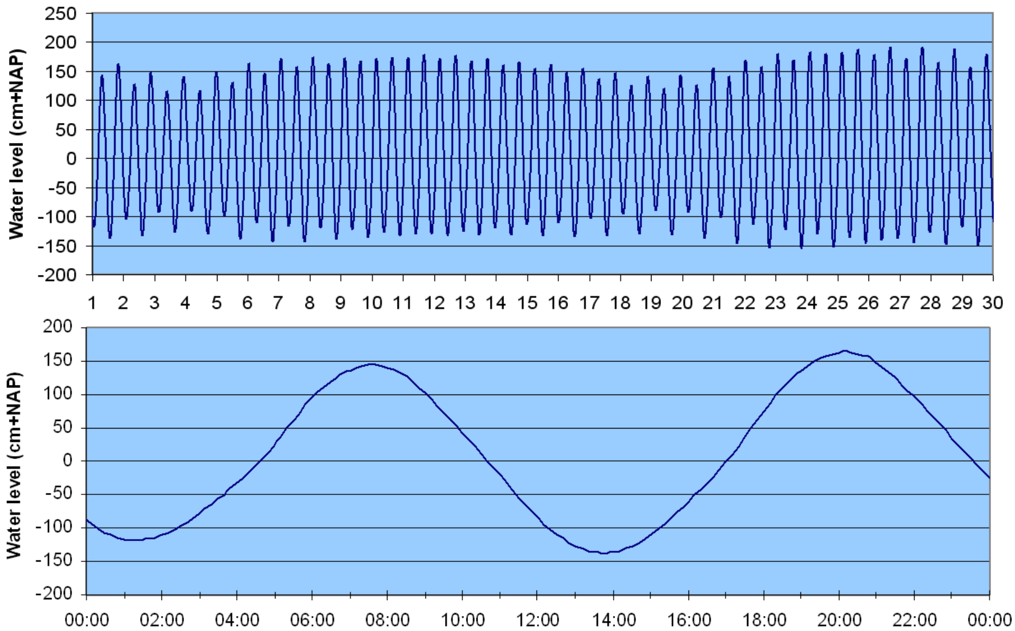
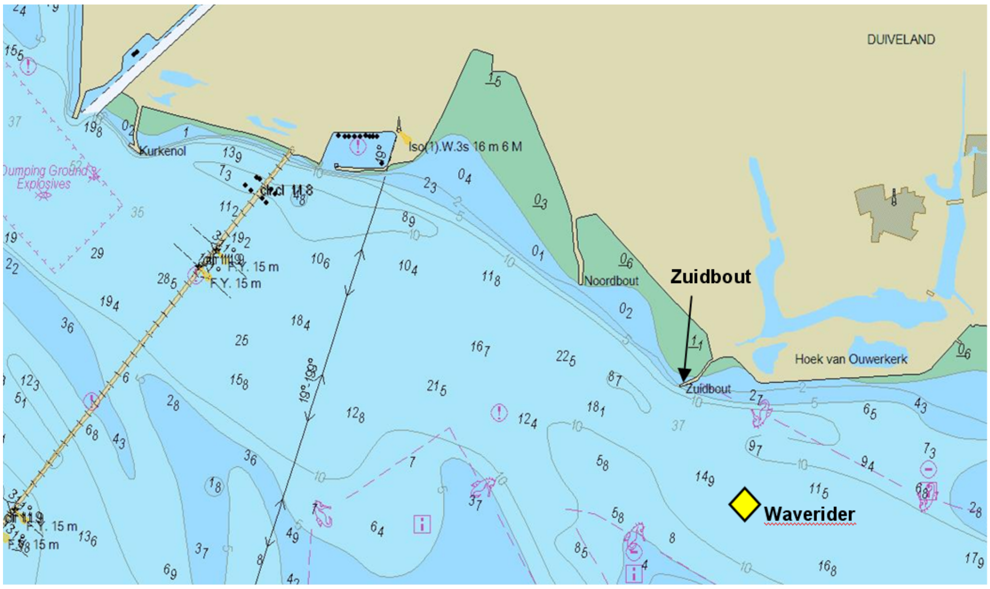


Figure 2.2
Predicted astronomical tide at Stavenisse for the month of November 2007 (above) and the predicted tide on November 1st 2007 (below)[3].

The bathymetry of the direct vicinity of the Zuidbout is shown in figure 2.3. The water depth at a distance of 300 m from the Zuidbout is about 10-20 m relative to NAP. 100 m from the Zuidbout the depth diminishes from 10 m to 2 m at the toe of the dike. Then, over a distance of 100 m along the length of the dike water depth runs from 2 m to 0 m.

Figure 2.3
Bathymetry in the vicinity of the Zuidbout[4].



2.2 ELASTOCOAST STRUCTURE

2.2.1 DESIGN

The Zuidbout dike consists of several types of revetment placed on a clay core. The crest height is 2.50 m to 2.95 m above NAP. The slope on the North-West side is 1:3 to 1:4. Parts of the dike are covered with placed stone linings of Vilvoordse rock[5] sometimes covered with concrete, other parts with granite blocks. Scattered across the dike small areas of basalt, Doornikse rock and Lessinese rock. The top of the dike is covered with concrete Stelcon® plates for accessibility. The great variety of revetment types is a result of a turbulent history of repairs. At approximately NAP-1.00 m to NAP+0.50 m the dike toe is protected by a dumped rock apron.

The layers of Elastocoast are placed on the North-West slope directly on top of the existing revetment, which is partially a Vilvoordse and partially a granite lining. Starting at NAP+0.50 m to NAP+1.50 m the Elastocoast is placed in three stretches, respectively with a layer thickness of 10 cm, 20 cm and 30 cm, each with a length of 40 m and a width of approximately 2.5 m. This results in a total construction volume of 90 m^3. The used Elastocoast system consists of limestone with a 20-40 mm grading and a stone to PU volume ratio prescribed at 2.8 %. Two cross sections are given in figure 2.4

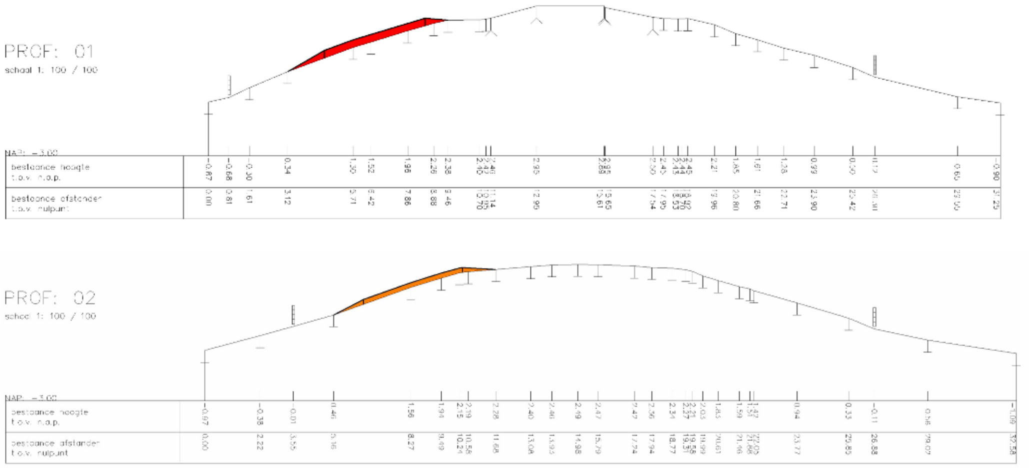


Figure 2.4
Cross sections of the dike at the 30 cm and 20 cm stretch.

2.2.2 CONSTRUCTION

The construction of the pilot location Zuidbout was performed in the following steps:

1) 11 kg of component A (polyol-component, a mixture of polyol and additives) is mixed to a homogeneous substance in approximately 1 minute.
2) 5.5 kg of component B (a preparation containing diphenylmethane-diisocyanate, IsoPMD92140) is added and the two components are mixed for approximately 2 minutes.
3) The mixture is added to 0.5 m^3 of limestone while tumbling.
4) After tumbling for approximately 3 minutes the unhardened Elastocoast is dumped on the application area.
5) Within 20 minutes the Elastocoast is smoothened to profile height with help of a hydraulic crane and hand-rake.
6) Shortly after the profiling dry sand is scattered over the hardening Elastocoast by hand to create a rough surface.
7) The Elastocoast system hardens in several hours. It can be loaded after 24 hours and is almost fully cured (90%) after 2-3 days.

The construction of the Zuidbout pilot took place in the period of September 11th to 20th (2 weeks). Weather conditions started out mostly favourable, with pleasant temperatures and a breeze. On two days in the second week work was cancelled due to rain. The aggregate was then covered with a plastic sheath, which was very effective at first. A too high humidity of the aggregate became a problem at the time of daybreak. Cold nights and humid weather resulted in formation of morning dew under the plastic sheaths. Then, lack of sun and wind made it very difficult to dry the moist aggregate before it was suitable for application in the Elastocoast. With a slight delay the work was finished on September 20th.

The actual areas that were covered with Elastocoast are given in figure 2.5 and table 2.1. At the Zuidbout, a quantity of 165 tons of limestone were used, resulting in a final actual mixing ratio of 2.2 % (table 2.2).

An area of 12 m^2 of the 30 cm stretch is covered with clean Vilvoordse rock, which are placed on top of and slightly pressed into the Elastocoast. These stones are not coated by Elastocoast and serve as an experiment to compare ecological development.

Figure 2.5
Plan view of Zuidbout, with stretches of Elastocoast of 10 cm, 20 cm, 30 cm and 10 cm (from left to right). In the 30 cm stretch 12 m^2 is covered with Vilvoordse rock.

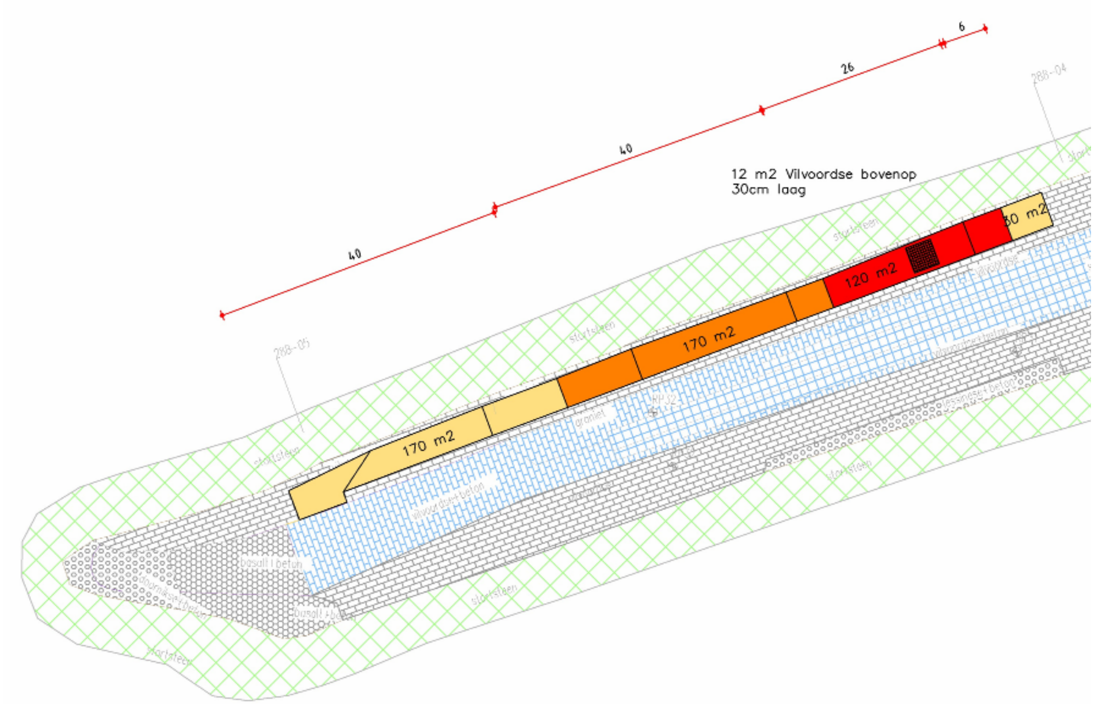


Table 2.1
Actual areas and volumes of Elastocoast constructed for the Zuidbout pilot test.

Stretch	Length	Surface Area	Total surface area	Total volume of limestone used	Average achieved layer thickness
1	40 m	170 m^2	480 m^2	118 m^3	0.246 m
2	40 m	170 m^2			
3*	26 m	120 m^2			
-	6 m	20 m^2			

* an area of 12m^2 of the 30cm stretch is covered with clean Vilvoordse rock.

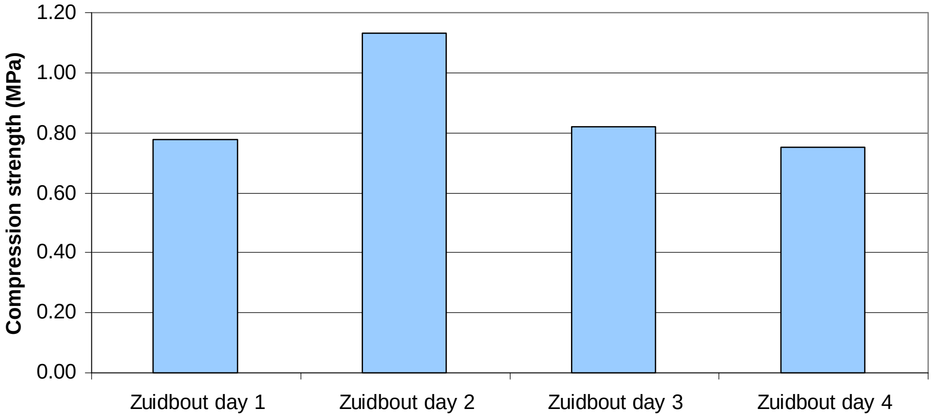
Table 2.2
Actual mixing ratios Elastocoast used for the Zuidbout pilot test.

	Bulk specific weight (kg/m^3)	Quantity (kg)	Quantity (m^3)	Mass percentage Elastocoast	Volume percentage Elastocoast
Limestone 20-40 mm	1,400	165,000	118	2.2 %	2.8 %
Elastocoast 6551/100	1,110	3,630	3.27		

2.3 QUALITY MONITORING DURING CONSTRUCTION

During construction several cube samples were taken by Elastogran for the purpose of quality monitoring. On 4 days, 150x150x150 mm cubes of Elastocoast were produced on site and tested in a laboratory for compressive strength. The results of these tests are shown in figure 2.6. Each value is averaged from five cube samples taken at the same day.

Figure 2.6
Results from compression strength tests on samples taken from the Zuidbout pilot.



Five months after construction, core samples were taken at the Zuidbout to verify the structural integrity over the layer thickness. The Elastocoast structure was very well capable of withstanding the mechanical forces of the drilling process and produced cylindrical samples that were completely intact from top to bottom.

Figure 2.7
Core drilling process (left) and the resulting cylindrical sample of Elastocoast.

2.4 AVAILABILITY OF HYDRAULIC DATA

Data is retrieved from the online database of the Hydro Meteo Centrum Zeeland (HMCZ). Water levels and wind data are measured at the city of Stavenisse and wave data are measured at a nearby buoy (see table 2.3 and figure 2.8).

Table 2.3
Used wind and water data sources.

Data	Source	Location	Interval	Measured parameters
Actual water levels	STAV WTr2	Stavenisse	10 min.	water level
Wind data	STAV WNr2	Stavenisse	10 min.	average wind speed wind gusts wind direction
Wave data	KEET GHr2 (Waverider)	51°36'27.91" N 3°57'59.01" E	30 min.	wave heights wave periods wave number wave spectrum

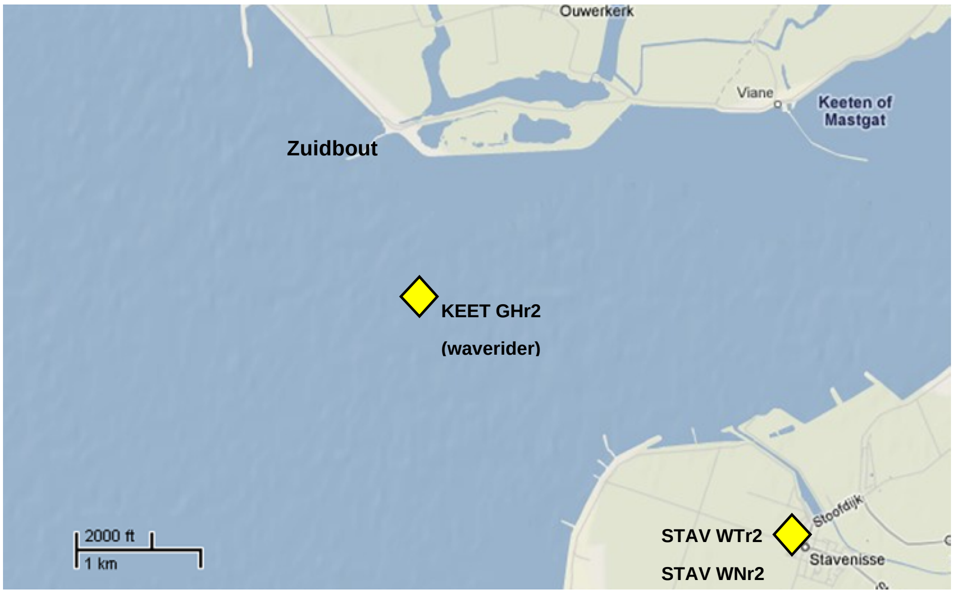
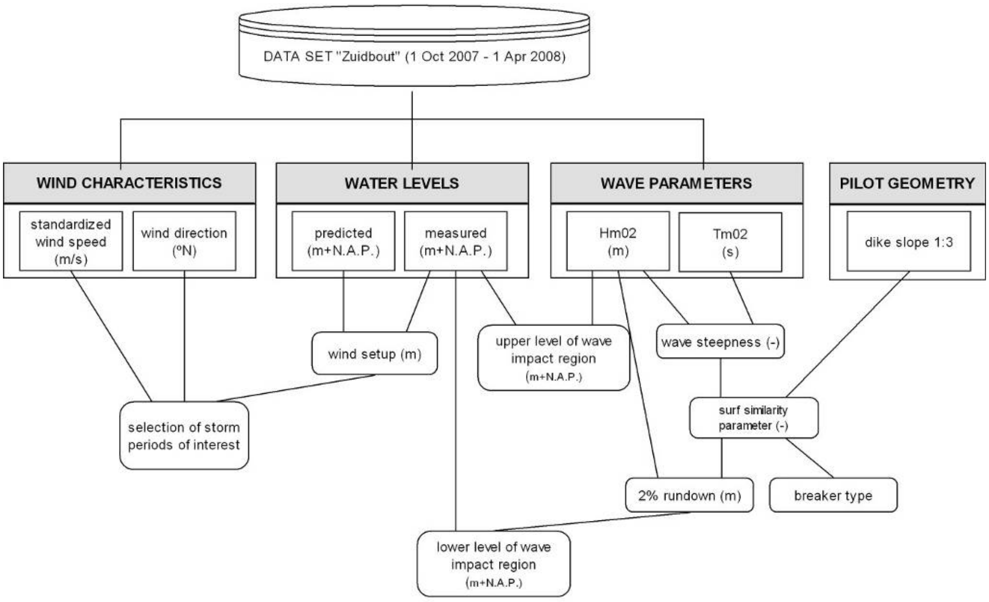


Figure 2.8
Locations of data sources.

Above figure shows that the instruments for the registration of wind, water levels and wave conditions are located some distance away from the pilot location Zuidbout. The conditions at the pilot location may deviate from the measured conditions, due to local effects between the observation point and the pilot location. Therefore analysis of these effects is necessary to establish the conditions at the pilot location.

For analysis of the storm season 2007 / 2008 data was retrieved from the period of October 1st, 2007 to April 1st, 2008. Figure 2.9 shows which parameters were selected from the available data to be used for the analysis. A combination of wind and water level data is used to determine which periods are representative and interesting for analysis. Then a combination of water level and wave data is used to determine the type of loads that the Elastocoast structure has been exposed to during those periods.

Figure 2.9
Scheme of data analysis for Zuidbout pilot.



2.5 DATA ANALYSIS OF STORMS AT THE ZUIDBOUT

2.5.1 STORM SEASON 2007/2008

The Dutch storm season
The Dutch storm season runs from October to April. This is the period of the year in which storms often occur. During the storm season no regular dike maintenance activities are planned, since the risk would be too high that a dike which is being worked on is damaged during a storm.

Wind setup by storms over the North Sea can cause elevation of water levels along the Dutch coast. When extreme water levels are predicted to occur along the Dutch coast, the storm surge warning system of the Dutch government can issue warnings or even alarms for different sectors of the coast. If needed, storm surge barriers are closed to prevent high water levels from reaching inland regions.

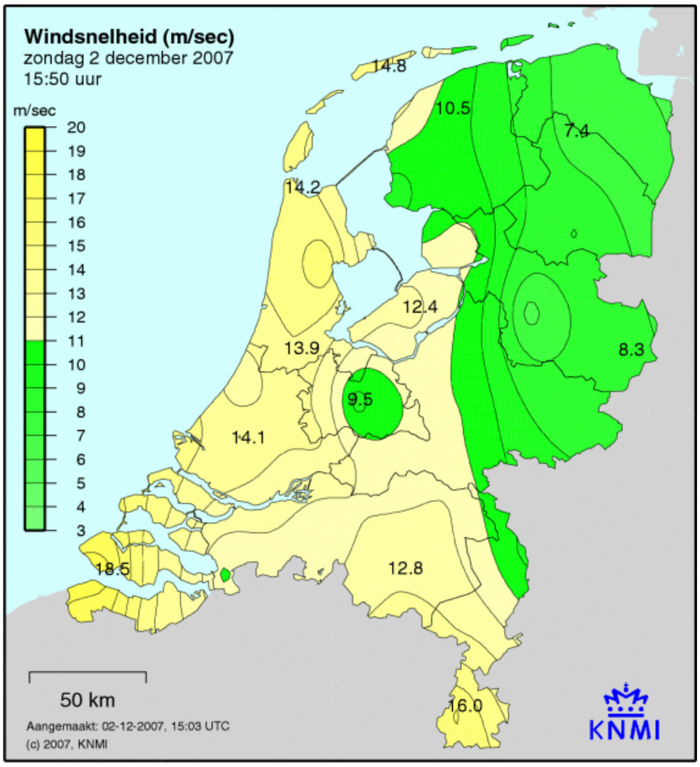
Definition of a storm
A storm is defined as an atmospheric disturbance, manifested in strong winds often accompanied by rain, snow, or other precipitation. A classification of wind speeds is given in the scale of Beaufort. In The Netherlands a storm is officially defined by sustained wind speeds of at least 9 Bft.

Table 2.4
Beaufort windscale[6]

Beaufort scale (Bft)	Wind speed at 10 m height above terrain (m/s)	Name
0	0-0.2	Calm
1	0.3-1.5	Light air
2	1.6-3.3	Light breeze
3	3.4-5.4	Gentle breeze
4	5.5-7.9	Moderate breeze
5	8.0-10.7	Fresh breeze
6	10.8-13.8	Strong breeze
7	13.9-17.1	Near gale
8	17.2-20.7	Gale
9	20.8-24.4	Strong gale
10	24.5-28.4	Storm
11	28.5-32.6	Violent storm
12	> 32.6	Hurricane

Obstructions and friction over land reduces the wind speed. Therefore, wind fields show spatial variability. However, the spatial scale of the variations in storms is such that no deviations between the measuring point and the location of the pilot are expected, provided that the measuring point is not too far away from the pilot location, say 10 km (see also figure 2.10).

Figure 2.10
Wind field on December 2nd, 2007[6]



A gale, i.e. wind speeds of 8 Bft, can already cause significant wave action. Knowledge of the behaviour of the Elastocoast structure under wave attack is of great importance for evaluation of its performance. Therefore a local wind speed of 17.2 m / s (8 Bft) is chosen as a threshold value for the definition of storms in this report.

Storms in the season of 2007-2008

In the period from October 2007 to April 2008 several storms occurred. To determine which of these storms are interesting for analysis, first a selection is made of the storms which had 10-minute average wind speeds of at least 17.2 m / s (8 Bft). The following graph shows wind speeds measured at the city of Stavenisse with the selected storm periods indicated with circles.

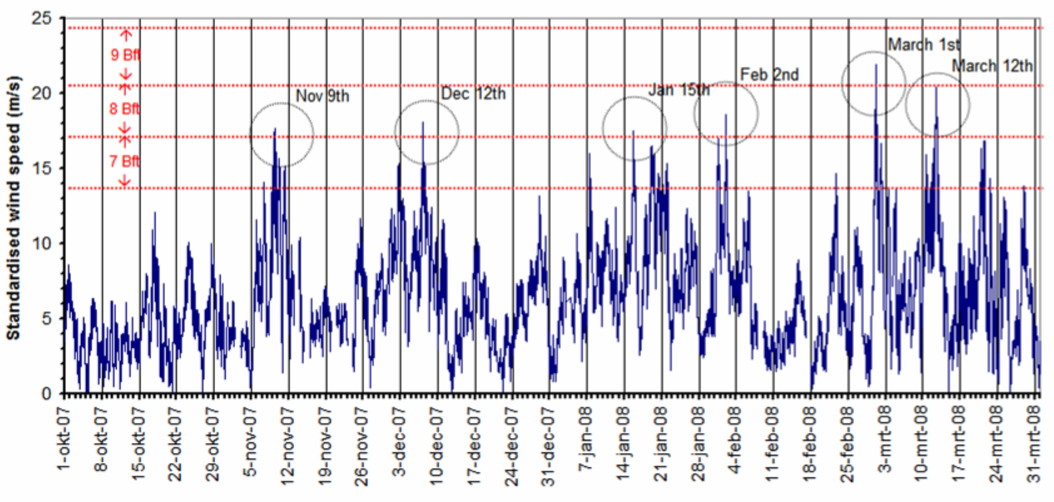


Figure 2.11
Wind measurements at Stavenisse; 10-minute average wind speeds at 10 m above surface.

This graph shows six individual periods in which wind speeds were higher than 8 Bft. For these periods the detailed analysis of measurements is given in Appendix III. The storms that caused most extreme conditions at the pilot location are further analysed in the next section.

During the storm of November 9th, the wind from the North West caused extreme water levels along the whole Dutch coast[7]. The storm surge warning system of the Dutch government issued high water warnings for every sector of the Dutch coast for the first time since 1976. To prevent high water levels from entering the Eastern Scheldt, the storm surge barrier was closed between 9 November 2007, 00:00 and 9 November 2007, 09:00[8].

2.5.2 HYDRAULIC EFFECTS AT THE STRUCTURE

The instruments for the registration of wind, water levels and wave conditions are located some distance away from the pilot location. The conditions at the pilot location may deviate from the measured conditions, due to local effects between the observation point and the pilot location. In this section, an analysis is made of these effects to establish the conditions at the pilot location.

Wind

Wind fields show spatial variability. However, the spatial scale of the variations in storms is such that no deviations between the station Stavenisse and the pilot location are to be expected[9].

Water levels

In an open basin, water level deviations between two points may occur due to:

- The presence of narrow channels, causing high flow resistance
- A funnel-shaped coastline near one of the two points

§ Long distance between the two points

The first two possible causes are not relevant here. The distance between Stavenisse and the pilot location is such that deviations, if present, are expected to be limited. Assuming the water level at the pilot location equal to the water level at Stavenisse appears to be reasonable.

Wave conditions

Wind waves are influenced by the following factors:

§ Wind speed and wind direction
§ Local water depth
§ Currents

Wind is the driving force of wind waves. The longer the distance over which the wind blows over the water surface, the higher the waves will be. If a location is a considerable distance down wind from the observation point, waves may therefore be higher than observed. On the other hand, if the location is down wind from a coast line, the wave heights will be limited since the distance is too short for wave growth.

The local water depth affects the waves in two ways:

§ If the wave height is too high for the local water depths, the waves will break and thus lose height
§ The bathymetry (sand ridges, channels) may alter the direction of wave progression. In the process, the wave height may change (bottom shapes can function as a “lens”, focusing or spreading wave energy)

Although the physical background is slightly different, currents affect waves in the same way as the local water depth.

Variation in wave conditions during storms at the pilot location will primarily depend on wind speed and direction. Currents and bathymetry will remain approximately the same for separate storms and will thus not cause much variation in the wave conditions.

Storm characteristics

The position of the Zuidbout in the Eastern-Scheldt estuary is such that it is expected that most extreme wave conditions will occur with a wind blowing from the West. From this direction the distance over which the wind blows over the water surface before reaching the pilot location is longest. This is illustrated in figure 2.12.

Besides, the Elastocoast structure is located on the North West face of the dike. This means that there is only indirect attack from waves travelling in a direction with an angle less than 250°N. The Elastocoast structure would then be on the lee-side of the dike, and is only attacked by waves that refract around the tip of the dike and consequently having a smaller wave height. This is illustrated in figure 2.13. The wave attack from the south is limited due to the presence of a shallow area.

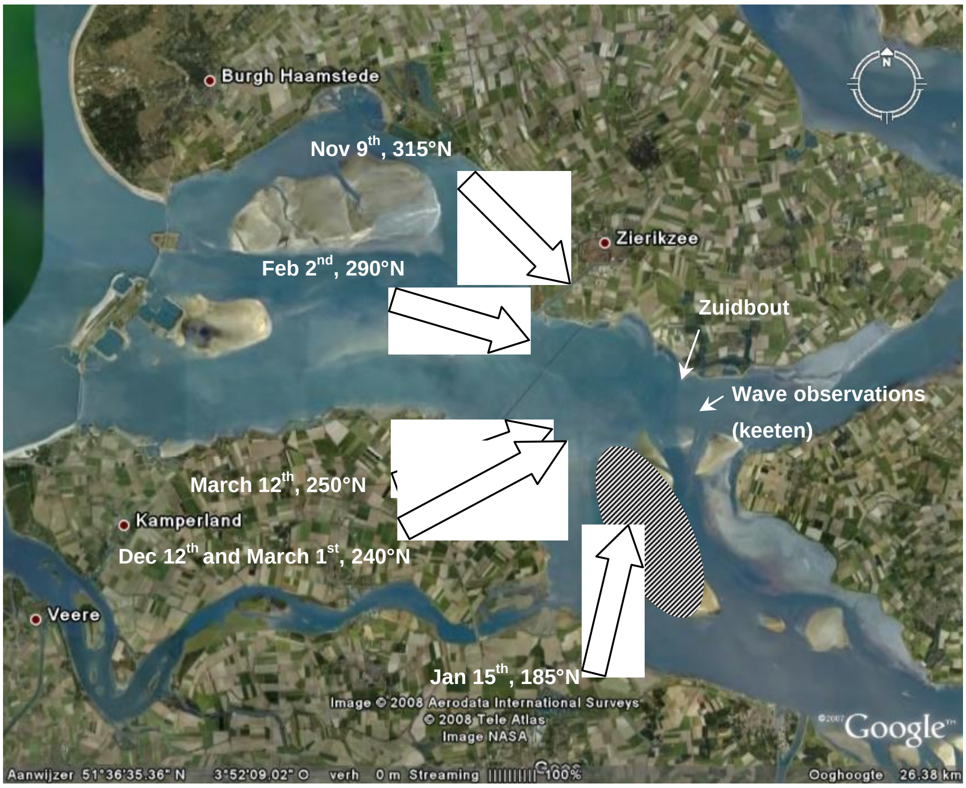


Figure 2.12
Eastern-Scheldt with wind direction of storms in the season of 2007/2008 and locations of the pilot and wave observations.

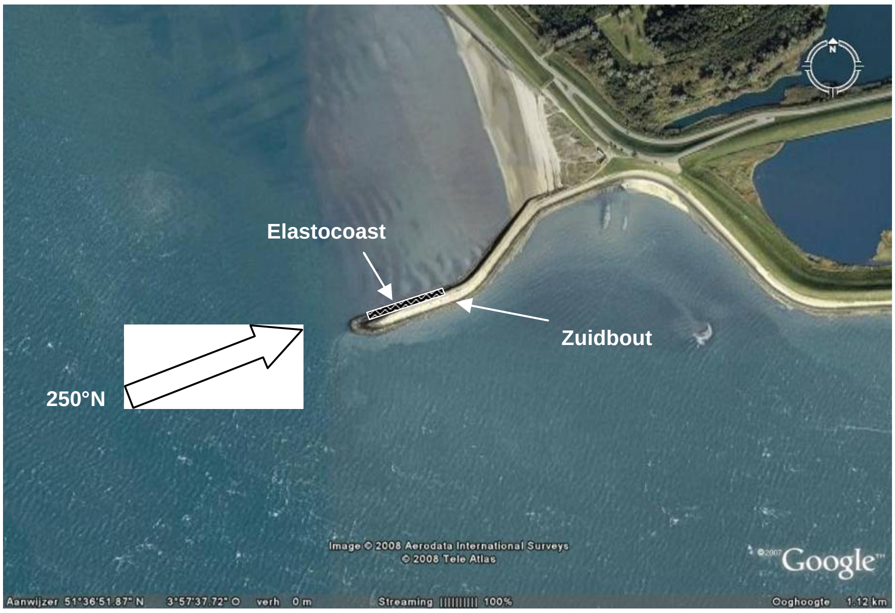


Figure 2.13
Orientation of the Elastocoast structure on the Zuidbout. Wind blowing from a direction with an angle smaller than 250°N only causes indirect wave loading on the structure.

The pilot location is slightly sheltered by the protruding coast line to the North West. However, the distance to this possible shelter is such that waves are expected to bend around the coast line and attack the pilot location. The sheltering is therefore expected to be limited. Concluding, the waves at the pilot location during storms with winds blowing from the West are expected to be similar to the waves at the observation point.

Additional support for this assumption is found in calculations made with the numerical wave forecasting model SWAN. Calculations have been made for different water levels and different wind directions[10]. From these results, a maximum difference in wave height between the two points of 0.05-0.10 m is found (wind direction 240-300°N), with the wave

height at the pilot location lower than the wave height at the observation point. This is in line with the conclusion based on engineering judgment.
Thus, for storms with winds blowing from the West, the wave conditions at the Zuidbout are considered to be equal to the measured conditions at the Keeten observation point.

The storm characteristics are summarized in table 2.5. Comparison of this table to figure 2.12 confirms that the combination of a high wind speed blowing from a direction close to the West (250-290°N) result in the most extreme wave conditions at the Zuidbout.

The two storms with the highest wave load are given in yellow in table 2.5. These two storms are elaborated in 2.5.3. An overview of the data of all storms is given in Appendix III.

Table 2.5

Characteristics per storm.

Storm date	Peak wind speed (m/s)	Wind direction (°N)	Water level extremities (m+N.A.P.)	Significant wave height (m)	Peak period (s)
November 9th, 2007	18	315	0.5 – 2,8	1.2	5.5
December 7th, 2007	18	240	-0.7 – 2.5	1.2	5.0
January 15th, 2008	17	195	-1.7 – 1.5	0.8	3.0
February 2nd, 2008	19	290	-0.2 – 1.9	1.4	4.5
March 1st, 2008	22	240	-0.7 – 2.8	1.3	4.5
March 12th, 2008	21	250	-0.7 – 2.5	1.4	5.5

2.5.3 LOADING OF THE ELASTOCOAST STRUCTURE

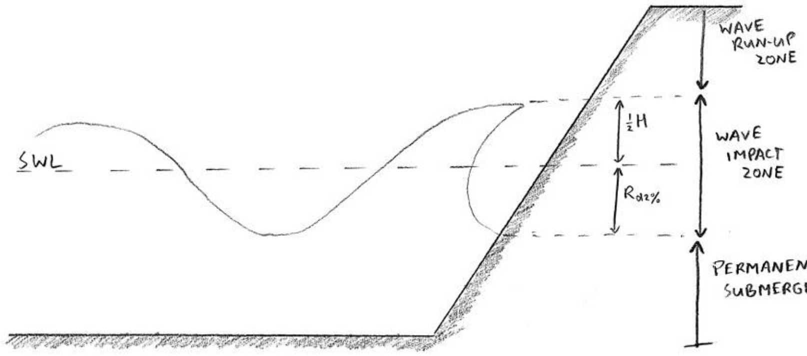
Loading of slopes under wave attack

In general, on the sea ward face of a sloping coastal structure, three zones can be defined with different load cases:

- Permanently submerged, loaded by pressure variations caused by waves
- Around still water level: wave impact zone, loading by breaking waves (impact loads) and uplift pressures

§ Higher than half the wave height above still water level: run-up zone, loading by high current velocities caused by wave run-up

Figure 2.14
Three zones with different load cases can be defined on a slope.

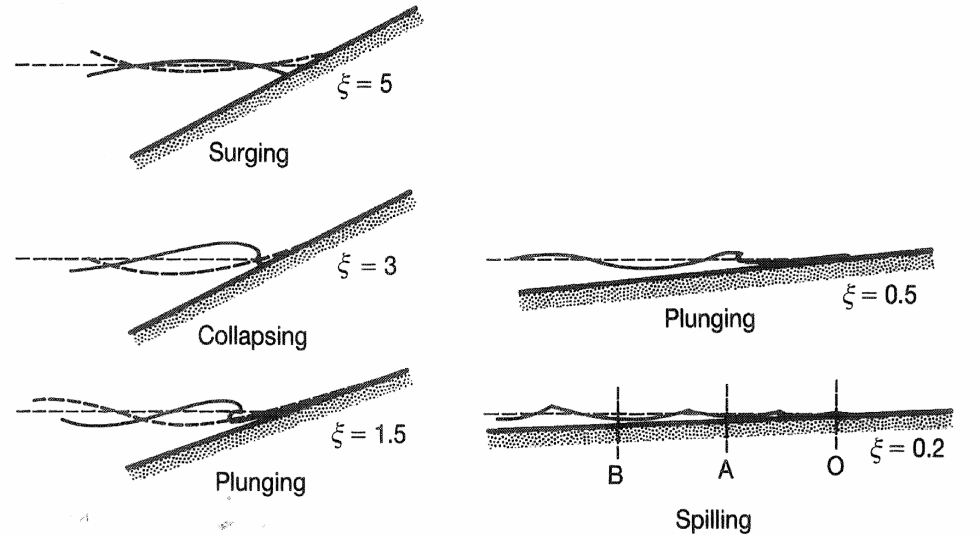


As long as the structure is permanently submerged, loading of the structure is limited. For the performance of the structure, this zone is of little interest.

In the impact zone the most unfavourable loads on the revetment occur. Impact loads due to waves breaking on the structure and uplifting of the structure due to retreat of the wave in the wave trough occur in this zone. This causes stresses in the layer which, in case of insufficient strength of the layer, causes the layer to crack and fail. In addition, individual stones may be washed from the top layer.

In the impact zone, for the same wave height, the severity of the loads depends on the type of wave breaking at the structure. Battjes[11] devised a method to establish the breaker type, based on the so-called "Iribarren-parameter" •. The most severe loading occurs in plunging and collapsing waves, where "hammer shock" type loading may occur.

Figure 2.15
Values for the Irribarren parameter for different breaker types[11].



In the run-up zone, high current velocities may cause individual stones to be washed away from the top layer by water up rush and down rush.

Two storms with the highest wave loads are elaborated in this paragraph. An overview of all storm data is given in Appendix III.

Loading of the Elastocoast structure during the storm of Feb 2nd, 2008

The following graph shows the wind conditions as measured at Stavenisse in the period in which the storm occurred.

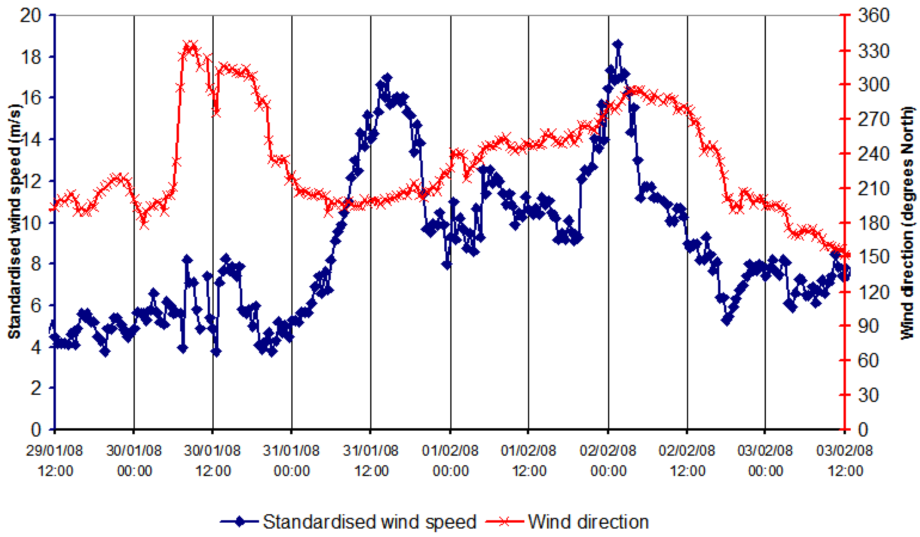


Figure 2.16
Wind speed and direction during the storm of February 2nd, 2008.

Disregarding the somewhat erratic behaviour of the observations, wind speed peaked around 16 m/s with a sustained direction around 290°N.

As stated in chapter 2, the Eastern-Scheldt estuary normally shows varying water levels as a result of the tide. The wind field caused an additional increase of the water level. The tide can be forecasted for a long period ahead. The difference between forecasted tide and actual water level is called wind setup. The following graph shows the water levels and forecasted tides at Stavenisse during the storm. The effect of the wind on the water levels is clearly visible.

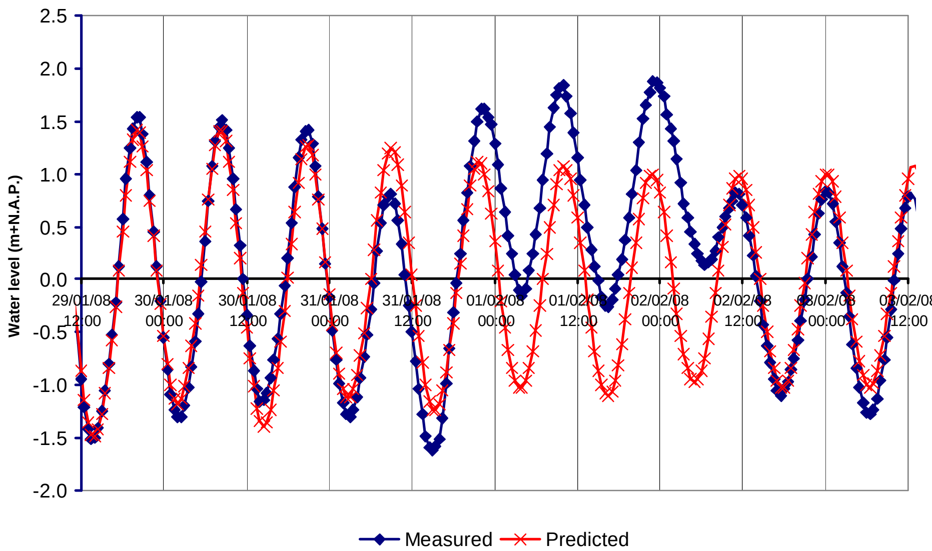
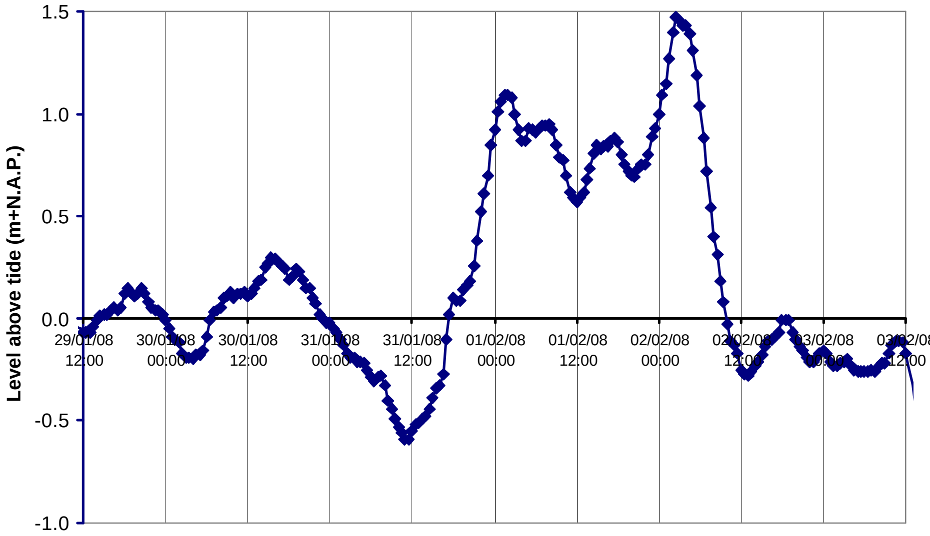


Figure 2.17
Predicted and actually observed water levels at Stavenisse.

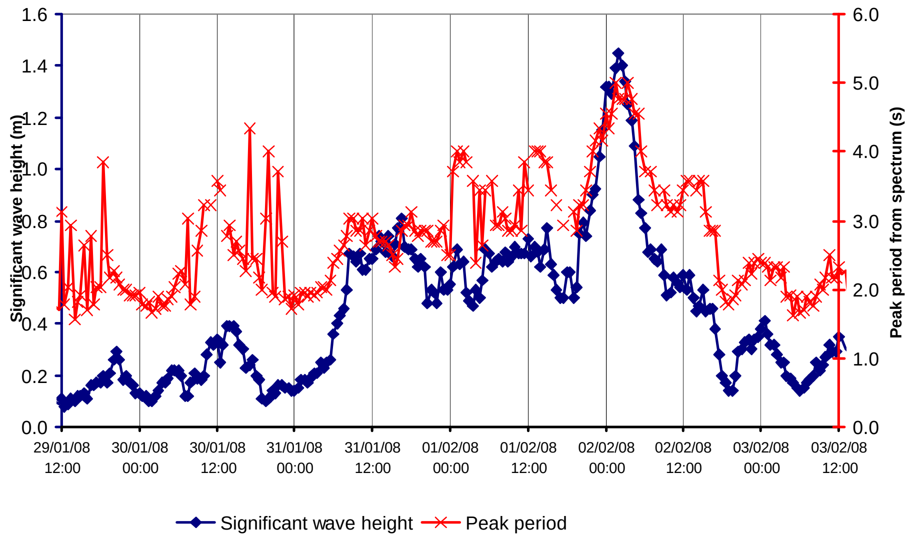
The following graph shows the wind setup, calculated as the difference between forecasted (tidal) water level and actually observed water level.

Figure 2.18
Wind setup.



The wave conditions in the Eastern-Scheldt, measured at the location Keeten are shown below.

Figure 2.19
Significant wave height and peak period.

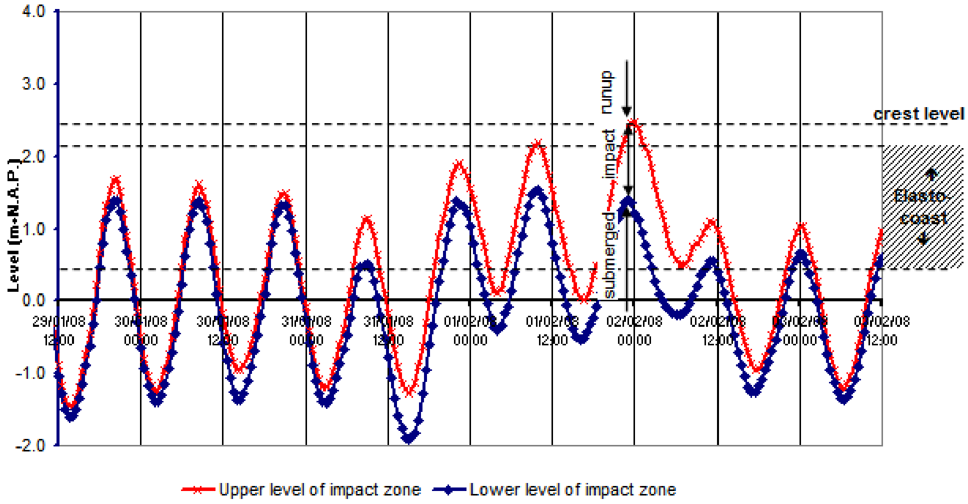


The significant wave height at Keeten peaked around 1.4 m. At the same time the peak period peaked around 4.5 s.

For the Zuidbout Elastocoast structure properties that determine the type of loading are:
- Slope: 1:3 to 1:4
- Range: NAP+0.5 m to NAP +2.2 m

The following graph shows the upper and lower level of the wave impact zone in comparison to the level of the Elastocoast structure.

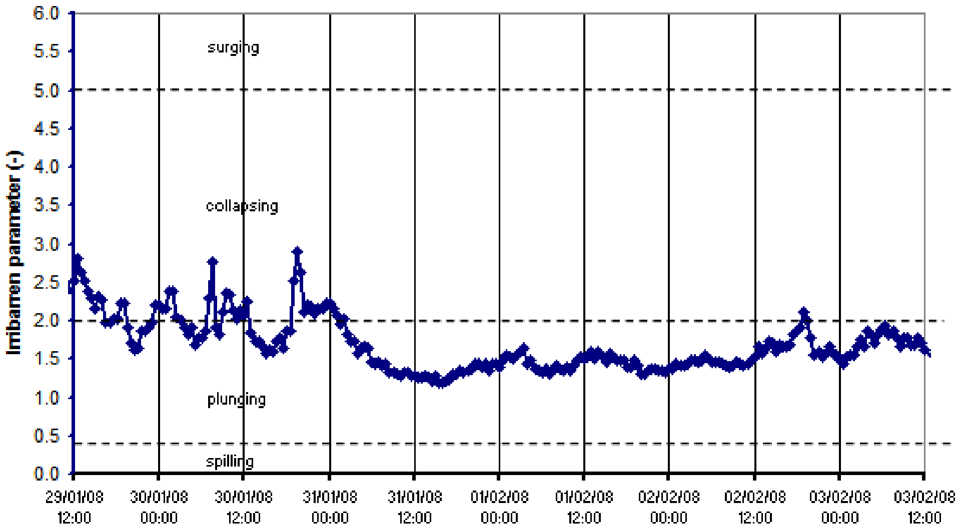
Figure 2.20
Position of upper and lower level of the impact zone.



The graph shows that the Elastocoast structure has suffered from all load cases during the storm. Comparison to the observed wave conditions shows that a persistent heavy wave attack was present from February 1st 23:00 PM to February 2nd 05:00 AM. Therefore, all load cases have occurred in combination with heavy wave attack.

The graph below shows the Irribarren-parameter at the Zuidbout during the storm and the corresponding breaker type. During the storm, the Elastocoast layer was persistently subjected to breaking waves in the plunging regime.

Figure 2.21
Breaker types that occurred at the Zuidbout during the storm of February 2nd.



Loading of the Elastocoast structure during the storm of March 12th, 2008

The following graph shows the wind conditions as measured at Stavenisse in the period in which the storm occurred.

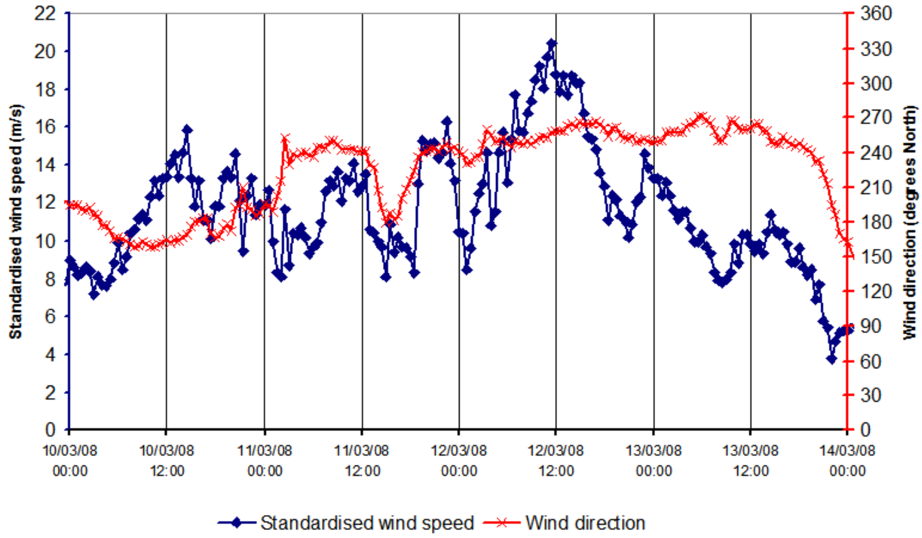


Figure 2.22
Wind speed and direction during the storm of March 12th, 2008.

Disregarding the somewhat erratic behaviour of the observations, wind speed peaked around 18 m/s with a sustained direction around 250°N.

The following graph shows the water levels and forecasted tides at Stavenisse during the storm. The effect of the wind on the water levels is clearly visible.

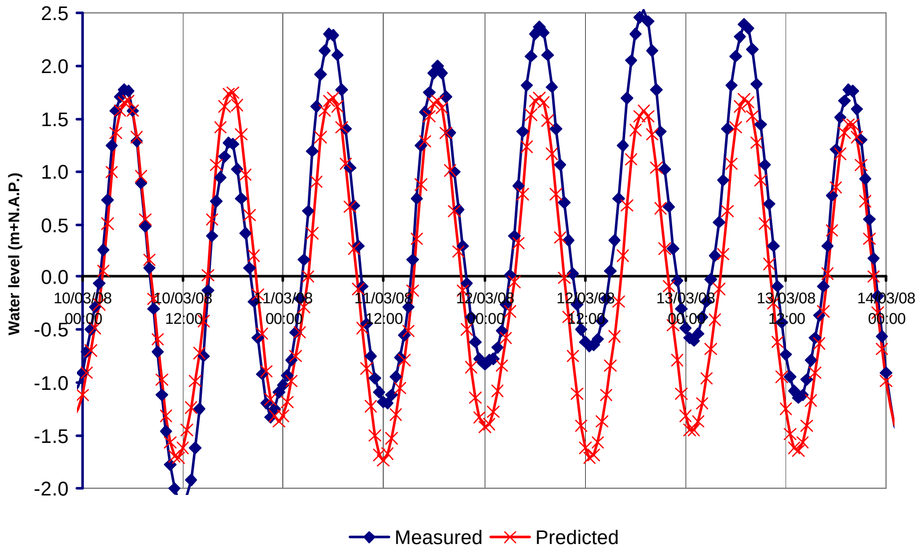


Figure 2.23
Predicted and actually observed water levels at Stavenisse.

The following graph shows the wind setup, calculated as the difference between forecasted (tidal) water level and actually observed water level.

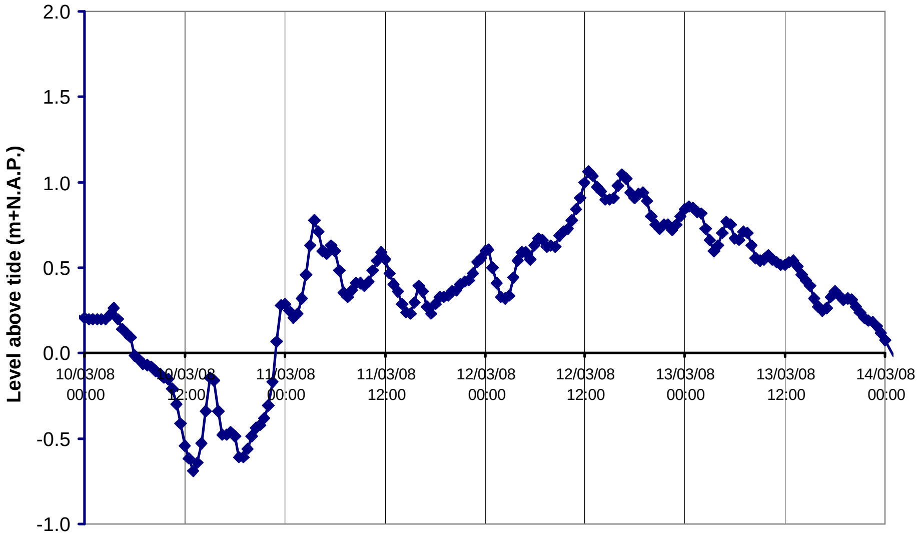


Figure 2.24
Wind setup.

The wave conditions in the Eastern-Scheldt, measured at the location Keeten are shown below.

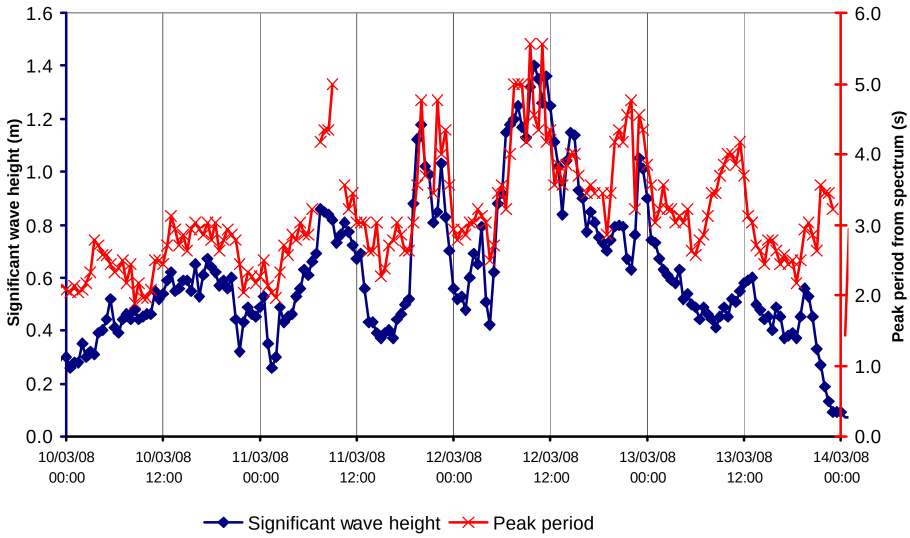
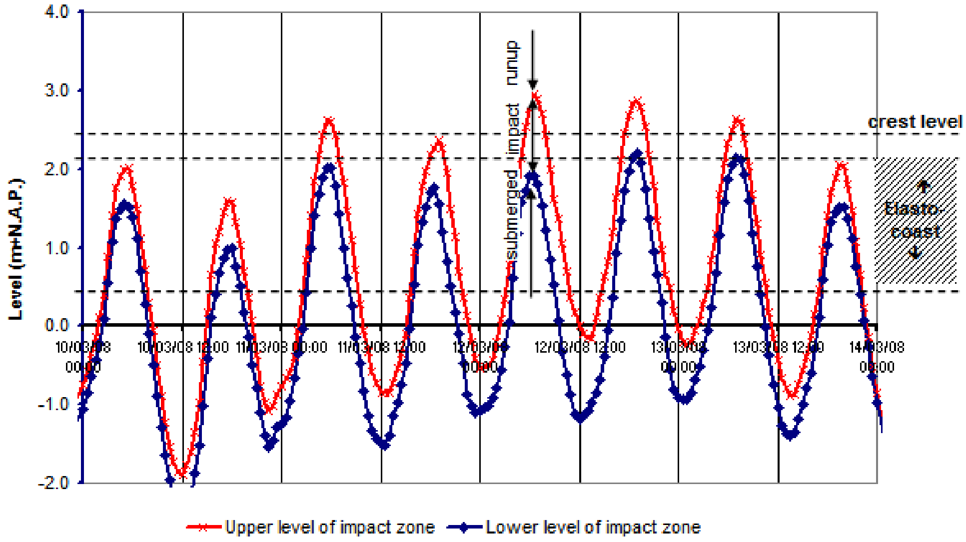


Figure 2.25
Significant wave height and peak period.

The significant wave height at Keeten peaked around 1.4 m. At the same time the peak period peaked around 5.5 s.

The following graph shows the upper and lower level of the wave impact zone in comparison to the level of the Elastocoast structure.

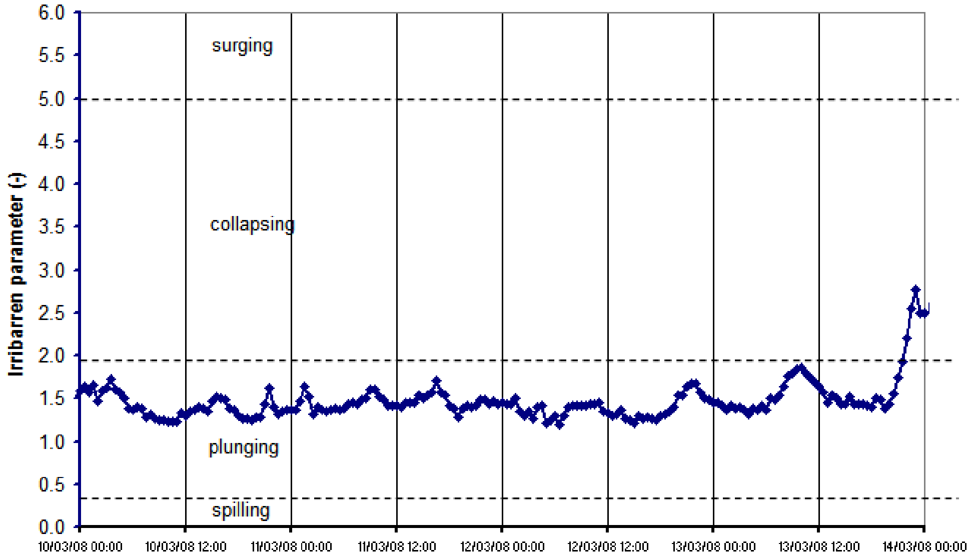
Figure 2.26
Position of upper and lower level of the wave impact zone.



The graph shows that the Elastocoast structure has suffered mostly from the impact and submerged load cases during the storm. Comparison to the observed wave conditions shows that a persistent heavy wave attack was present on March 12th from 6:00 AM to 15:00 PM. Due to the high water level, loading by wave run-up took place above the Elastocoast structure.

The graph below shows the Irribarren-parameter at the Zuidbout during the storm and the corresponding breaker type. During the storm, the Elastocoast layer was persistently subjected to breaking waves in the plunging regime.

Figure 2.27
Breaker types that occurred at the Zuidbout during the storm of March 12th.



2.6 CONCLUSION

In the storm season of 2007 / 2008 six periods were observed in which sustained wind speeds of above 17.2 m / s (8 Bft) were measured. From these periods, two storms with wind blowing from the West were the most extreme, namely the storm of February 2nd and that of

March 12th. During both storms a significant wave height of 1.4 m was measured and a peak wave period of around 5 s.

During the most extreme conditions, the Elastocoast revetment at the Zuidbout pilot was persistently subjected to high flow velocities and the most unfavourable form of wave loading on a dike slope; namely plunging and collapsing waves.

CHAPTER 3 Pilot location Petten

3.1 LOCATION AND BATHYMETRY

The Elastocoast pilot in Petten is constructed on the head of a beach groyne (no. 20.9) near the Pettemer Zeewering (fig 3.1). The structure lies outside of the sea-defense of Petten and is directly exposed to the tidal movement and wave action of the North Sea. The North Sea tide is semidiurnal, with one high and one low water every 12 hours. Average water level is NAP+0.10 m and the tidal variation ranges from approximately NAP-0.85 m to NAP+1.15 m. An example of the astronomical tide measured at Petten is shown in figure 3.2.

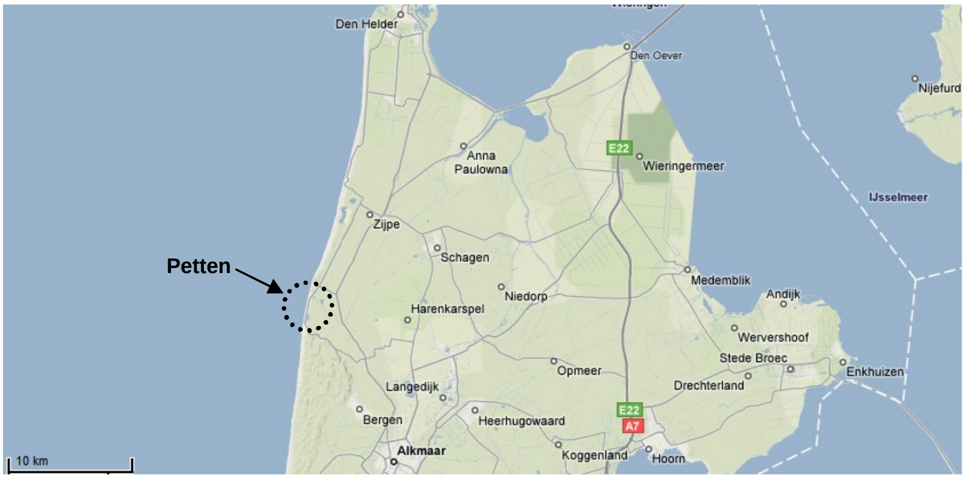


Figure 3.1
The Petten pilot is located on a beach groyne near the Pettemer Zeewering[2].

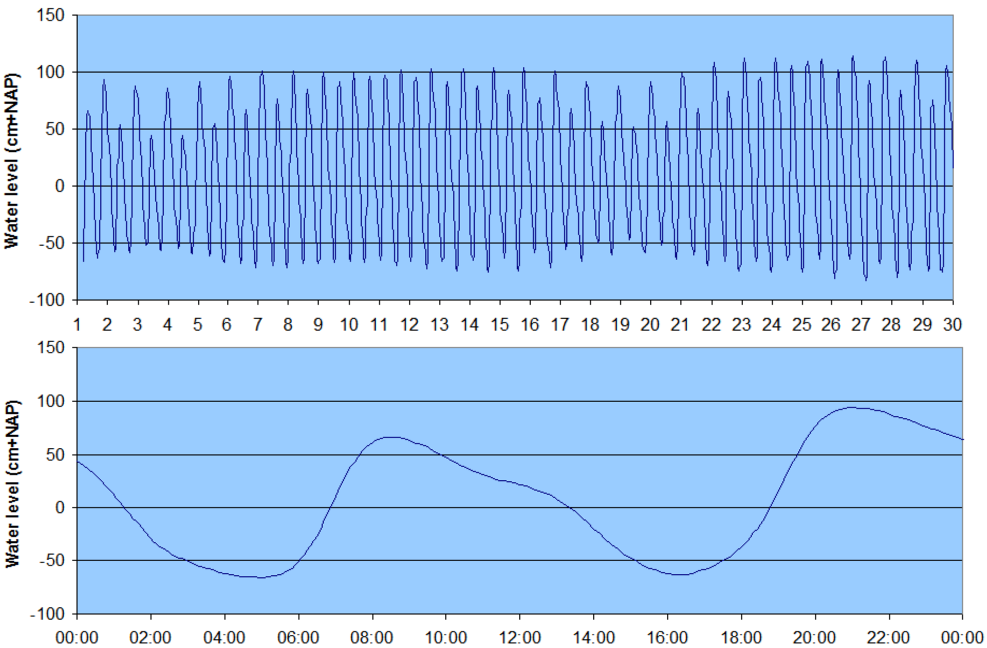
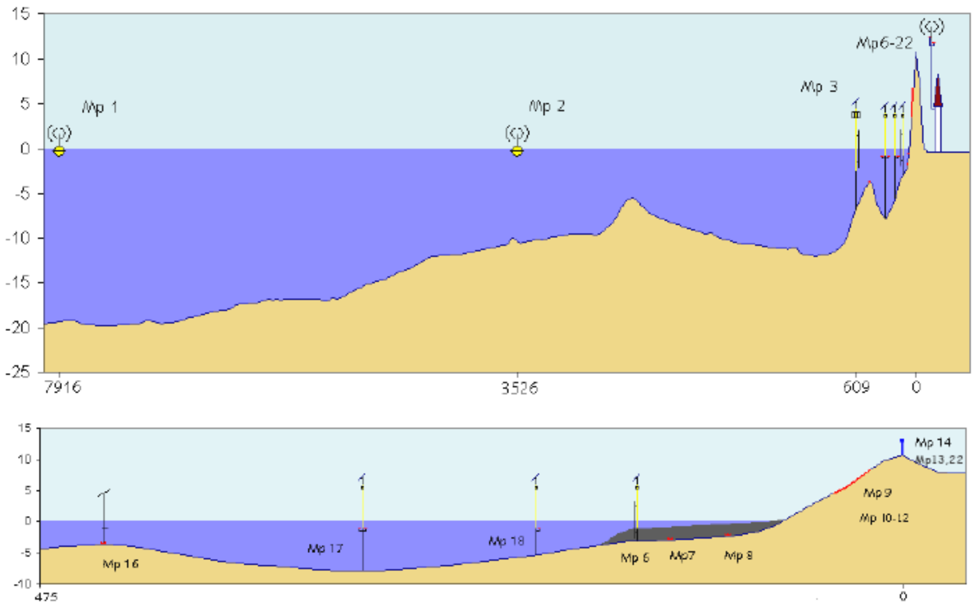


Figure 3.2
Predicted astronomical tide at Petten Zuid for the month of November 2007 (above) and the predicted tide on November 1st 2007 (below)[3].

The beach profile at Petten is constantly rearranging during the seasons under influence of sediment transporting currents resulting from wave action and tidal currents. Figures 3.3 and 3.4 give an indication of the bathymetry in the vicinity of the pilot location. In these figures also the measuring devices are shown, that Rijkswaterstaat uses to constantly monitor hydraulic conditions at Petten. This measuring equipment is situated close to the pilot location. In section 2.3 the use of the data from these devices is discussed.

Figure 3.3
Bathymetry in the vicinity of the Petten pilot[4].

Figure 3.4
Beach profile at the Petten pilot, heights and distances measured in meters[12].



3.2 ELASTOCOAST STRUCTURE

3.2.1 DESIGN

At Petten the Elastocoast structure is constructed directly on top of an existing beach groyne. This groyne extends approximately 100 m seawards from the beach and has a nearly horizontal crest, the top of which lies at about NAP-0.30 m.

The layers of Elastocoast are placed on the top part of the groyne, which has a cover layer of natural basalt columns. The Elastocoast is placed in six stretches, three of which are oriented parallel to the coastline and the other three perpendicular to the coastline. The layer thicknesses of the stretches are 10 cm, 20 cm and 30 cm. For this pilot test Elastocoast is used consisting of limestone aggregate with a 20-40 mm grading and a predefined stone to PU volume ratio of 2.8 %.

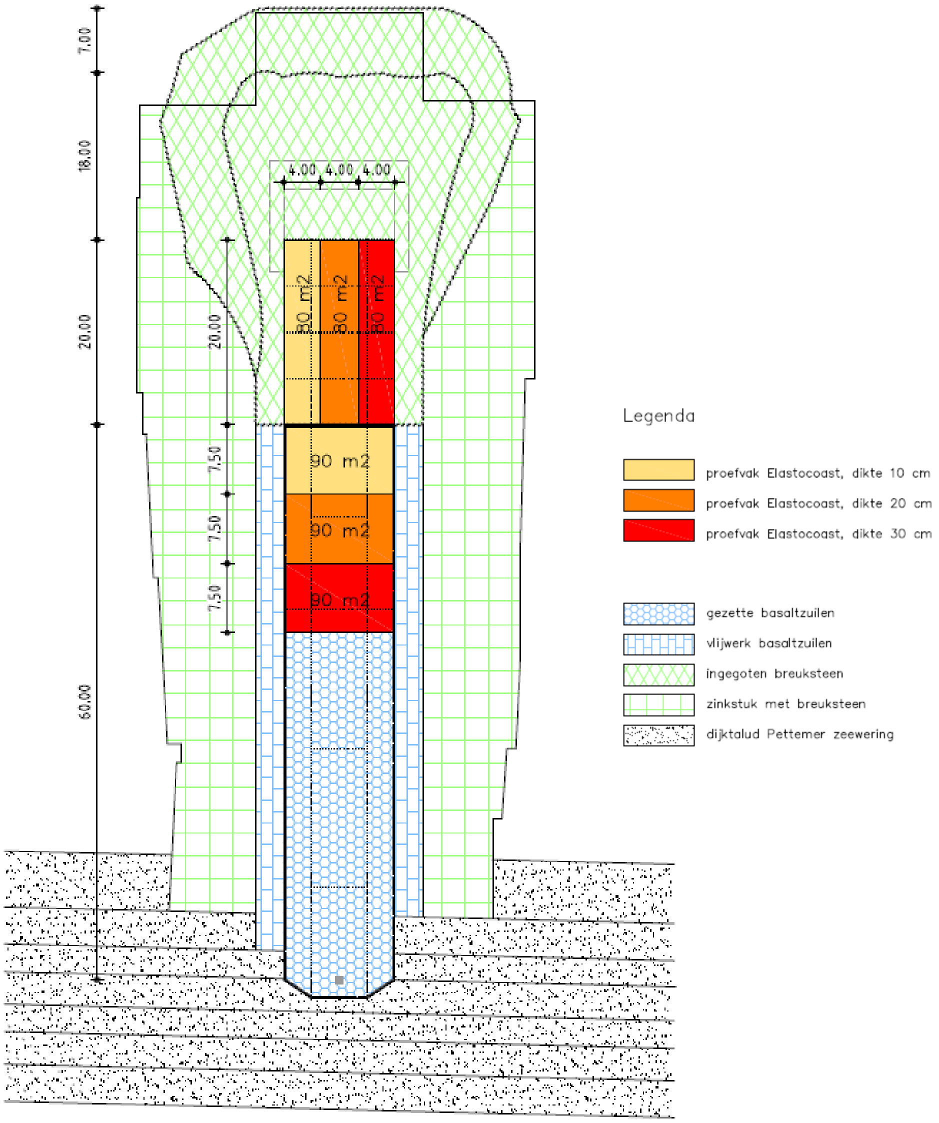


Figure 3.5
Plan view of the design of the Petten pilot, with stretches of Elastocoast of 10 cm, 20 cm, 30 cm.

3.2.2 CONSTRUCTION

The construction of the Petten pilot took place from October 1st, 2007 to October 3rd, 2007 during spring tide. The same method and equipment were used as in the construction of the Zuidbout (section 2.2.2). Because the available working time was shorter, a second tumbler with a capacity of 0.25 m^3 was brought into action.

The low crest level of the construction area resulted in only short periods of time in which the groyne was accessible. This time varied from one to three hours per low water period during spring tide and zero hours during neap tide. Delay of the work beyond October 4th was not possible, since during neap tide the water level would not go lower than the crest. Therefore the construction was done at daytime as well as night time, making maximum use of the two low tides per day.

During construction several mishaps were encountered. At first, the aggregate was delivered to the building site with too high moisture content. The polyurethane adhesive does not bond well to wet rocks. The aggregate was then sent back to be dried in an industrial heating tumbler, normally used to warm up asphalt. This however heated the aggregate to such an extent that the rocks were too hot now to be applied with Elastocoast. Temperatures above 30°C accelerate the hardening process, such that handling time becomes too short. Therefore the aggregate had to be spread over a large surface to quicken the cooling process. A side effect of the tumbling was that the amount of fine fragments in the aggregate increased, resulting in a higher polyurethane consumption. In Appendix II a more detailed construction report is given.

The actual areas that were covered with Elastocoast are given in figure 3.6 and table 3.1. At the Petten pilot a quantity of 148 tons of limestone were used, resulting in a final actual mixing ratio of 2.1 % (table 3.2).

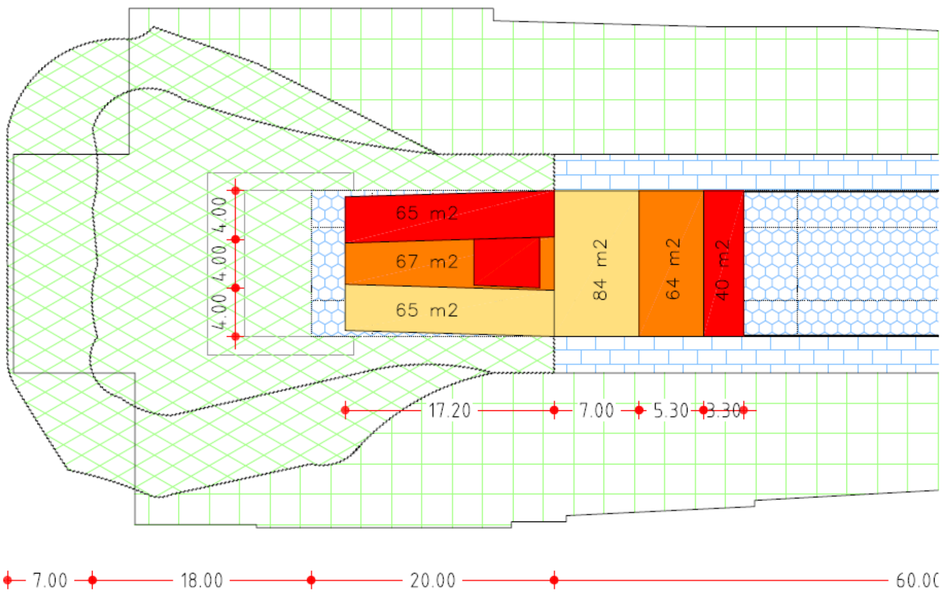


Figure 3.6
Plan view of the actual construction of the Petten pilot, with stretches of Elastocoast of 10 cm, 20 cm, 30 cm.

Table 3.1
Actual areas and volumes of Elastocoast constructed for the Petten pilot test.

Stretch	Dimensions	Surface Area	Total surface area	Total volume or limestone used	Average achieved layer thickness
1	17 m x 4 m	65 m^2	385 m^2	106 m^3	0.275 m
2*	17 m x 4 m	67 m^2			
3	17 m x 4 m	65 m^2			
4	7 m x 12 m	84 m^2			
5	5 m x 12 m	64 m^2			
6	3 m x 12 m	40 m^2			

* approximately 6 m^2 of the 20 cm stretch was repaired during construction with an extra 10 cm.

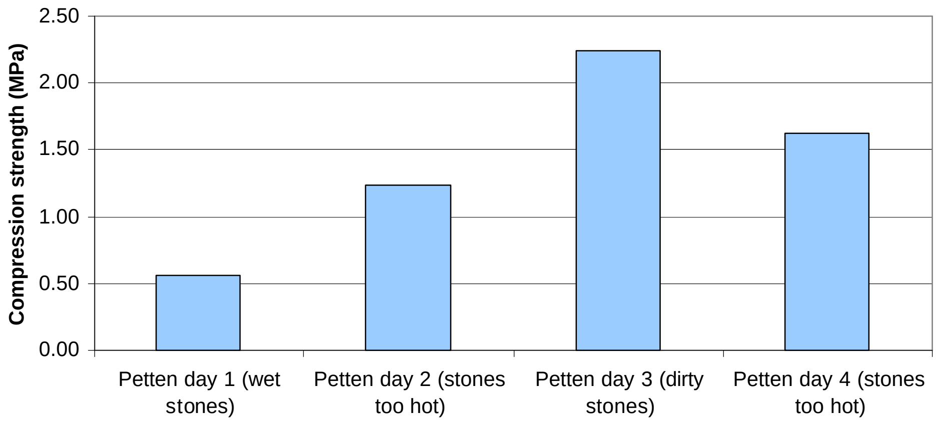
Table 3.2
Actual mixing ratios Elastocoast used for the Petten pilot test.

	Specific weight (kg/m^3)	Quantity (kg)	Quantity (m^3)	Mass percentage Elastocoast	Volume percentage Elastocoast
Limestone 20-40 mm	2720	148410	106	2.1 %	2.7 %
Elastocoast 6551/100	1110	3135	2.82		

3.2.3 QUALITY MONITORING DURING CONSTRUCTION

The construction mishaps show clearly in the results from compression tests performed on samples from the construction site. The use of wet stones results in a significant decrease in strength. However, the average strength of the other samples is higher than those from the Zuidbout pilot. This is a result of the presence of fine fragments in the dry tumbled aggregate.

Figure 3.7
Results from compression strength tests on samples taken from the Petten pilot.



3.3 AVAILABILITY OF DATA FOR ANALYSIS

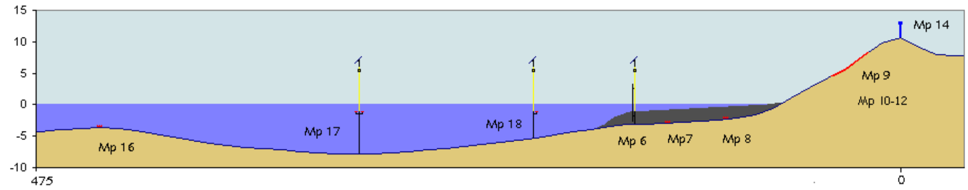
Data is retrieved from instruments that were already in place and used by the RIKZ for the project “SBW-Field measurements”. Since 1994 field measurements are constantly being performed at the Pettemer Sea Defence. Waves, water levels, currents, air-pressures and wind are all measured by an extensive series of instruments that are placed on poles and buoys in a line from the top of the sea defence to 8 km into the sea. The data from these instruments are analyzed and interpreted by the RIKZ with a data analysis tool designed for this purpose: WAVES2007.

The Elastocoast pilot is located right next to measuring pole number 6. The data from this pole can therefore conveniently be used for data analysis without the necessity of translating measured conditions into local conditions. The appropriate data is retrieved[13] from the output files of WAVES2007. Table 3.3 and figure 3.8 show the type and location of data that is used for analysis in this report.

Table 3.3
Used wind and water data sources.

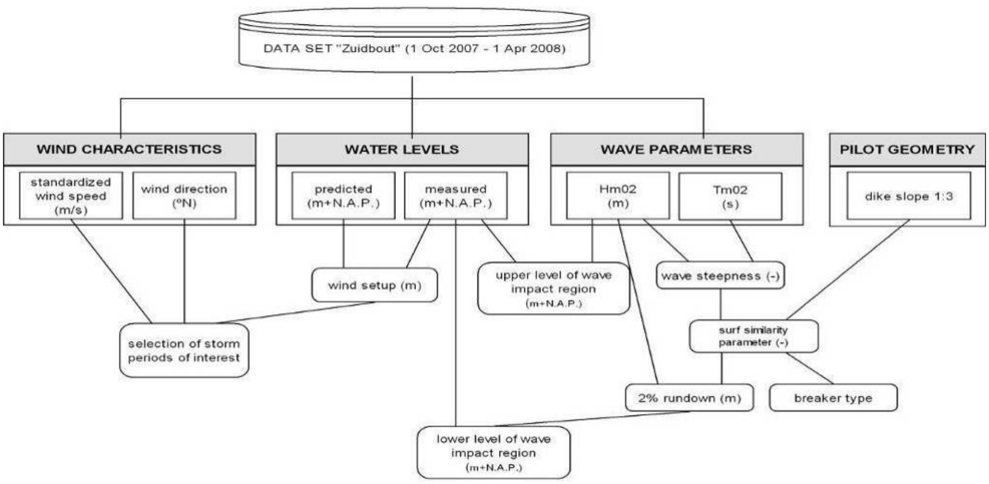
Data	Location	Instrument	Interval	Measured parameters
Water levels	Mp6	Step gauge (066)	0.39 sec.	Actual water level Predicted water level
Wind data	Mp6	Anemometer (064) Wind vane (065)	1 min. 1 min.	Average wind speed Average wind direction
Wave data	Mp6	Capacitive wire (061) Step gauge (066)	0.25 sec. 0.39 sec.	Surface elevation Actual water level

Figure 3.8
Locations of data sources.



The data analysis tool WAVES2007 interprets instrument data and delivers output into parameters that are suitable for further analysis. Figure 3.9 shows which parameters were selected from the output of WAVES2007 to be used. A combination of wind and water level data is used to determine which periods are representative and interesting for analysis. Then a combination of water level and wave data is used to determine the type of loads that the Elastocoast structure has been exposed to during those periods.

Figure 3.9
Scheme of data analysis for the Petten pilot.



Due to defects of the measuring equipment data, an analysis of the storm season 2007 / 2008 could not be retrieved for the entire periods of October to April. No data is available for the month of December and beyond February 12th. During a storm at the beginning of February the foundation of measuring pole 6 was undermined and the entire pole collapsed. Therefore the rendering measurements from this point on are useless (figure 3.11).

Figure 3.10
Measuring pole number 6 before and after the storm of February. Although the pole is marked with a '7', it really is number '6' as was indicated in figure 2.8. The Elastocoast structure is visible in the front of the left picture.

3.4 DATA ANALYSIS OF STORMS AT PETTEN

3.4.1 STORM SEASON 2007/2008

At the pilot location in Petten the following wind field was measured during the storm season of 2007 / 2008. In analogy to the analysis for the Zuidbout pilot, a threshold wind velocity of 17.2 m / s is used for selection of actual storm periods.

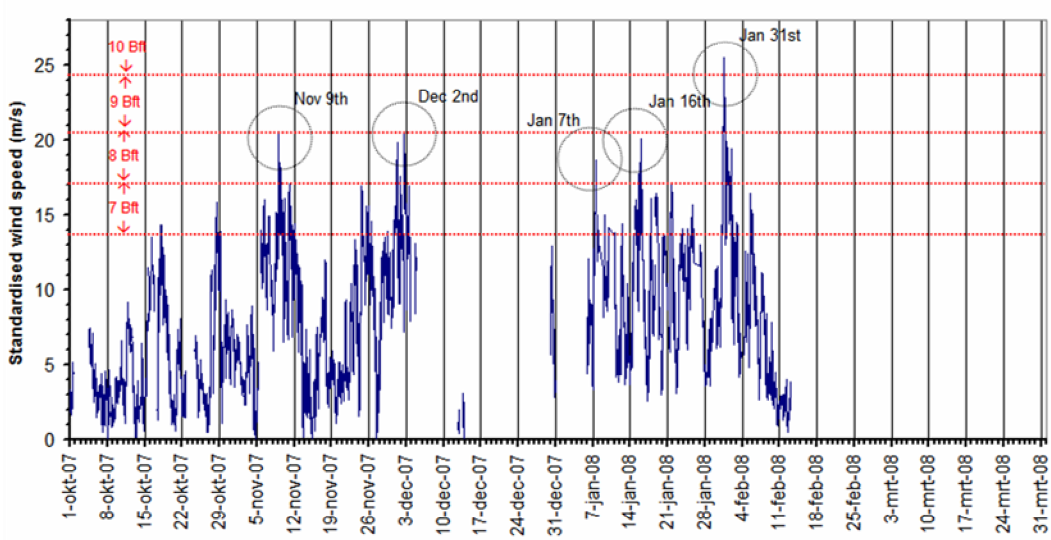


Figure 3.11
Wind measurements at measurement pole 6; average wind speeds.

The missing data reveals itself in gaps in the wind speed graph of Figure 3.11. In the remaining periods, five storms were observed in which sustained wind speeds higher than 17,2 m / s were measured.

A quick comparison with measurements from the archives of the Dutch meteorological institute KNMI with measurements from a weather station at the city of Den Helder shows that the consequences of missing data are limited. Only around March 1st, 2008 and March

12th, 2008 storms have occurred that are not included in the measurements from Petten and these were not the most extreme.

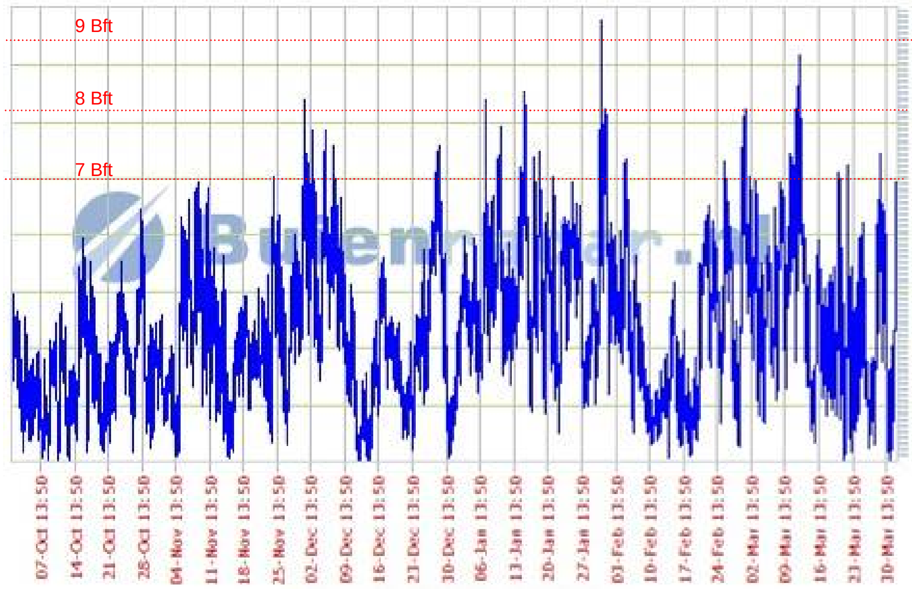


Figure 3.12
Wind measurements at the weather station of Den Helder[14].

For the five storms of which data is available, a detailed analysis of measurements is given in Appendix III. The storms that caused most extreme wave loading on the Elastocoast structure are further analysed in the next section.

3.4.2 HYDRAULIC EFFECTS AT THE STRUCTURE

Wind, water levels and wave conditions
The position of the measuring instruments is next to the pilot location. The protruding beach groyne influences the local hydraulic conditions. Yet, the spatial dimensions of the groyne are of such a small scale, that it is appropriate to assume no significant deviation between the measured conditions at measuring pole 6 and the local conditions at the pilot structure. The measured data can therefore be used without any modification.

Storm characteristics
The Elastocoast pilot at Petten is located in the North Sea and consequently processes of wave creation and growth take place on a much larger scale than at the Zuidbout in the relatively small and sheltered Eastern-Scheldt estuary. The dimensions of the North Sea basin are large enough for high waves to develop with wind blowing over the water ranging from South-West to North-West direction. As they approach the Dutch coast two important processes take place:

§ The direction of wave progression is altered by the coastal bathymetry, such that waves approaching from any direction are turned towards the coastline;
§ High waves break in the relatively shallow coastal waters and are therefore strongly depth limited.

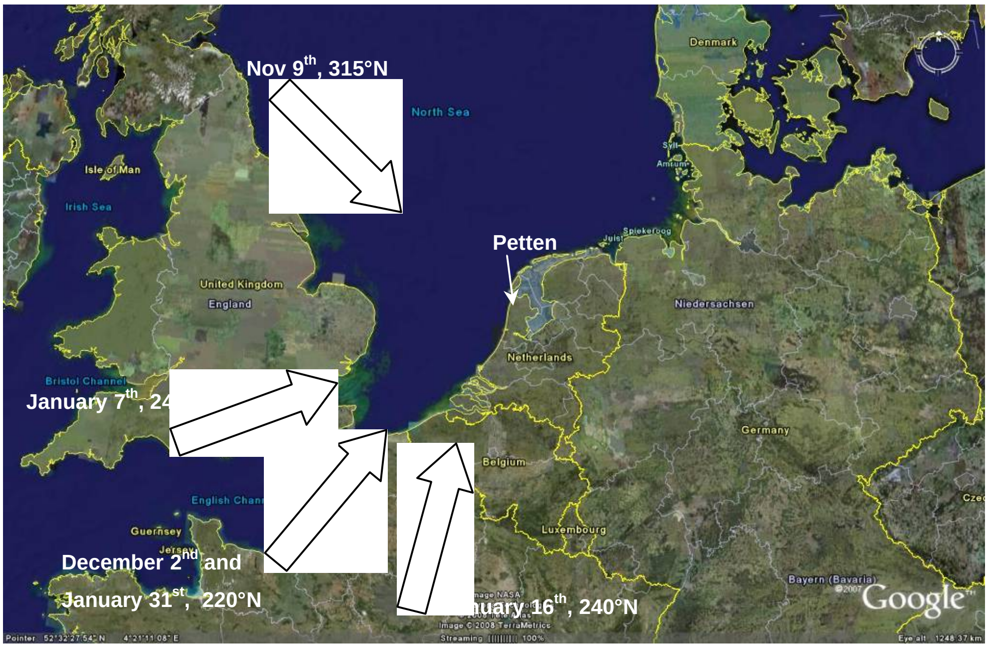
The first process makes that most waves approach the coast and thus the Elastocoast structure from approximately the same direction, which is perpendicular to the coastline shown in figure 3.13.

Figure 3.13
Orientation of the coastline at the Petten Elastocoast pilot.

The implications of the second process are more significant. Most high waves break on the shallow ridges (see figure 3.4), such that the largest waves have lost much of their height when the Elastocoast structure is reached. This effect is always present, but more strongly when the sea water level is low and depth is even more decreased.

Along the Dutch coast sea water levels are strongly dependent on the direction from which the wind is blowing. This is caused by the funnel shaped basin, which is wide in the North West direction and shallow in the South West direction (see figure 3.14). Consequently water is pushed into the funnel when wind is blowing from North West direction, causing high water levels at the Dutch coast and low water levels when blowing from the South West.

Figure 3.14
Wind direction of storms at Petten.



The characteristics of the five storms are given in the following table. It can clearly be seen that the water levels and also the significant wave height were highest during the storm of November 9th, which had winds blowing from the North West. During the storm of January 31st the wind speeds were much higher, but the direction of the wind resulted in lower water levels and a lower significant wave height.

Table 3.4
Characteristics per storm.

Storm date	Peak wind speed (m/s)	Wind direction (°N)	Water level extremities (m+N.A.P.)	Significant wave height (m)	Significant wave period (s)
November 9th, 2007	21	315	0.3 – 2.8	3.5	10
December 2nd, 2007	20	220	-0.1 – 1.7	2.0	6.5
January 7th, 2008	19	240	-0.2 – 1.5	-	-
January 16th, 2008	20	195	-0.5 – 1.2	-	-
January 31st, 2008	25	220	-0.2 – 1.7	2.4	7.0

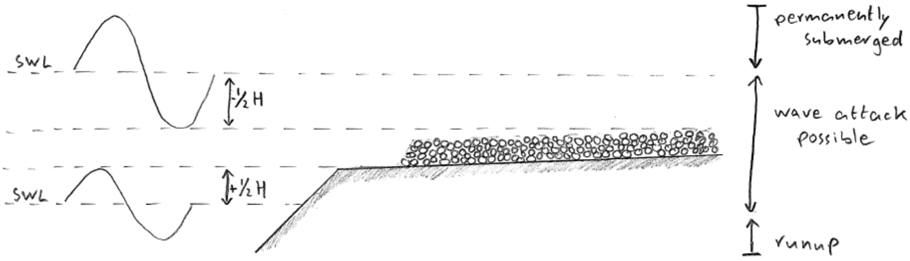
3.4.3 LOADING OF THE ELASTOCOAST STRUCTURE

Wave impact

In contrast to the Zuidbout pilot structure, the slope of the Elastocoast structure at Petten is nearly horizontal. Therefore the hydraulic loading is different in nature. There is only a limited combination of water levels and wave height, in which the structure is subjected to wave impact loading. The rest of the time the structure remains either dry or is completely submerged. This is illustrated in figure 3.15.

Figure 3.15

Load cases at the Petten pilot based on water level.



Loading by wave action takes place in the zone between still water level minus half the wave height and still water level plus half the wave height. Only if this zone coincides with the height of the Elastocoast structure it is attacked directly by waves. Also, due to the nearly horizontal slope (approximately 1:40) the breaker type in this region mostly remains in the spilling regime (figure 2.12). Therefore direct loading by wave impact is not expected for the Petten Elastocoast structure.

The Petten pilot is situated at a level of NAP-0.30 m. In table 3.4 the extreme water levels during the storms are given. From this it can be concluded that the Elastocoast structure was probably lying 1-2 m under the still water level during most of the storm. Therefore, despite the fact that the wave height offshore of this location is more extreme than it is in the Eastern Scheldt, the loading of the structure is expected to be less severe.

Two storms with the highest wave loads are elaborated in this paragraph. An overview of all storm data is given in Appendix III.

Loading of the Elastocoast structure during the storm of November 9, 2008

The following graph shows the wind conditions as measured at measuring pole 6 in the period in which the storm occurred.

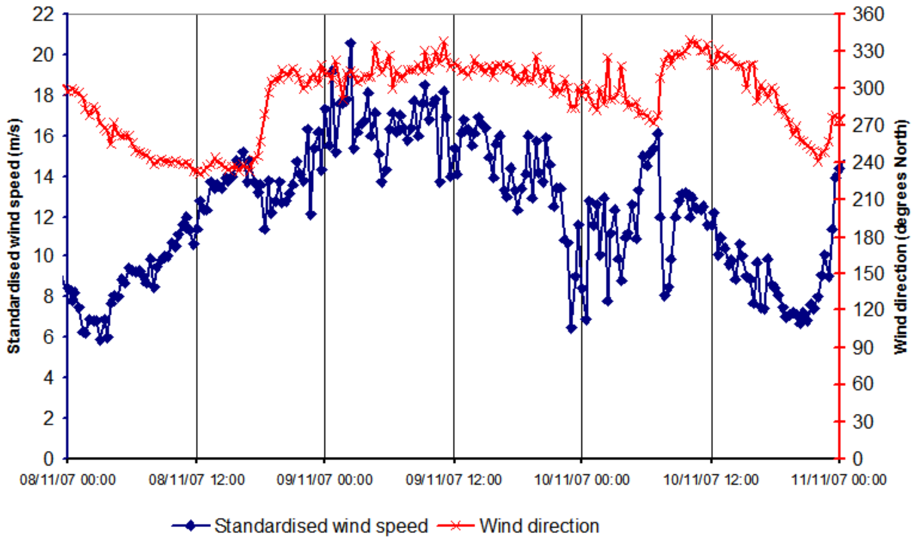


Figure 3.17
Wind speed and direction during the storm of November 9th, 2008.

Disregarding the somewhat erratic behaviour of the observations, wind speed peaked around 17 m/s with a sustained direction around 315°N.

Due to instrument failure, no tidal prediction is available at the location of measuring pole 6. Therefore the prediction at Petten Zuid is used. This is sufficiently close to the pilot location to give representative results. In the following graph the prediction from Petten Zuid is given next to the actual observed water levels at the pilot.

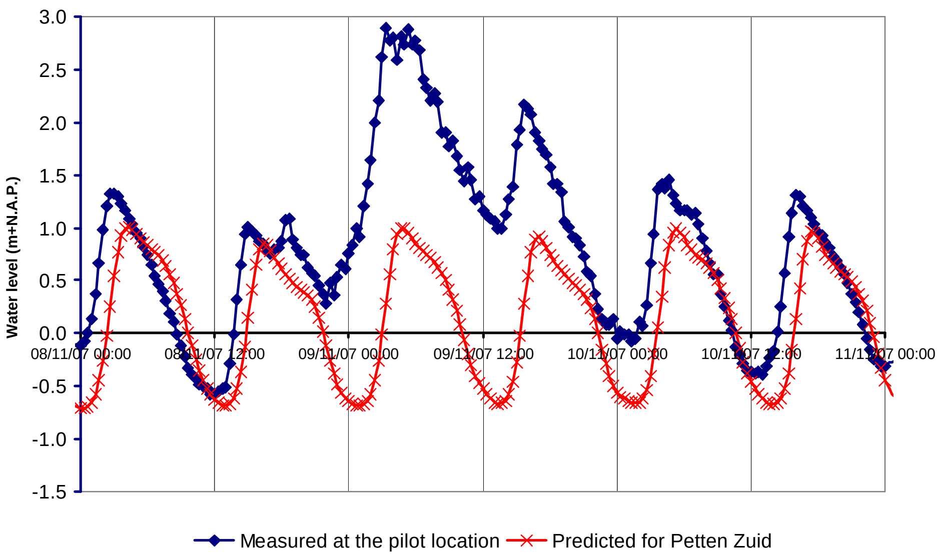
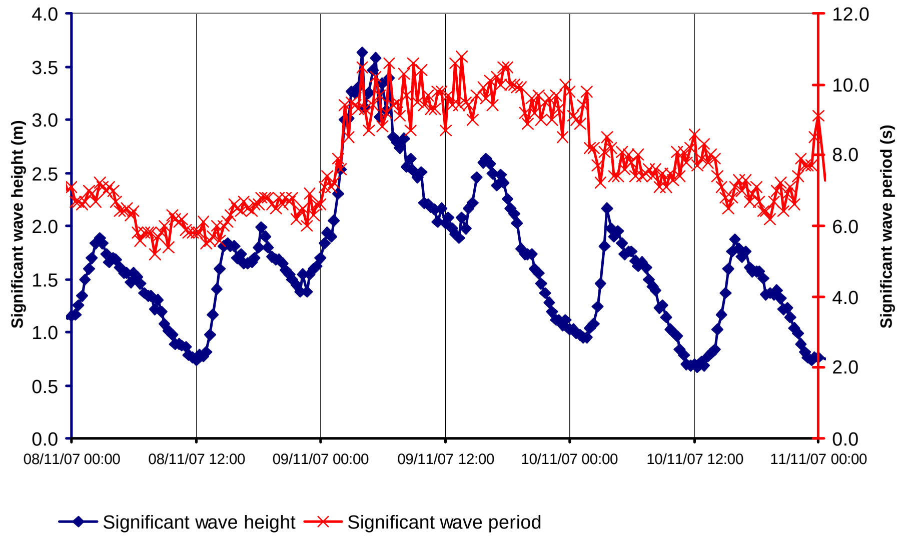


Figure 3.18
Predicted water levels from Petten Zuid and actually observed water levels at measuring pole 6.
(The small phase shift in the water levels is probably caused by the wind setup itself)

The wave conditions at the North Sea coast, measured at the measuring pole 6 are shown below.

Figure 3.19
Significant wave height and significant wave period.



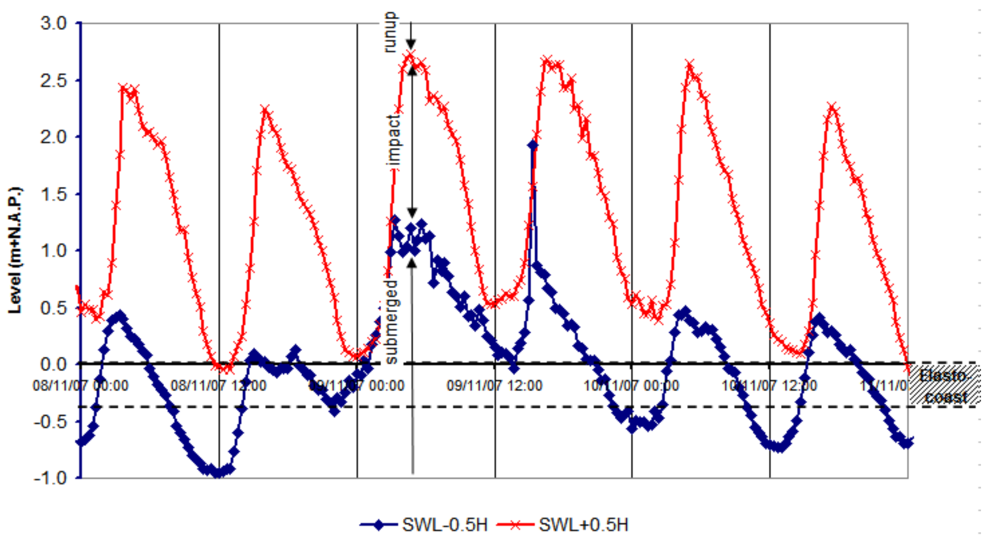
The significant wave height peaked around 3.5 m. At the same time the significant wave period peaked around 10 s. (The peak period is not available for this dataset.)

For the Petten Elastocoast structure properties that determine the type of loading are:

- Slope: nearly horizontal 1:40
- Range: NAP-0.30 m to NAP +0.0 m

The following graph shows the upper and lower level of the wave attack zone in comparison to the level of the Elastocoast structure. The graph shows that the Elastocoast structure was completely submerged for most part of the time, especially when the most extreme waves were measured.

Figure 3.20
Position of upper and lower level of the wave attack zone.



Loading of the Elastocoast structure during the storm of January 31st, 2008

The following graph shows the wind conditions as measured at measuring pole 6 in the period in which the storm occurred.

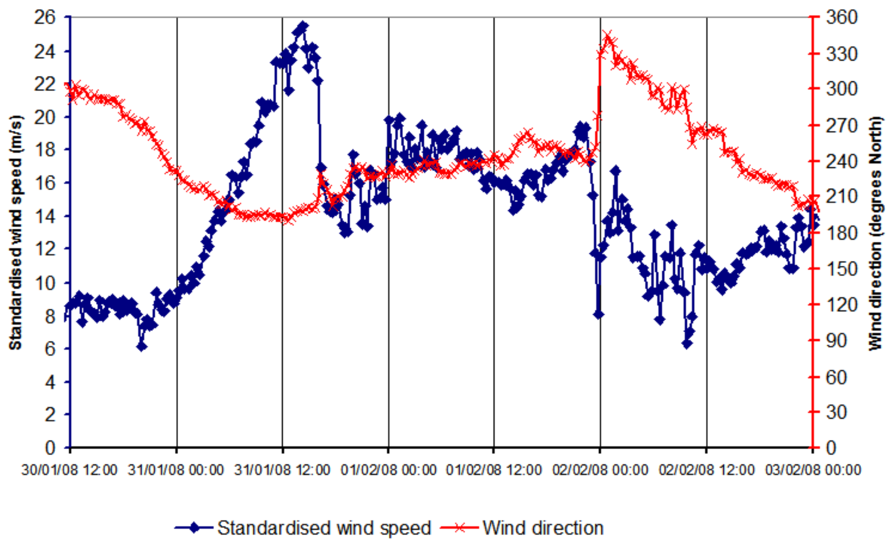


Figure 3.22
Wind speed and direction during the storm of January 31st, 2008.

Disregarding the somewhat erratic behaviour of the observations, wind speed peaked around 24 m / s and then dropped to around 17 m / s with a sustained direction around 220° N.

In the following graph the prediction from Petten Zuid is given next to the actual observed water levels at the pilot.

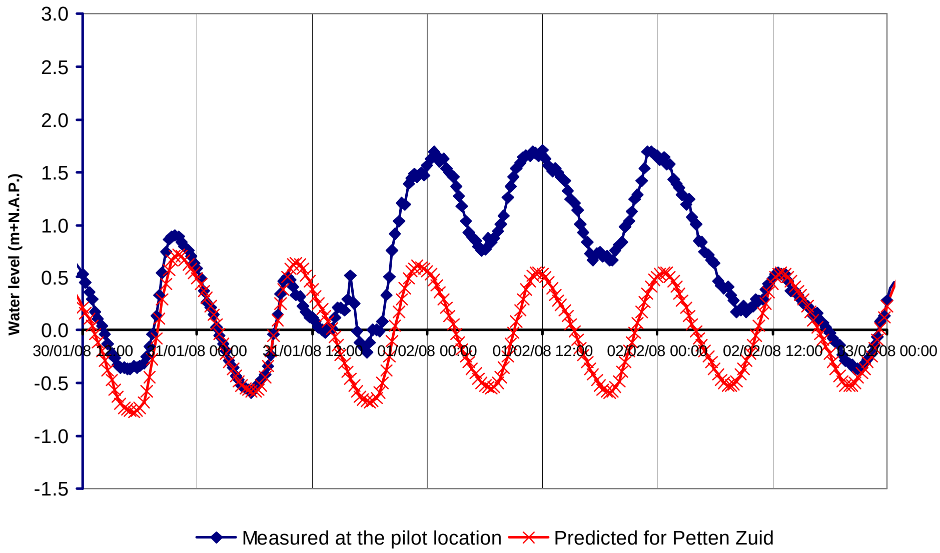


Figure 3.23
Predicted water levels from Petten Zuid and actually observed water levels at measuring pole 6.

The wave conditions at the North Sea coast, measured at the measuring pole 6 are shown below.

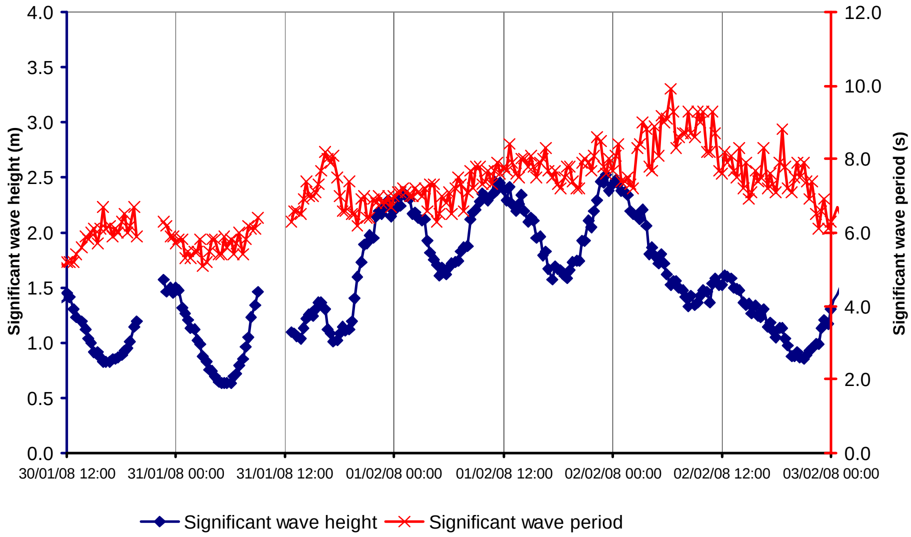


Figure 3.24
Significant wave height and significant wave period.

The significant wave height peaked around 2.4 m. At the same time the significant wave period peaked around 7 s.

For the Petten Elastocoast structure properties that determine the type of loading are:
- § Slope: nearly horizontal 1:40
- § Range: NAP-0.30 m to NAP +0.0 m

The following graph shows the upper and lower level of the wave attack zone in comparison to the level of the Elastocoast structure. The graph shows that the Elastocoast structure was completely submerged for most part of the time, especially when the most extreme waves were measured.

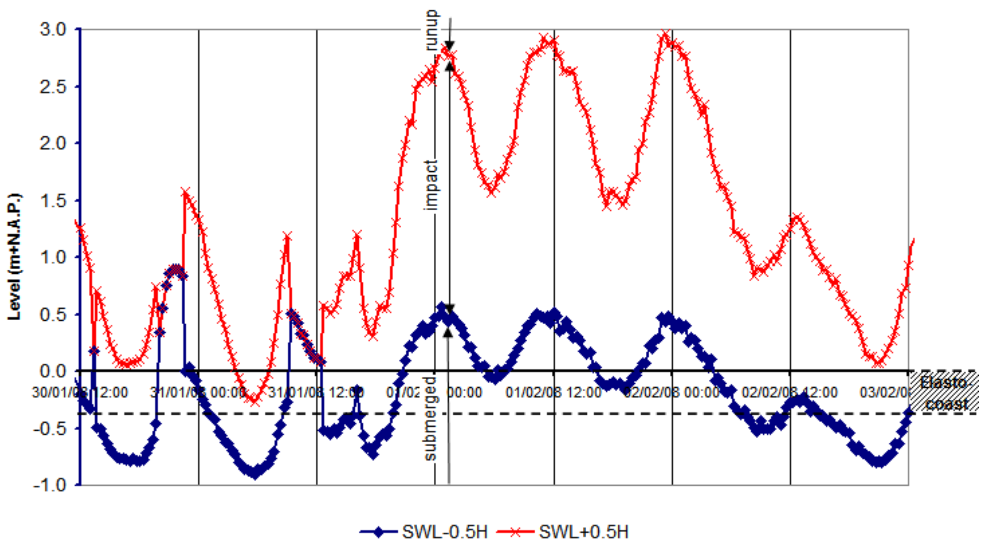


Figure 3.25
Position of upper and lower level of the wave attack zone.

3.5 CONCLUSION

From the storm season of 2007 / 2008 only limited data is available due to instrument failure. No data is available for December and beyond February 12th. In the remaining periods five storms were observed in which wind speeds were measured of above 17.2 m / s (8 Bft). Beyond February 12th another two storms occurred, but no data is available from these storms.

During the most extreme conditions, the Elastocoast revetment at the Petten pilot was completely submerged the largest part of the time, especially when the highest waves were measured. Therefore there was no direct wave impact loading on the structure during the most extreme conditions. However, when submerged, the Elastocoast structure was persistently subjected to strongly varying near bed flow velocities.

CHAPTER 4 Site Monitoring

4.1 POSSIBLE FAILURE MECHANISMS

4.1.1 GENERAL

A slope protection fails to fulfil its function when the cover layer is damaged so that the underlying layer is exposed. The underlying layer is normally not designed to withstand loads by direct wave attack. For the time this layer is exposed, damage can progress further into the structure, possibly resulting in a breach in the dike.

Several failure mechanisms of slope protections are known from extensive research and experience on existing structures. To determine the mechanisms that apply to the Elastocoast system analogies are sought with these existing types of structures.

Apart from the polyurethane binding, seen on a micro scale Elastocoast is similar to a dumped rock protection with a relatively small stone size. For rock protections an important failure mechanism is:

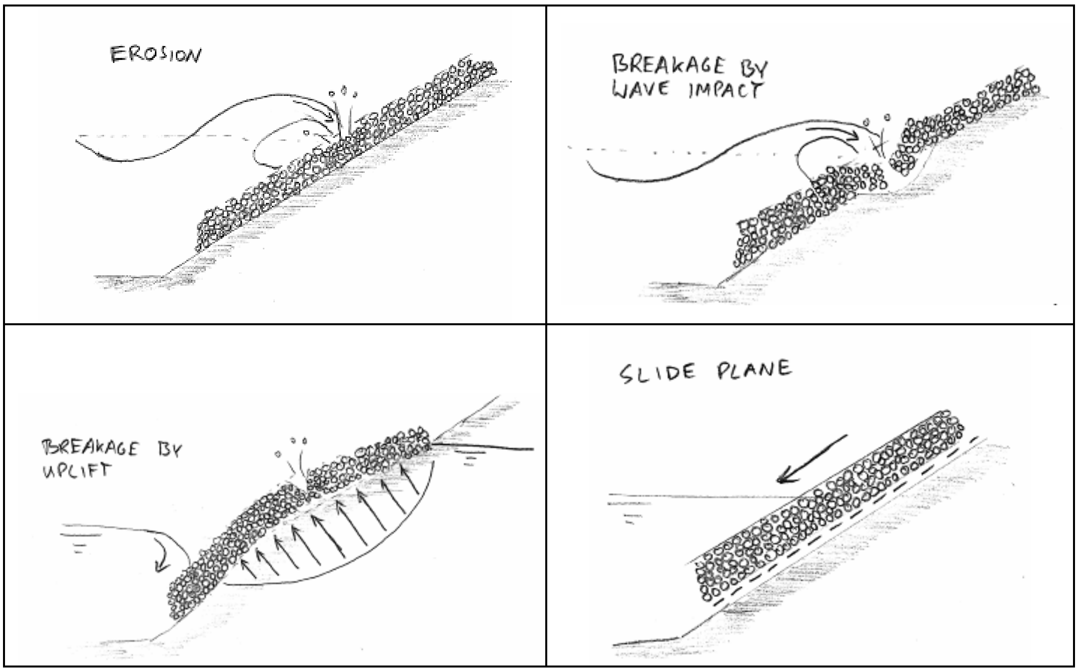
§ Erosion and abrasion of rocks by turbulent flow;

On a macro scale the Elastocoast system behaves like a plate structure. For this kind of structure, on a macro scale the following mechanisms can occur:

§ Fracture of the top layer under loading of wave impact;
§ Fracture by uplift of the top layer, caused by excessive pressures under the top layer;
§ Slipping of the top layer over a slide plane on the interface with the sub layer;

See figure 4.1 for an overview of the failure mechanisms.

Figure 4.1
Possible failure mechanisms for Elastocoast structure.



4.1.2 EXPECTED MECHANISMS AT THE PILOTS

Both at the Zuidbout pilot as at the Petten pilot the Elastocoast layer has been put directly on top of an existing revetment. It can be assumed that the underlying revetment forms a very firm support for the Elastocoast, resulting in minimal bending deformations. With minimal deformation, the maximum bending strength of the material will not be exceeded, which crosses out the failure mechanism of breach under wave impact loading.

Also, the Elastocoast layer is very open when compared to the underlying layers. Therefore it is unlikely that water pressures will build up underneath. This means that the failure mechanisms of uplift and the development of a slide plane will not occur.

Concluding, because of the relatively open structure of Elastocoast and a firm support from the under lying existing revetment, damage at the pilot location is only expected on a micro scale namely erosion and abrasion of surface rocks.

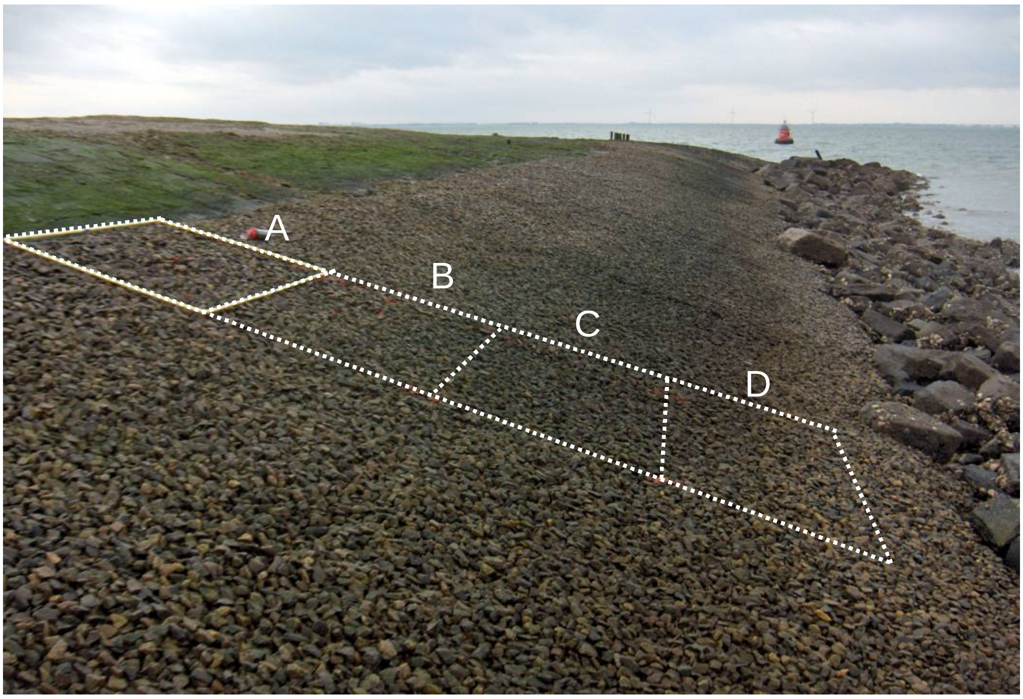
The monitoring method will therefore be mainly focused on the erosion and abrasion of surface rocks. Though the other failure mechanisms are not expected, an eye is also kept out for cracks and fissures that could indicate failure on a macro scale.

4.2 MONITORING METHOD

On the site fixed areas on the Elastocoast protection are marked with paint for systematic inspection. These areas have been selected during construction to be representative, i.e. there were no irregularities during construction or in the underlying base layer that could negatively or positively affect the strength or behaviour of the material.

For the Zuidbout pilot, monitoring areas with a width of 1.50 m and a length of 4.00 m are chosen respectively on the 10 cm, 20cm and 30 cm stretch. These areas reach from a level of approximately NAP+0.50 m to NAP+1.50 m.

Figure 4.2
Example monitoring area of 1.50 m x 4.00 m, divided in four parts.

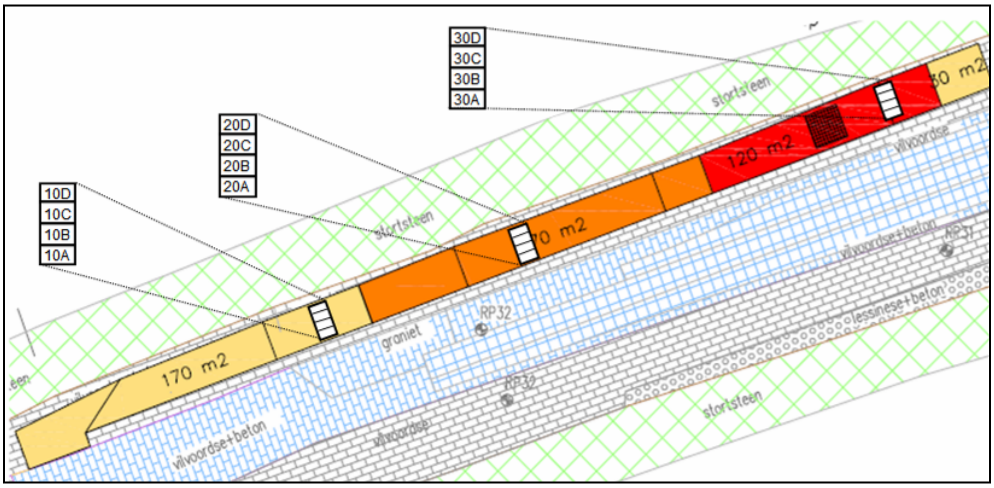


Each monitoring area is divided in four parts: A, B, C and D. A tube frame is then used to create a grid, so that the location of damage can be noted down.

Figure 4.3
Tube frame subdivided with a grid. Damage is marked with a red paint dot.

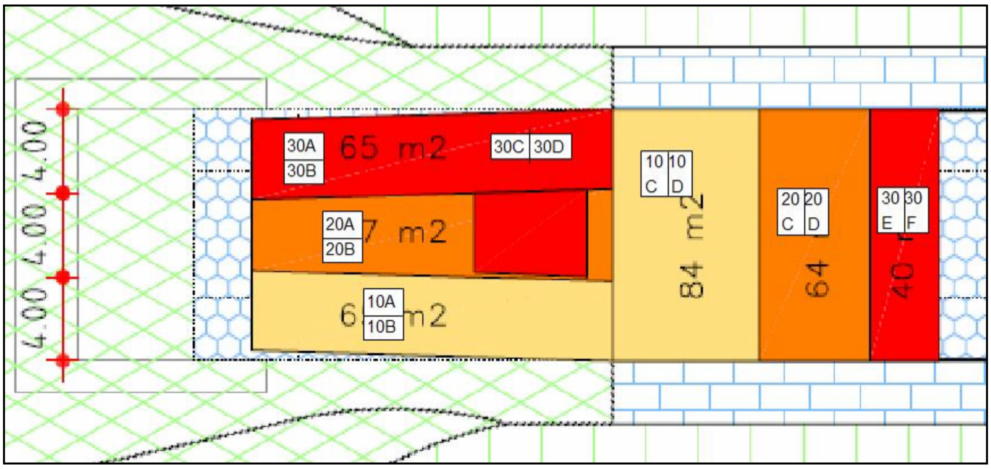
The monitoring areas are laid out on the Elastocoast structure in figure 4.4:

Figure 4.4
Monitoring areas on the Zuidbout pilot.



At the Petten pilot the same technique is used for monitoring. Here the monitoring areas are laid out as shown in figure 4.5. For the 30 cm stretches an extra area of 3 m^2 was marked in the part of the structure were it was known that aggregate with a too high moist content was used during construction (areas 30A and 30B).

Figure 4.5
Monitoring areas on the Petten pilot.



During each visit all marked areas are examined and photographed. If damage is detected, it is marked on the surface with a dot of paint and noted down on a monitoring sheet.

The rest of the Elastocoast stretches are also examined visually to detect damages on a macro scale. If any significant damage is found in a particular area this area is marked and added to the list for periodical monitoring.

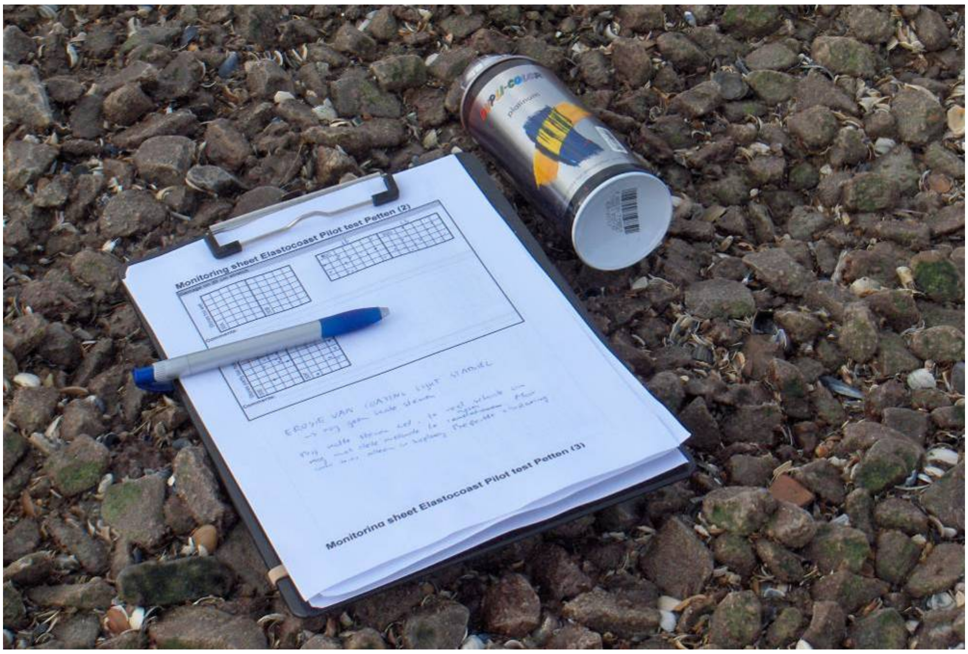


Figure 4.6
Monitoring equipment: marking paint and monitoring sheet.

4.3 OBSERVED BEHAVIOUR OF THE STRUCTURES

4.3.1 OBSERVATIONS AT THE ZUIDBOUT

Macroscopic failure

The following observations were made:

1) No visible deformations;
2) No cracks or fissures in the surface of the Elastocoast layer;
3) No visible movement or sliding of the structure.

Other observations regarding macroscopic failure:

4) Dirt in the form of plants and debris carried in by waves collect on the surface, but do not clot the open structure of the Elastocoast revetment.

Microscopic failure

The number of dislocated stones on the structure's surface is an indication of the magnitude of erosion damage. The numbers of dislocated stones within the monitoring areas throughout time are given in the next table.

Table 4.1
Number of dislocated units in the monitoring areas at the Zuidbout pilot.

Layer thickness	Reference area	Number of dislocated units 20 Sep (day 0)	26 Oct (day 36)	16 Nov (day 57)	6 Dec (day 77)	13 Dec (day 84)	16 Jan (day 118)	13 Mar (day 175)
10 cm	Z10A	0	3	4	5	5	7	12
	Z10B	0	0	4	5	5	6	4
	Z10C	0	3	4	4*	4	4	4
	Z10D	0	0	2	2*	2	3	4
	Total	0	6	14	16	16	20	24
20 cm	Z20A	0	1	1	5	9	10	11
	Z20B	0	3	4	5	5	5	10
	Z20C	0	4	4	7	7	8	10
	Z20D	0	0	0	5*	5	5	7
	Total	0	8	9	22	26	28	38
30 cm	Z30A	0	0	6	10	8	15	14
	Z30B	0	4	4	13	12	13	27
	Z30C	0	4	4	5	6	6	10
	Z30D	0	3	9	9	9	11	13
	Total	0	11	23	37	35	45	64

* Actual data not available due to bad weather conditions, values copied from day 84 (one week later).

Other visual observations regarding microscopic failure:

1) Stone loss only takes place under the most protruded rocks at the surface layer; there is no damage to newly exposed rocks in the underlying layer.
2) Most rocks break away by failure of the polyurethane contact points; in the total monitoring area only 2 rocks are found to have fractured.
3) There are no signs of stripping of the polyurethane coating from the rocks.
4) There are no signs of abrasion on the polyurethane coating.


1


2

Figure 4.7
Three types of microscopic failure:
1) failure of polyurethane contact point (Zuidbout)
2) fracture of rock (Zuidbout)
3) stripping of Elastocoast coating from rock (Petten)

3

4.3.2 OBSERVATIONS AT PETTEN

Macroscopic failure

The following observations were made:

1) No visible deformations;
2) No cracks or fissures in the surface of the Elastocoast layer;
3) No visible movement or sliding of (parts of) the structure.

Other observations regarding macroscopic failure:

8) 22 days after construction significant amounts of dirt (mostly sand and shell material) have collected in the pores of the open structure. Sand has been washed out from the top part of the structure, but is still present at some depth (1-2 times stone size). There seems to be no difference in amount of dirt between the different layer thicknesses. Water does not form puddles on the structure.
9) 43 days after construction more sand has collected in the structure, predominantly in the middle part of the structure: next to monitoring areas P10CD and P20CD.
10) 139 days after construction also algae growth is found over the entire structure. The structure is clogged by sand, shells and vegetation. Water now remains in puddles on the structure after a wave has passed.
11) 188 days after construction the vegetation has grown excessively. Clogging of the structure remains.

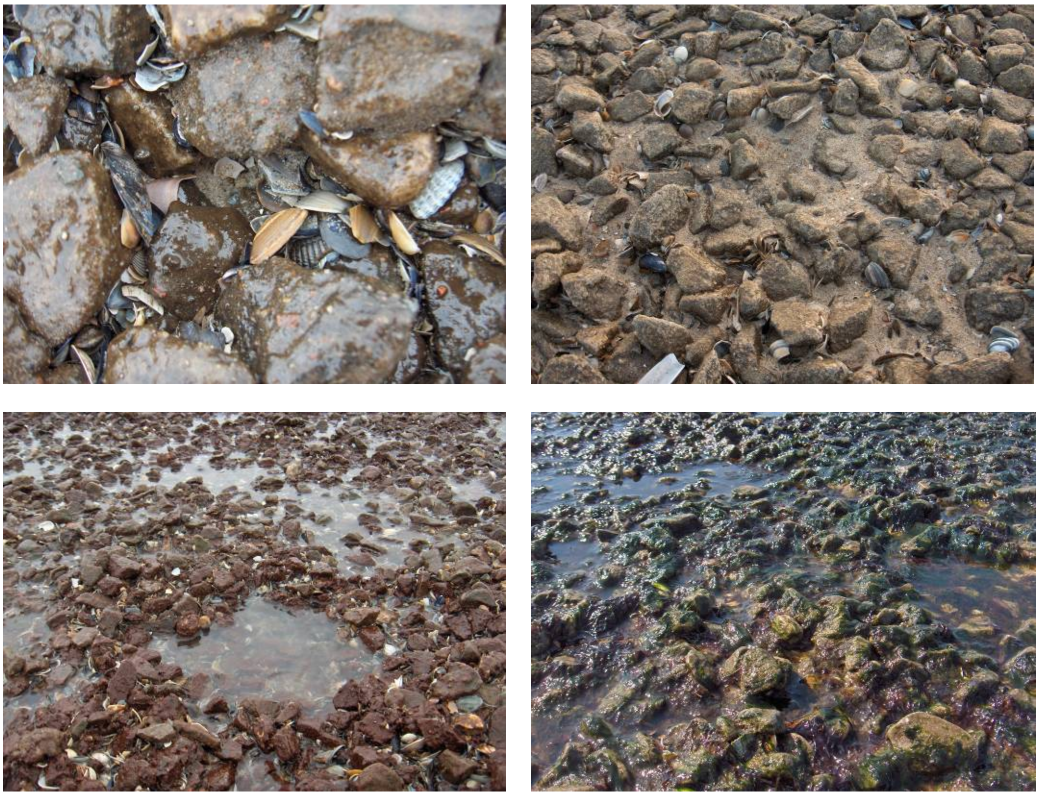


Figure 4.8
Clogging with:
- shells (top left)
- sand and shells (top right)

Formation of puddles on clogged Elastocoast (bottom).

Microscopic failure

The numbers of dislocated stones within the monitoring areas throughout time are given in the next table.

Table 4.2
Number of dislocated units in the monitoring areas at the Petten pilot.

Layer thickness	Reference area	Number of dislocated units					
		3 Oct (day 0)	25 Oct (day 22)	15 Nov (day 43)	15 Dec (day 73)	19 Feb (day 139)	8 Apr (day 188)
10 cm	P10A	0	0	1	2	5	**
	P10B	0	0	1	2	1	**
	P10C	0	0	1	1	3	**
	P10D	0	0	1	1	4	**
	Total	0	0	4	6	13	**
20 cm	P20A	0	2	18	17	18	**
	P20B	0	3	10	13	17	**
	P20C	0	0	1	3	7	**
	P20D	0	1	7	12	16	**
	Total	0	6	36	45	58	**
30 cm *	P30A	0	24	57	44**	**	**
	P30B	0	24	53	57**	**	**
	Total	0	48	110	101	**	**
30 cm	P30C	0	1	7	9	16	**
	P30D	0	3	9	9	13	**
	P30E	0	0	3	9	8	**
	P30F	0	0	0	2	6	**
	Total	0	4	19	29	43	**

* Extra measurement areas which were constructed with wet aggregate.

** Reliable measurements were no longer possible due to weathering and growth on surface.

Other visual observations regarding microscopic failure:

8) Stone loss only takes place under the most protruded rocks at the surface layer; there is no damage to newly exposed rocks in the underlying layer.
9) All rocks break away by failure of the polyurethane contact points; no rocks are found to have fractured.
10) 22 days after construction only the rocks in section P30AB (where wet aggregate was used) show clear signs of stripping (figure 4.7).
11) 43 days after construction the polyurethane film of rocks all over the structure has been weathered superficially by abrasive material (sand and shells). Shells are often jammed firmly between the rocks.

Due to the high moisture content, the polyurethane adhesive did not bond well to the rocks and resulted in a significant higher number of dislocated rocks. See the table 4.2. Despite the larger extent of damage in this location, the structure remained intact.

4.4 DISCUSSION OF RESULTS

General

Macroscopic failure of the structure was not observed at either of the pilots. It is likely that this is due to the properties of the underlayer, which is practically impermeable. Since this is a very specific and favourable situation, it does not give information on whether macroscopic failure could occur in other situations, such as an Elastocoast cover layer placed directly on a sand foundation.

On microscopic level damage was observed. The strength of the Elastocoast bonding on this level can be divided in three parts:

- Adhesive strength of Elastocoast to rock surface;
- Strength of contact points (i.e. the Elastocoast 'bridge' in between rocks);
- Material strength of the rock itself.

From the visual observations on microscopic failure it can be derived that stone loss is caused by failure at the contact points. Fracture of the rock itself seldom occurs and stripping is only observed at parts were wet aggregate was used during construction. On the basis of these observations it can be concluded that the contact points between the rocks are the weakest elements in the Elastocoast system.

Evaluation of damage

In The Rock Manual (2007) the amount of damage for rock structures is quantified with the number of displaced units N_{od} (-), or as a damage percentage, N_d (%):

$$N_{od} = \frac{number\ of\ units\ displaced\ out\ of\ armour\ layer}{width\ of\ tested\ section / D_n}$$

$$N_d = \frac{number\ of\ units\ displaced\ out\ of\ armour\ layer}{total\ number\ of\ units\ within\ reference\ area} \cdot 100\%$$

In which D_n is the nominal rock size. Take note that the actual number of units depends also on the porosity, the grading of the armour stones. For rock structures generally a damage percentage of N_d = 0-5 % is found acceptable and is referred to as the no damage condition.

Disregarding the effect of the polyurethane bonding and simplifying the Elastocoast revetment to a layer of dumped rocks, the values of N_{od} and N_d can be used as an indication of damage. The total number of units within the reference area for calculation of N_d can be calculated with the nominal rock diameter and the porosity:

$$total\ of\ units\ within\ reference\ area = \frac{nA_{ref}d}{(D_{n50})^3}$$

With:

n	= porosity (-)
A_{ref}	= size of reference area (m^2)
d	= thickness of protection layer (m)
D_{n50}	= nominal rock diameter (m)

The porosity of Elastocoast is n = 0,5; the reference area A_{ref} = 6 m^2 and D_{n50} = 22 mm. Combined with the results from tables 4.1 and 4.2 we find for the damage at the end of the monitoring period:

Table 4.3
Number of displaced units and damage percentage for 10 cm, 20 cm and 30 cm stretch.

Elastocoast stretch	Damage after monitoring period, N	Total number of units	Number of displaced units, N_{od}	Damage percentage, N_d
Zuidbout 0.10 m	24	28174	0.35	0.09 %
Zuidbout 0.20 m	38	56349	0.56	0.07 %
Zuidbout 0.30 m	64	84523	0.94	0.08 %
Petten 0.10 m	13	28174	0.19	0.05 %
Petten 0.20 m	58	56349	0.85	0.10 %
Petten 0.30 m *	> 101	42261	> 1.48	> 0.24 %
Petten 0.30 m	43	84523	0.63	0.05 %

* Extra measurement sections which were constructed with wet aggregate. These sections have a total area of 3 m^2.

According to this method of damage evaluation, the damage to the Elastocoast structure is relatively very small. Values of 0.05-0.24 % are very small compared to the no damage condition for rock structures of N_d = 0-5 %. The 30 cm section where wet aggregate was used has significantly more damage than the other parts, but is still very well in the range of the no damage condition.

The no damage condition however, is originally intended for dumped rock structures. These are normally constructed with a layer thickness of 2 times D_{n50}. The Elastocoast structure has a layer thickness from 4 to 14 times D_{n50}. Therefore, to make a better comparison it is now assumed that only the top layer of the structure, with a thickness of 2 times D_{n50} takes part in the erosion process. Then, the thickness of the reference area d is set equal to 2 times D_{n50}. The number of displaced units N_{od} remains the same, but the total number of units within the reference area reduces and becomes independent of the original layer thickness. With modification the damage percentage N_d becomes:

Table 4.4
Adjusted damage percentage when only the upper part (2 times D_{n50}) of the structure is taken into account.

Elastocoast stretch	Alternative layer thickness (=2*D_{n50})	Damage after monitoring period, N	Total number of units	Modified damage percentage, N_d
Zuidbout 0.10 m	44 mm	24	12396	0.19 %
Zuidbout 0.20 m	44 mm	38	12396	0.31 %
Zuidbout 0.30 m	44 mm	64	12396	0.52 %
Petten 0.10 m	44 mm	13	12396	0.10 %
Petten 0.20 m	44 mm	58	12396	0.47 %
Petten 0.30 m *	44 mm	> 101	6198	> 1.63 %
Petten 0.30 m	44 mm	43	12396	0.35 %

This shows that also when only the top part of the structure is taken into account, the damage percentage is still safely within the 0-5 % condition. While for a larger layer thickness a higher damage percentage would be expected. With this analogy to the damage evaluation of dumped structures, it is concluded that the amount of measured damage at the pilots is negligible.

Increasing damage with increasing layer thickness?
It shows from the observations that there is a clear deviation in the amounts of damage between the different layer thicknesses. However, at the Zuidbout the 30 cm layer shows most damage, whereas at Petten the 20 cm layer is on top.

An explanation of this phenomenon could be found in the way of construction. A thicker layer takes more time to construct. Yet the handling time of the polyurethane adhesive is only 20 minutes after mixing. It is conceivable, that the optimal handling time is sometimes exceeded for thicker layers. The increased viscosity of the adhesive can then result in a reduced bonding at the contact points between the individual rocks. Ultimately this leads to a weaker top part of the structure, since this is the part that is handled last when profiling.

Scenarios for damage development
For description of the damage development of an Elastocoast protection there are roughly three possible scenarios:

- Burn-in period;
- Linear damage development;
- Progressive damage development.

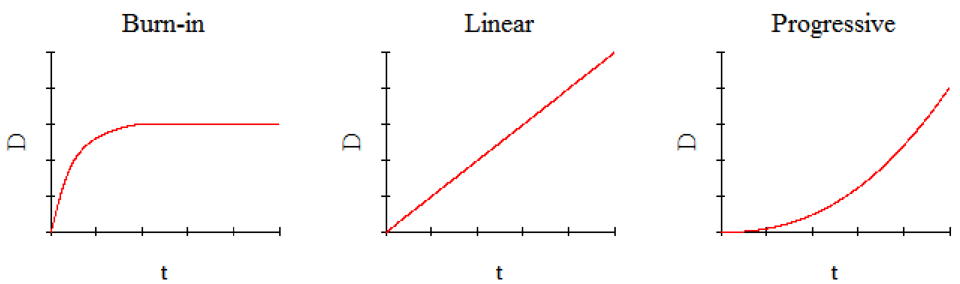


Figure 4.9
Damage development scenarios.

The structure has a so-called burn-in period when the weaker rocks on the structure's surface are removed in the period after construction. Rocks located at the surface have an inevitably weaker attachment than underlying rocks, since surface rocks are more protruded which results in fewer contact points with neighbouring rocks. The underlying rocks do have more attachments and thus more strength. Therefore damage development will come to a halt when the weak surface rocks have been removed and the stronger underlying rocks remain. Structure lifespan can be very long, since damage progression after the burn-in period is very slow.

With linear damage development rocks are dislocated from the structure with a constant speed. The underlying rocks then become exposed to wave loads and will also be dislocated during following storms. This development will continue until finally the rocks at the bottom of the structure are removed and the underlying layer is exposed to direct wave attack. Structure lifespan now depends on the rate of damage development and can be predicted by extrapolation.

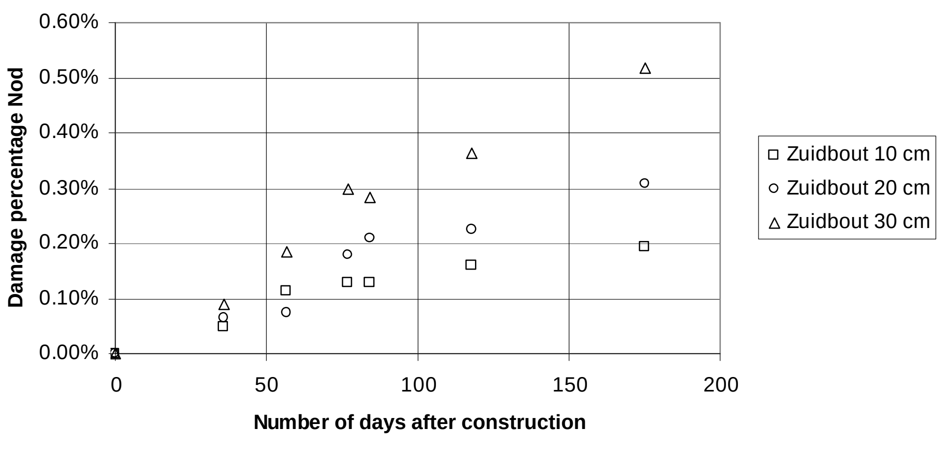
Progressive damage development implies that the initial damage is only small, but as soon as damage occurs at one point it will spread rapidly to the surrounding area. This type of damage development can be seen with structures such as stone pitchings, where part of the strength depends on the interlocking or friction between its elements. As soon one element is missing, the surrounding parts lose strength. Structure lifespan becomes uncertain, since the time of first damage is unpredictable.

Observed damage development

On basis of the plots we can draw no conclusions in favour of one of the three scenarios. A longer period of measurements is needed to see whether the damage development will continue or will stop to remain constant. The visual observations however, point towards the burn-in scenario: damage was limited to rocks in the top layer and did not seem to progress in the newly exposed rocks underneath.

In the following figures the development of the damage percentage is shown for the two pilot locations. The damage percentage is calculated with the previously introduced method in which only the top 2*D_{n50} part of the structure is taken into account.

Figure 4.10
Damage development at the Zuidbout.



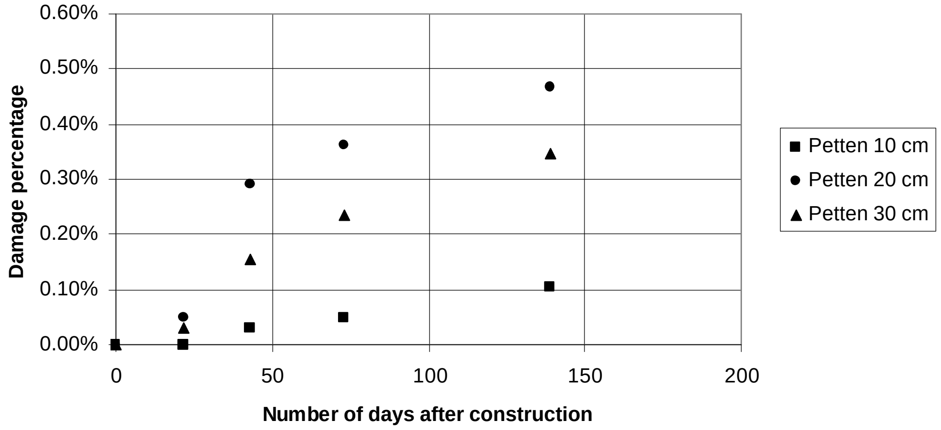


Figure 4.11
Damage development at Petten.

By only taking into account the top $2*D_{n50}$ part of the structure in calculation of the damage percentage, the assumption is made that the surface damage development is not related to the layer thickness. This implicitly means that deviations in the measurements from different parts of the structure are natural variable and can be averaged into a single value. This produces the following graph.

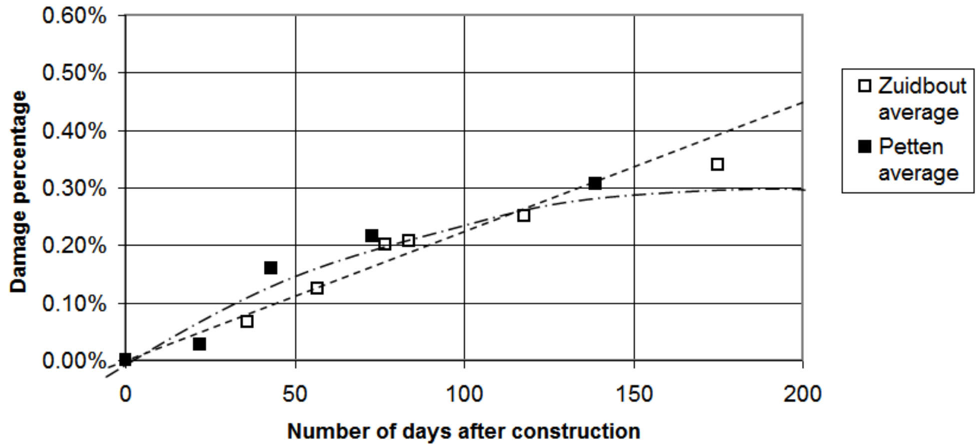


Figure 4.12
Averages of damage development for the Zuidbout and Petten.

Although the length of the record is limited, the data does not support progressive growth of damage. Also the visual observations show no indication of additional damage at locations with missing stones. Therefore the scenario of progressive damage development is considered unlikely. However, both of the two other scenarios produce a reasonable fit. Based on the data, a definitive choice for one of the other two damage models can not be made. The visual observations point towards the burn-in scenario.

4.5 CONCLUSION

Pilot location Zuidbout
From the results of the monitoring period October 2007 to April 2008 the following conclusions can be drawn:

- Microscopic damage to the Zuidbout Elastocoast revetment after the storms of October 2007 to April 2008 is negligible and of no influence on the structure's performance;
- The polyurethane contact points in between rocks are the weakest parts of the structure;

- There is no abrasion damage to the Zuidbout Elastocoast revetment;
- There is no clotting of the open structure of Elastocoast at the Zuidbout.

Pilot location Petten

From the results of the monitoring period October 2007 to February 2008 the following conclusions can be drawn:

- Microscopic damage to the Petten Elastocoast revetment after the storms of October 2007 to February 2008 is negligible and of no influence on the structure's performance;
- There is only superficial abrasion damage to the Petten Elastocoast revetment;
- There is significant clotting of the open structure of Elastocoast at Petten, due to high amounts of sediment, shells and organic material in the coastal water of the North Sea.

General

From the total of the two Dutch pilot locations the following conclusions can be drawn:

- At neither of the two pilot locations signs of macroscopic failure were observed. This is structure related and on basis of these results no conclusions be drawn whether the Elastocoast system is susceptible to macroscopic failure mechanisms.
- In contrast to the Zuidbout, the Petten pilot showed excessive amounts of sediment and dirt clogging the open structure and weathering its surface. However, this fine abrasive material does not seem to have any influence on the damage development of the Elastocoast structure.
- Although the length of the record is limited, it can be concluded on the basis of visual observations that the damage development rate is not progressive, meaning that initial damage does not initiate the development of larger damage. From the visual observations at the pilot locations, the burn-in scenario seems likely. Under this scenario, the rate of erosion diminishes over time as initially poorly bonded stones are eroded from the revetment.

CHAPTER 5 Conclusion

5.1 CONCLUSIONS FROM STORM ANALYSIS

Pilot location Zuidbout

In the storm season of 2007/2008 six periods were observed in which sustained wind speeds of above 17.2 m/s (8 Bft) were measured. From these periods, two storms with wind blowing from the West were the most extreme, namely the storm of February 2nd and that of March 12th. During both storms a significant wave height of 1.4 m was measured and a peak wave period of around 5 s.

During the most extreme conditions, the Elastocoast revetment at the Zuidbout pilot was persistently subjected to high flow velocities and the most unfavourable form of wave loading on a dike slope; namely plunging and collapsing waves.

Pilot location Petten

From the storm season of 2007/2008 only limited data is available due to instrument failure. No data is available for the month of December and beyond February 12th. In the remaining periods five storms were observed in which wind speeds were measured of above 17.2 m/s (8 Bft). Beyond February 12th another two storms occurred, but no data is available from these storms.

During the most extreme conditions, the Elastocoast revetment at the Petten pilot was completely submerged the largest part of the time, especially when the highest waves were measured. Therefore there was no direct wave impact loading on the structure during the most extreme conditions. However, when submerged, the Elastocoast structure was persistently subjected to strongly varying near bed flow velocities.

5.2 CONCLUSIONS FROM SITE MONITORING

Pilot location Zuidbout

From the results of the monitoring period October 2007 to April 2008 the following conclusions can be drawn:

- Microscopic damage to the Zuidbout Elastocoast revetment after the storms of October 2007 to April 2008 is negligible and of no influence on the structure's performance;
- The polyurethane contact points in between rocks are the weakest parts of the structure;
- There is no abrasion damage to the Zuidbout Elastocoast revetment;
- There is no clotting of the open structure of Elastocoast at the Zuidbout.

Pilot location Petten

From the results of the monitoring period October 2007 to February 2008 the following conclusions can be drawn:

§ Microscopic damage to the Petten Elastocoast revetment after the storms of October 2007 to February 2008 is negligible and of no influence on the structure's performance;

§ There is only superficial abrasion damage to the Petten Elastocoast revetment;

§ There is significant clotting of the open structure of Elastocoast at Petten, due to high amounts of sediment, shells and organic material in the coastal water of the North Sea.

General

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§ In contrast to the Zuidbout, the Petten pilot showed excessive amounts of sediment and dirt clogging the open structure and weathering its surface. However, this fine abrasive material does not seem to have any influence on the damage development of the Elastocoast structure.

§ Although the length of the record is limited, it can be concluded on the basis of visual observations that the damage development rate is not progressive, meaning that initial damage does not initiate the development of larger damage. From the visual observations at the pilot locations, the burn-in scenario seems likely. Under this scenario, the rate of erosion diminishes over time as initially poorly bonded stones are eroded from the revetment.

5.3 LESSONS THAT CAN BE LEARNED FROM THE PILOTS

In general, the Dutch pilots were very successful. Two stretches of good quality were produced and performed well during the tempestuous storm season of 2007/2008. Still, important lessons can be learned to assure the quality and performance in future Elastocoast applications.

With analysis of the monitoring data it became clear that the erosion damage to the 20 cm and 30 cm layers of Elastocoast was significantly higher than that of the 10 cm layer. The reason for this is expected to be the small scale of the production process. With batches of only 0.5 m^3 it takes a relatively long time before enough material is dumped for a layer of 20-30 cm thick to be finished and brought to profile. Thus:

The handling time of 20 minutes from the moment of mixing can lead to time shortage when applying thick layers of Elastocoast with small scale production equipment. Consequently, the exceeding of handling time before profiling leads to a decreased bonding strength of the aggregate.

Also, with the construction of the two Dutch pilots the importance of quality monitoring during construction is emphasized:

§ The use of moist aggregate as a base material reduces the strength of the Elastocoast significantly; the structure becomes more vulnerable to material loss through erosion and stripping of the polyurethane film from the rocks.

- The tumble-heating of aggregate to reduce moist content has two implications:
  - presence of more fine fragments in the aggregate on the one hand increases the strength of the Elastocoast system, but on the other hand increases polyurethane consumption and produces a 'dirty' looking end product;
  - the high temperature of the aggregate accelerates the curing process of the polyurethane adhesive, resulting in a reduction of the already short handling time. This could be problematic for the application.

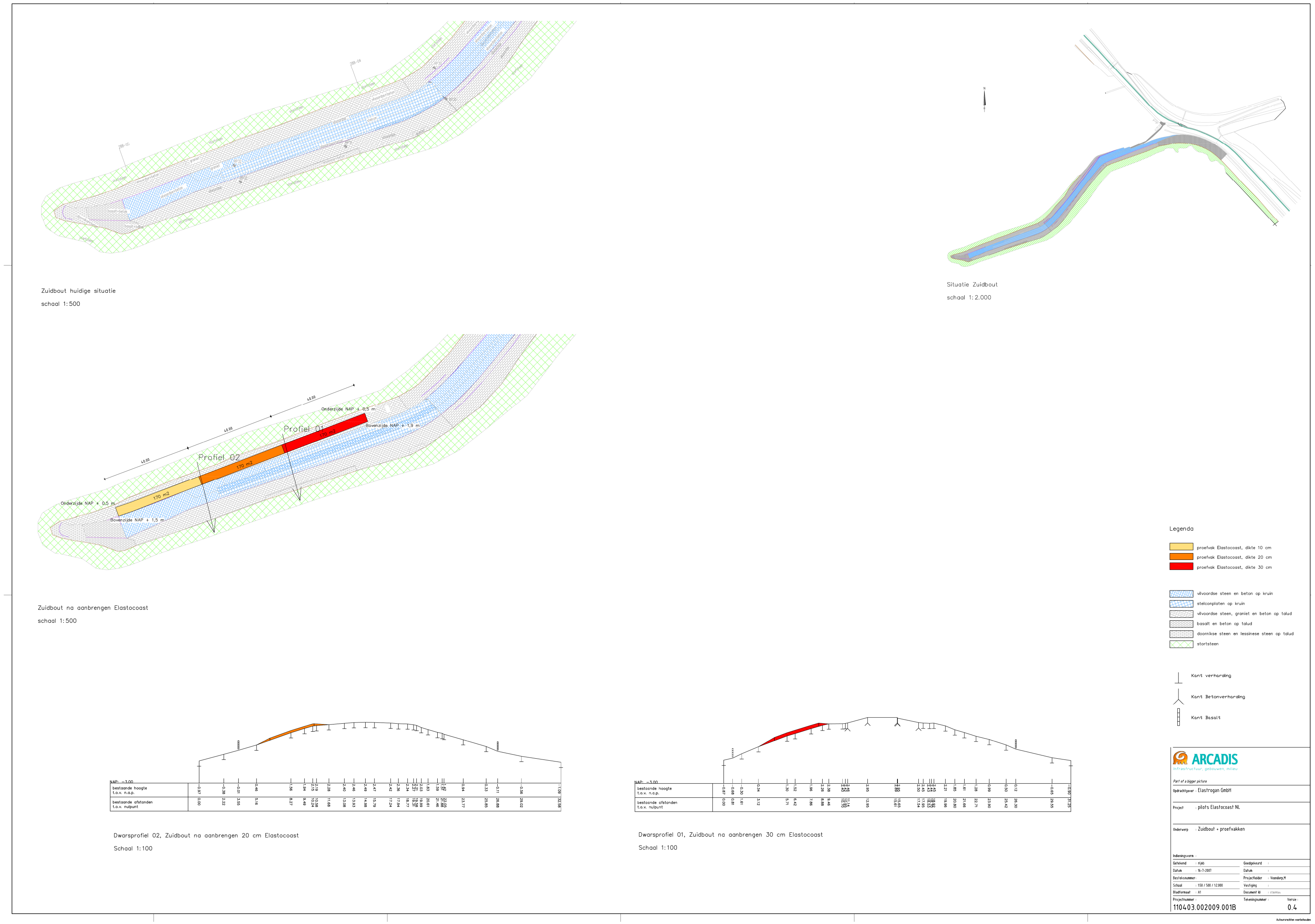
5.4 RECOMMENDATIONS

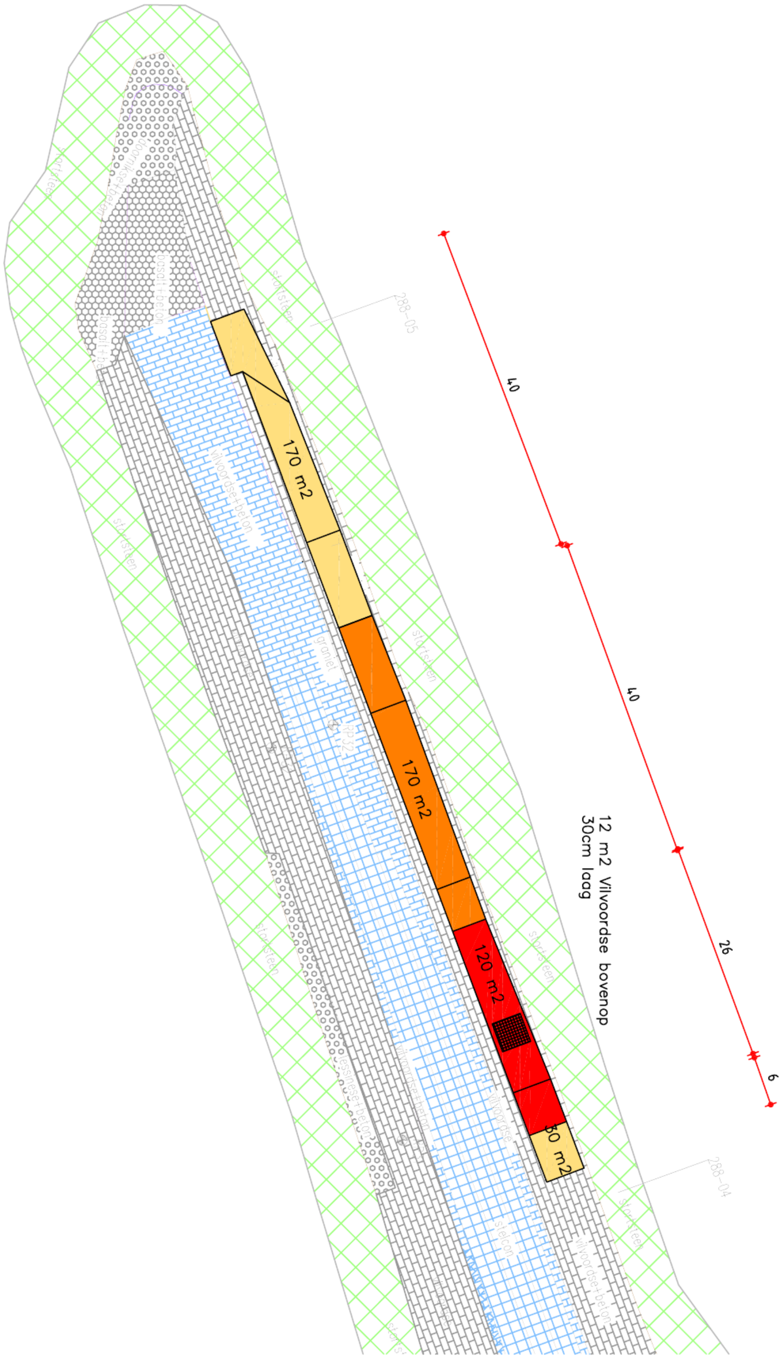
From the research and conclusions of this report the following recommendations can be done:

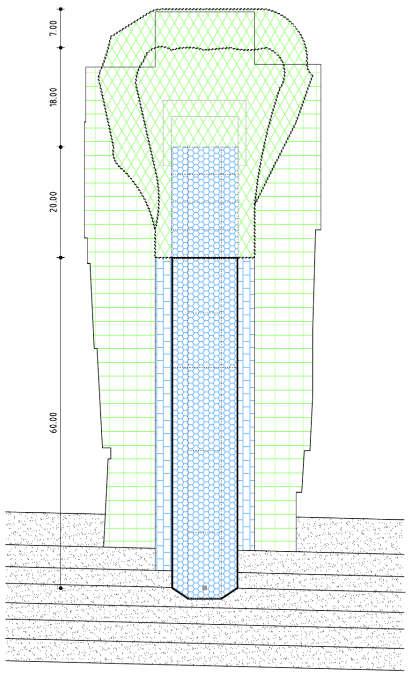
- Further model or prototype research for macroscopic failure mechanisms of a sloping Elastocoast cover layer placed on top a filter layer or directly on a sand bed. Special attention could be given to the clogging of Elastocoast and its influence on macro stability.
- Assurance of quality of the end product can be further improved by development of a standardized on-site quality control system. In this system, for instance, moist content, temperature and processing time should be regularly set to record.

ANNEX 1 Layout drawings of the pilot locations

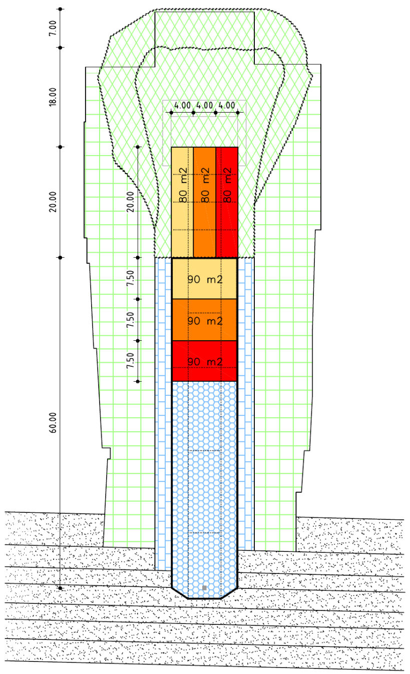
See following pages for drawings of pilot locations on respectively the Zuidbout and near Petten.


Zuidbout huidige situatie
schaal 1:500
Situatie Zuidbout
schaal 1:2.000
Profiel 01
Profiel 02
170 m2
Onderzijde NAP + 0,5 m
Bovenzijde NAP + 1,9 m
Bovenzijde NAP + 1,5 m
Zuidbout na aanbrengen Elastocoast
schaal 1:500
Legenda
proefvak Elastocoast, dikte 10 cm
proefvak Elastocoast, dikte 20 cm
proefvak Elastocoast, dikte 30 cm
vilvoordse steen en beton op kruin
stelconplaten op kruin
vilvoordse steen, graniet en beton op talud
basalt en beton op talud
doornikse steen en lessinese steen op talud
stortsteen
Kant verharding
Kant Betonverharding
Kant Basalt
bestaande hoogte t.o.v. n.a.p.
bestaande afstanden t.o.v. nulpunt
Dwarsprofiel 02, Zuidbout na aanbrengen 20 cm Elastocoast
Schaal 1:100
Dwarsprofiel 01, Zuidbout na aanbrengen 30 cm Elastocoast
Schaal 1:100
ARCADIS
Infrastructuur, gebouwen, milieu
Part of a bigger picture
Opdrachtgever : Elastrogan GmbH
Project : pilots Elastocoast NL
Onderwerp : Zuidbout + proefvakken
Indieningsvorm :
Getekend : rijnb
Datum : 16-7-2007
Besteksnummer :
Schaal : 1:50 / 500 / 1:2.000
Bladformaat : A1
Goedgekeurd :
Datum :
Projectleider : Veendorp,M
Vestiging :
Document Id :
Projectnummer :
Tekeningnummer :
Versie :
110403.002009.001B
0.4
Auteursrechten voorbehouden


170 m2
170 m2
120 m2
12 m2 Vilvoordse bovenop
30cm laag
40
40
26
6



Strekdam 20.9 huidige situatie



Strekdam 20.9 na aanbrengen Elastocoast

Legenda

- proefvak Elastocoast, dikte 10 cm
- proefvak Elastocoast, dikte 20 cm
- proefvak Elastocoast, dikte 30 cm
- gezette basaltzuilen
- vlijwerk basaltzuilen
- ingegoten breuksteen
- zinkstuk met breuksteen
- dijktalud Pettemer zeewering

ARCADIS

Infrastructuur, gebouwen, milieu

Part of a bigger picture

Opdrachtgever : Elastrogan GmbH

Project : Pilots Elastocoast Nederland

Onderwerp : Proefvakken strekdam Pettemer zeewering

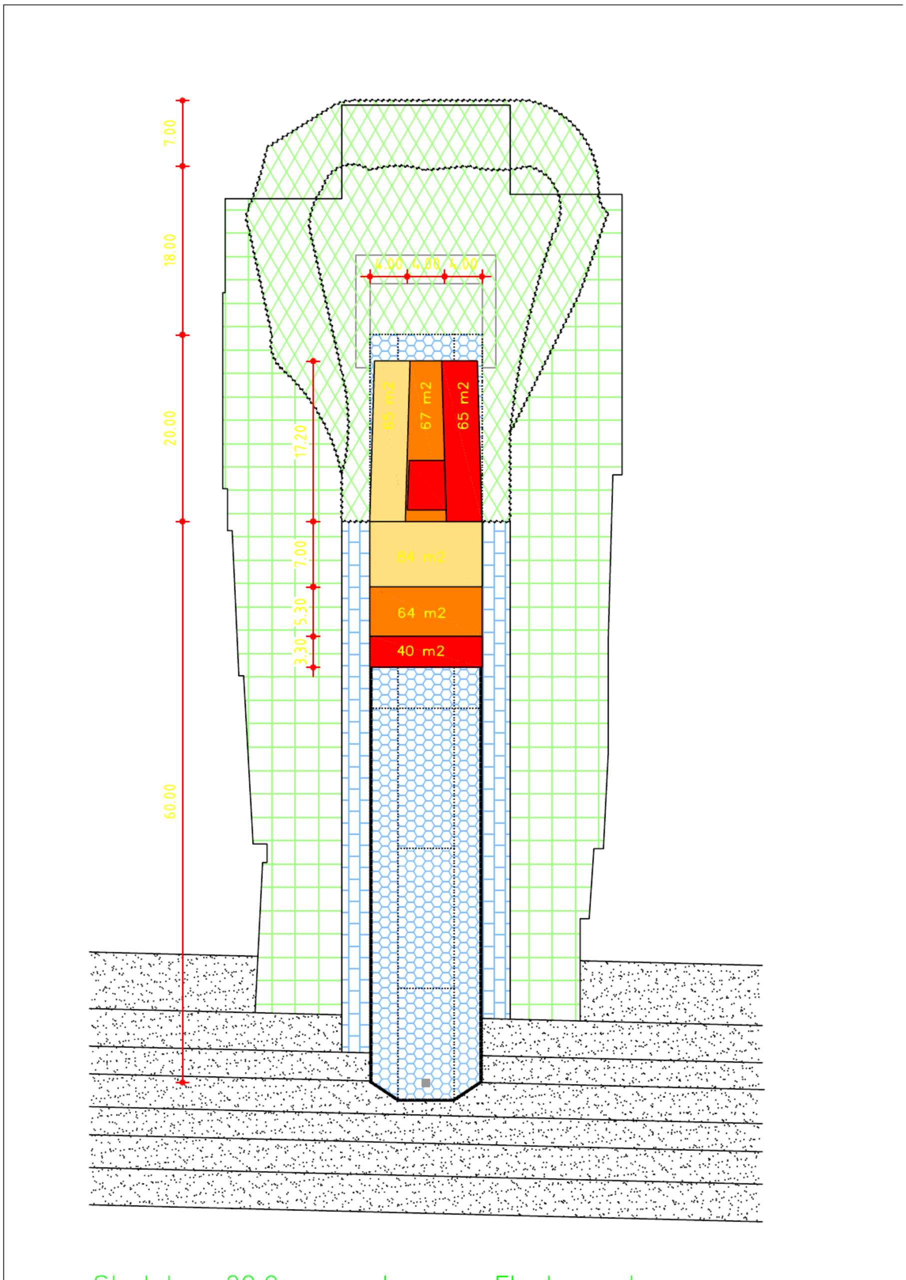
Indieningsvorm :

Getekend	: rijnb	Goedgekeurd	:
Datum	: 4-6-2007	Datum	:
Besteksnummer	:	Projectleider	: Veendorp,M
Schaal	: 1:500	Vestiging	: Hoorn
Bladformaat	: A2	Document Id	: 073699391

Projectnummer : 110403.002009.001B

Tekeningnummer :

Versie : 0!1



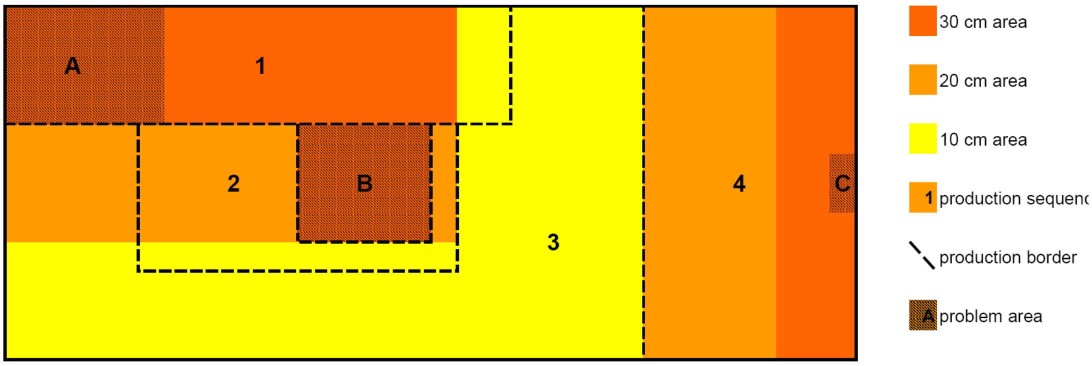
Strekdam 20.9 na aanbrengen Elastocoast

ANNEX 2 Construction report Elastocoast pilot at Petten

Egon Bijlsma, Delft (NL), October 18th 2007

Construction of the Elastocoast Pilot at Petten took place from October 1st to October 3rd 2007. Work was done during two low water periods per day. This gave a time window of about 1-2 hours during daytime and 3 hours during night time. The total construction was finished in 4 shifts.

The following sketch gives an overview of the production during each tide:



Problems during construction

During construction the following problems were encountered:

- October 1st, 14:45 - Stones arrive at construction site with too high of moisture content. Stones are spread out to dry and construction is postponed to next low water period.
- October 2nd, 02:50 - The first stretch of Elastocoast is put about 3 meters further away from the head of the beach groyne than planned. This part of the groyne doesn't get dry due to wave action and puddles of water. The stones used for the first part of the 30 cm stretch are still a bit wet (area A). The furthest parts of the 10 cm layer are less thick than they should be. Production is high.
- October 2nd, 04:05 - The 0.5 m^2 mixer breaks down. Production continues with 1 / 3rd of initial capacity. A few cans of Elastocoast are discarded due to exceeding of time limit between mixturing and adding to the stones. Mixer is fixed at 08:00.
- October 3rd, 03:40 - Some parts of the tumble dried stones that have been placed during daytime were too hot. Bad parts of the 20 cm stretch are removed by hand and this part is heightened to 30 cm (area B).
- October 3rd, 15:00 - New tumble dried stones are also too hot (this time the burners in the tumble dryer were left off). Work starts 50 minutes later. Due to tumbling process the stones contain a high percentage of dirt and small fractions (causes red color). Quality varies per load. A small part of the stones is still too hot (area C).

Expected behaviour during storm season

Considering its open structure and high strength bonding it is expected that Elastocoast will show good performance under storm conditions. Large scaled failure is not expected on beforehand.

However, considering the previously mentioned problems during construction one can say that the quality of the Elastocoast stretches varies greatly. If failure occurs, it will show first in the mentioned problem areas. The other areas are good for the pilot test to give representative results.

Problem area B: extra 10 cm on top of bad area where stones were too hot.

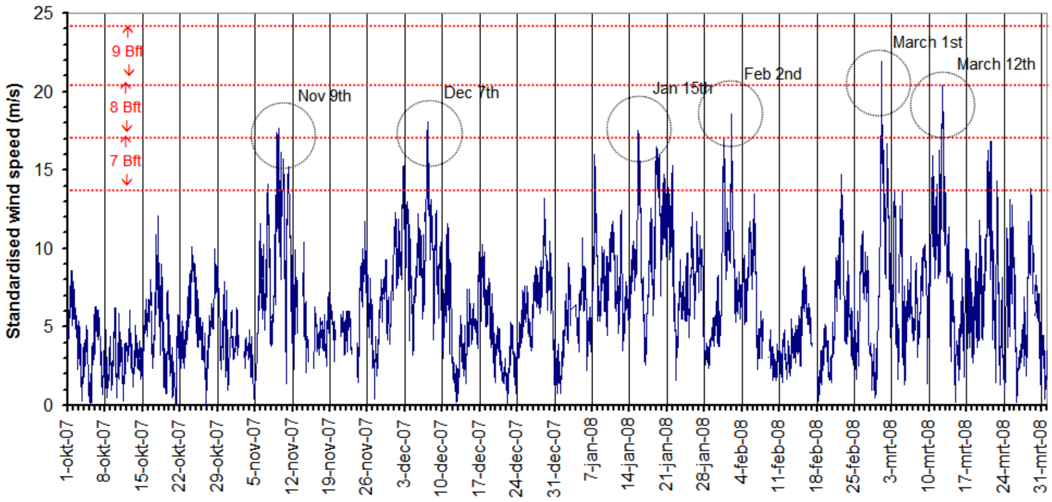
Problem areas A (left) and C (right): some stones can be removed by hand. Stones in Area C are red due to dust from tumbler.

ANNEX 3 Detailed storm analysis

Pilot location Zuidbout - wind field at Stavenisse:

Figure III.1

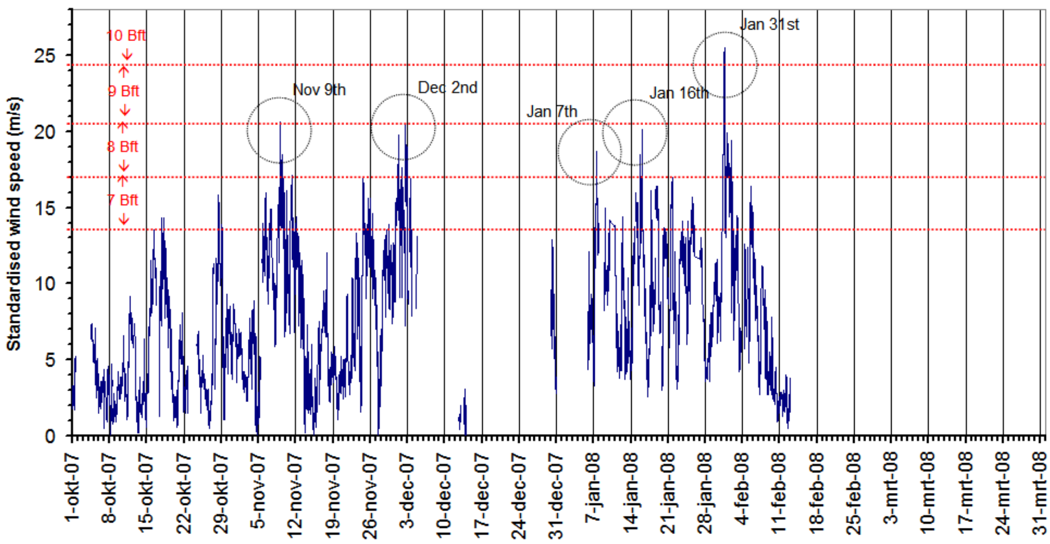
In the storm season of 2007/2008 at the Zuidbout there were six periods with sustained wind speeds above 17 m/s.



Pilot location Petten - wind field at measuring pole no. 6:

Figure III.2

In the storm season of 2007/2008 at Petten there were five periods with measured wind speeds above 17 m/s.



Pilot Zuidbout - storm of November 9th, 2007:

Figure III.3
Wind speed and direction from November 8th to November 11th.

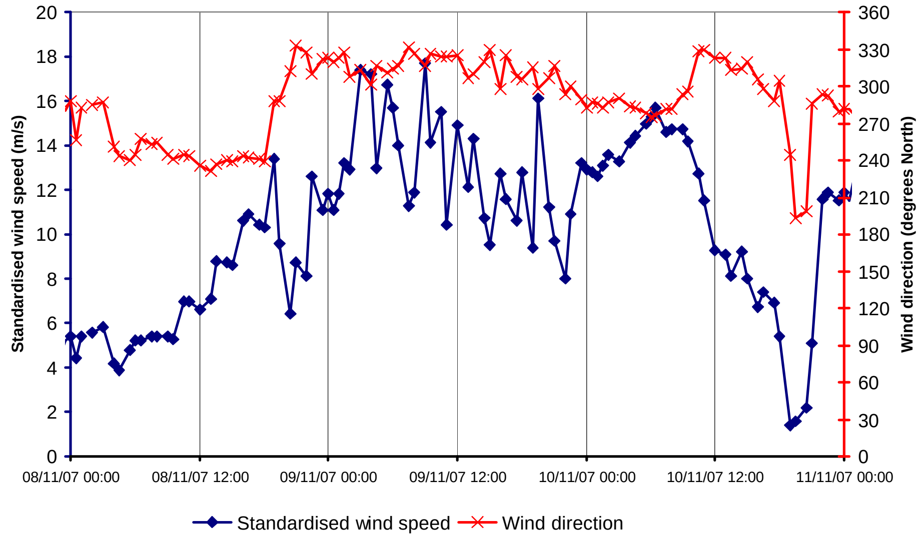


Figure III.4
Predicted and actually observed water levels at Stavenisse.

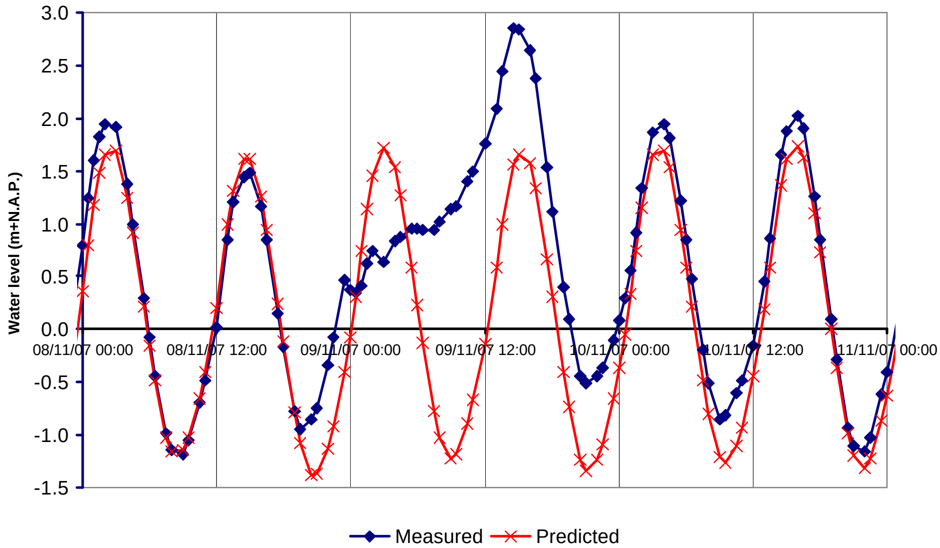


Figure III.5
Wind setup.

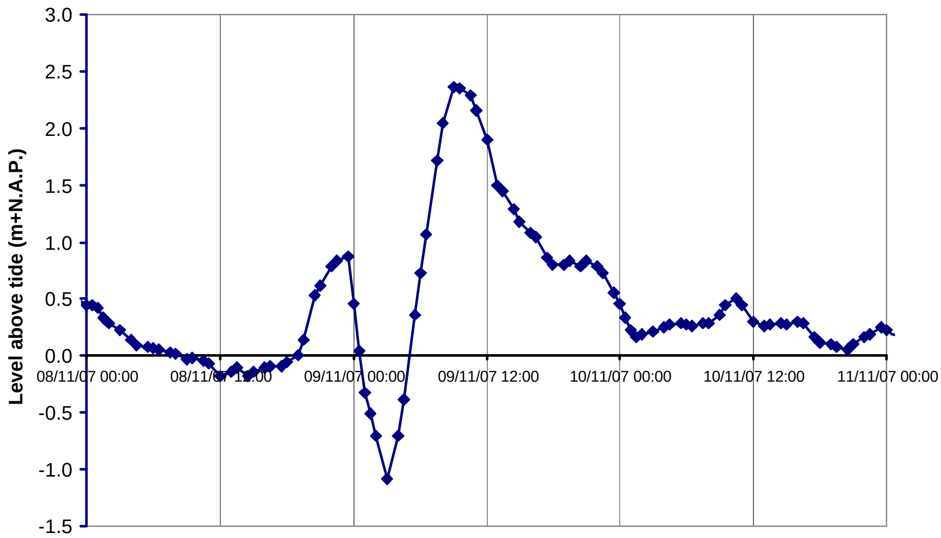
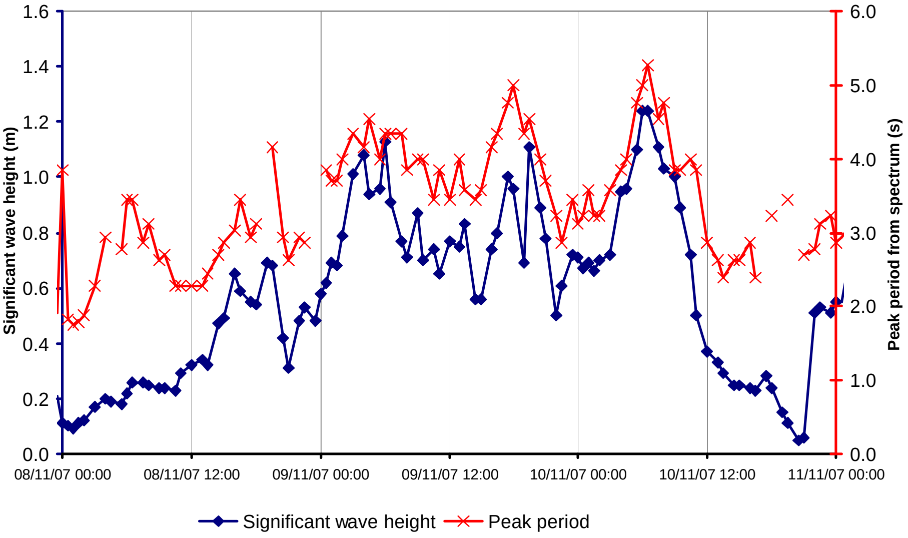


Figure III.6

Significant wave height and peak period.



Pilot Petten – storm of November 9, 2007:

Figure III.7

Wind speed and direction from November 8th to November 11th.

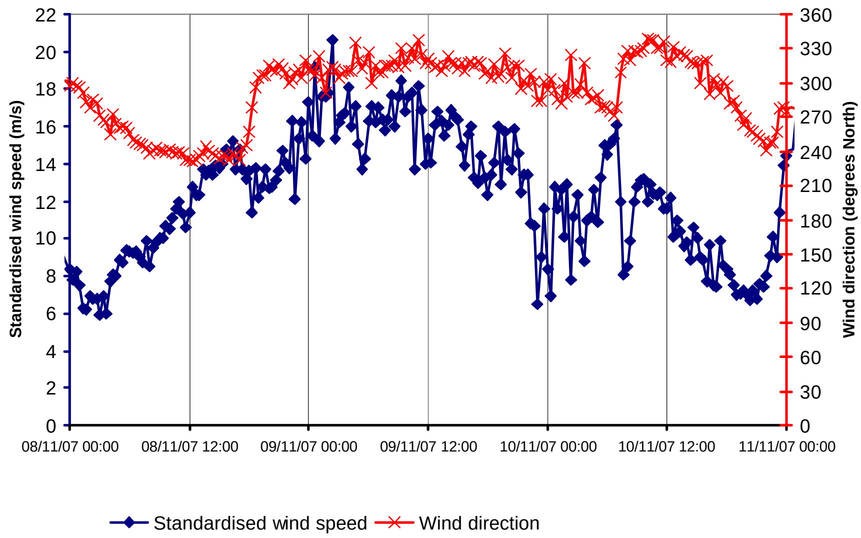


Figure III.8

Predicted water level for Petten Zuid and actually observed water levels at the pilot.

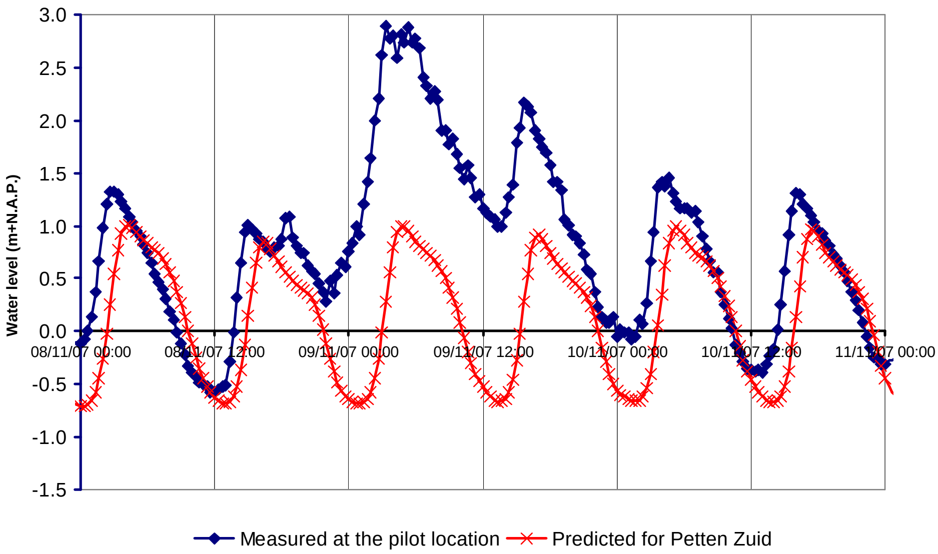


Figure III.9

Wind setup.

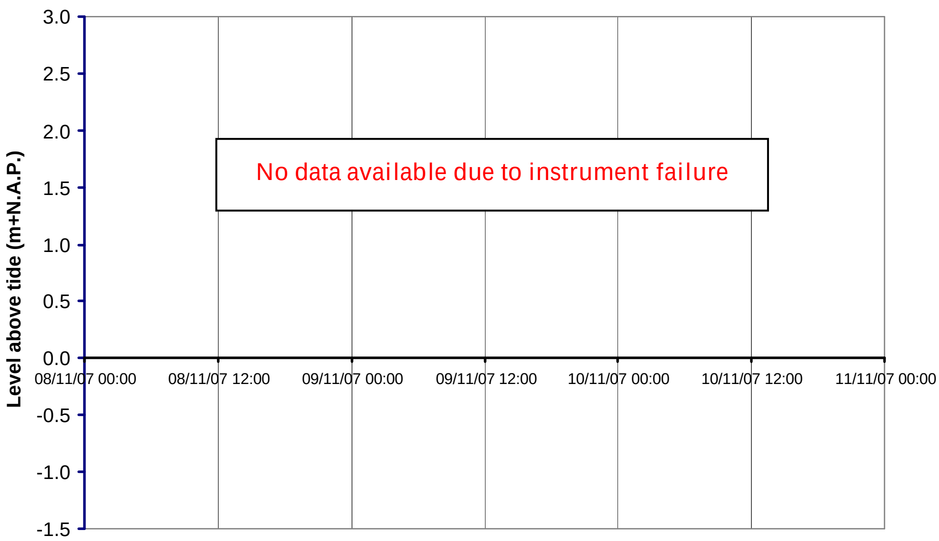
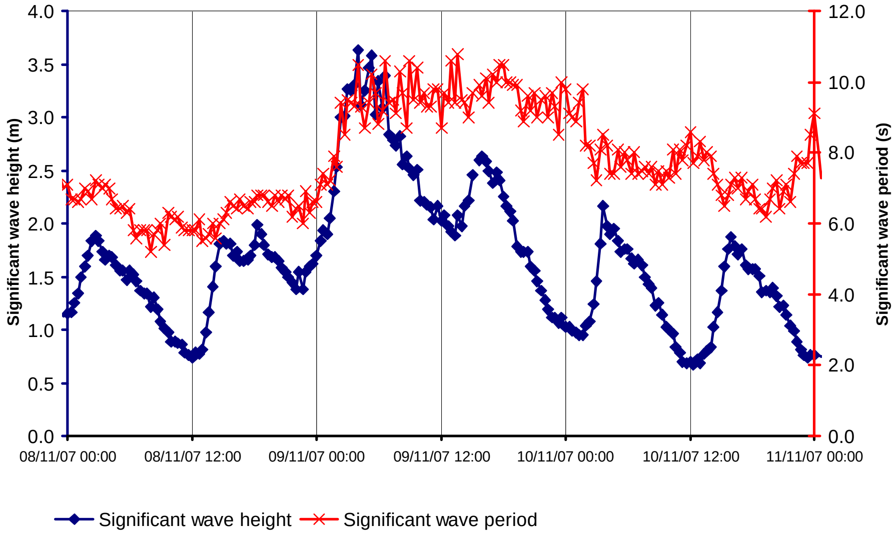


Figure III.10

Significant wave height and significant wave period.



Pilot Petten – storm of December 2nd, 2007:

Figure III.11
Wind speed and direction from November 30th to December 12th.

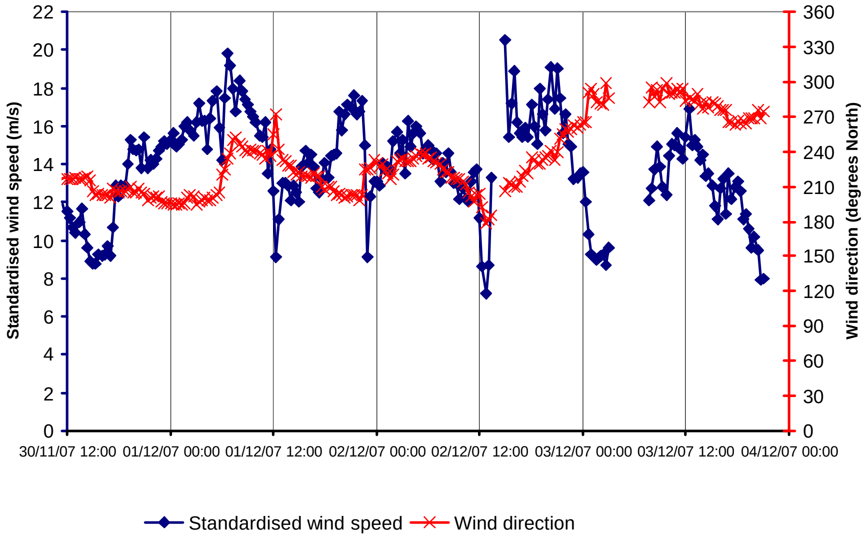


Figure III.12
Predicted water level for Petten Zuid and actually observed water levels at the pilot.

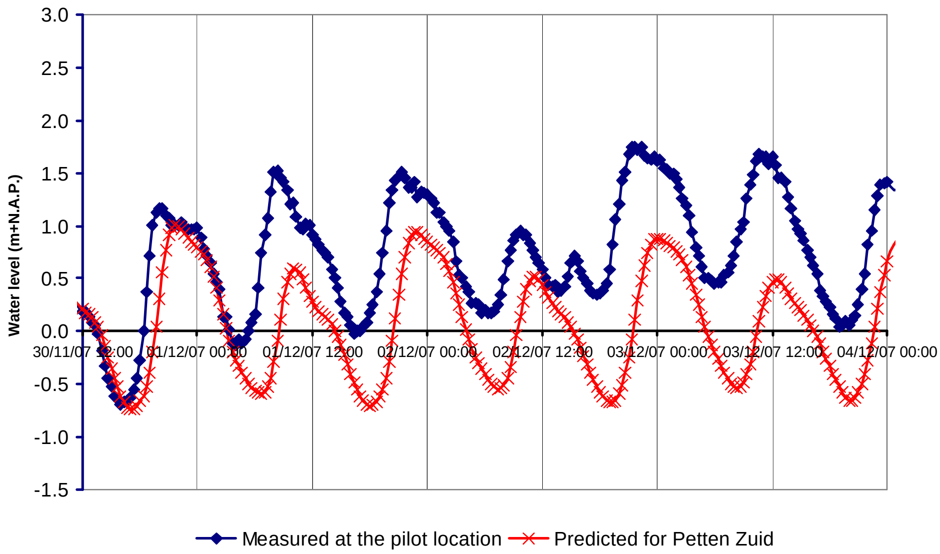


Figure III.13
Wind setup.

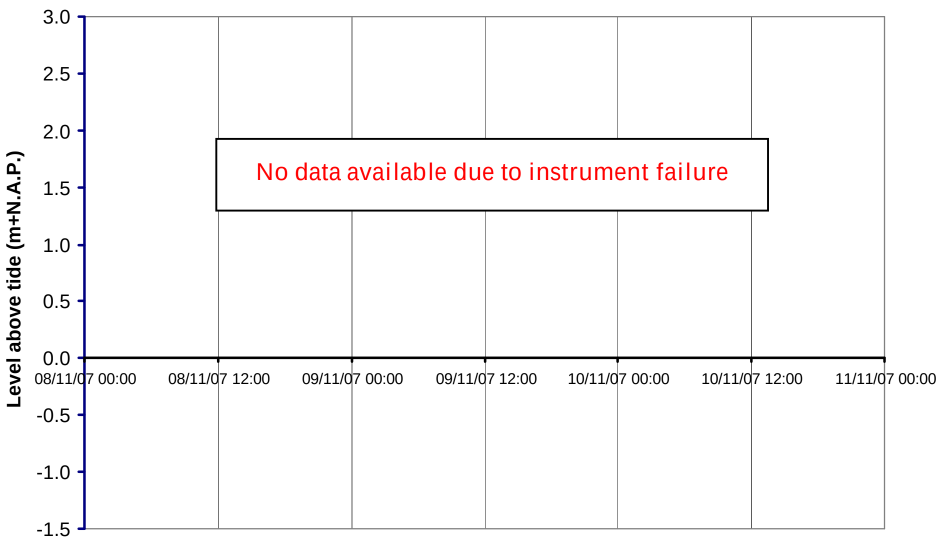
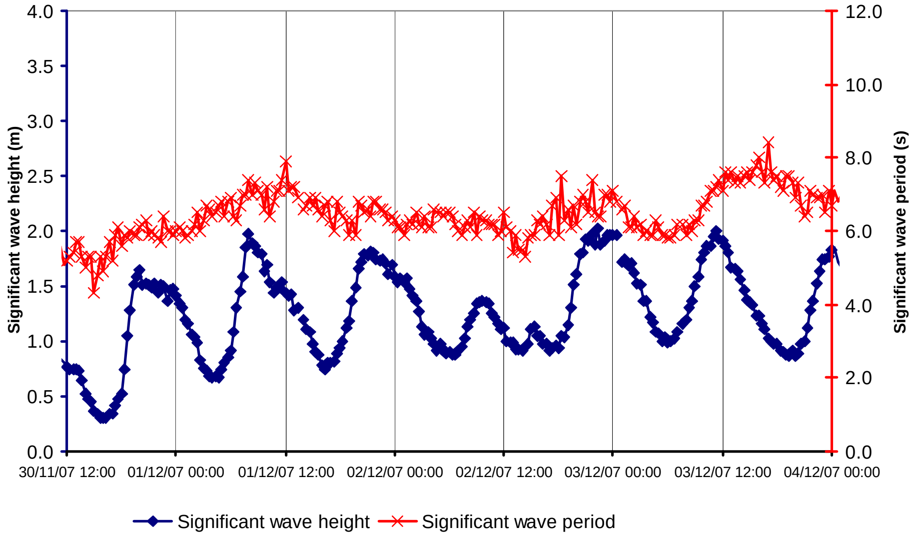


Figure III.14

Significant wave height and significant wave period.



Pilot Zuidbout – storm of December 7th, 2007:

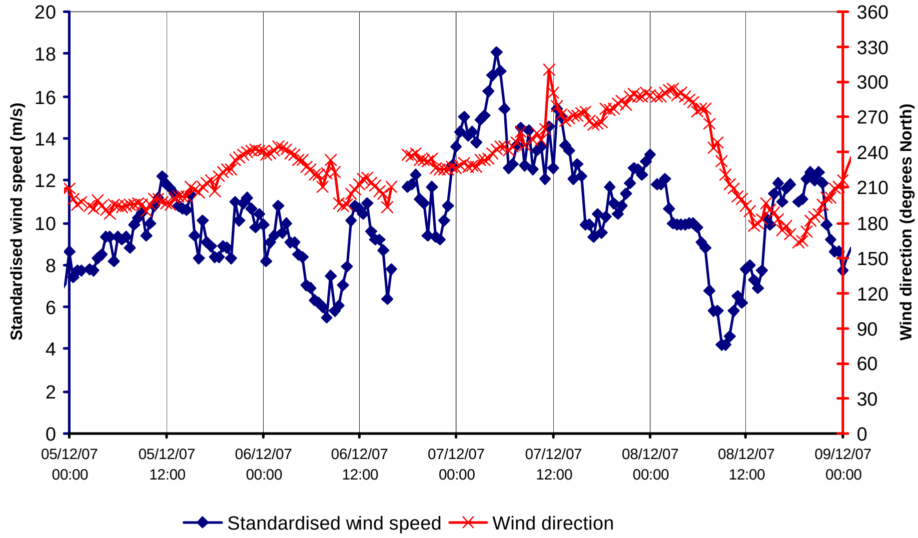


Figure III.15
Wind speed and direction from December 12th to December 9th.

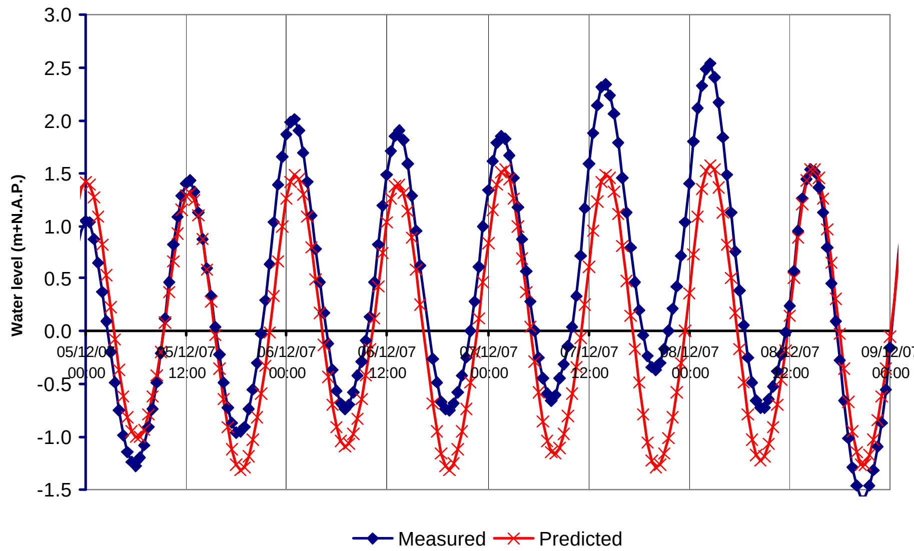


Figure III.16
Predicted and actually observed water levels at Stavenisse.

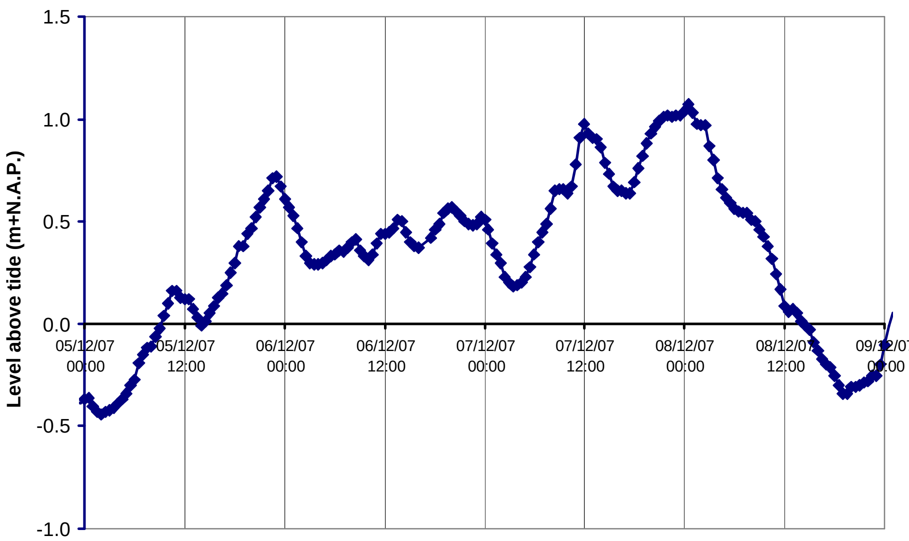
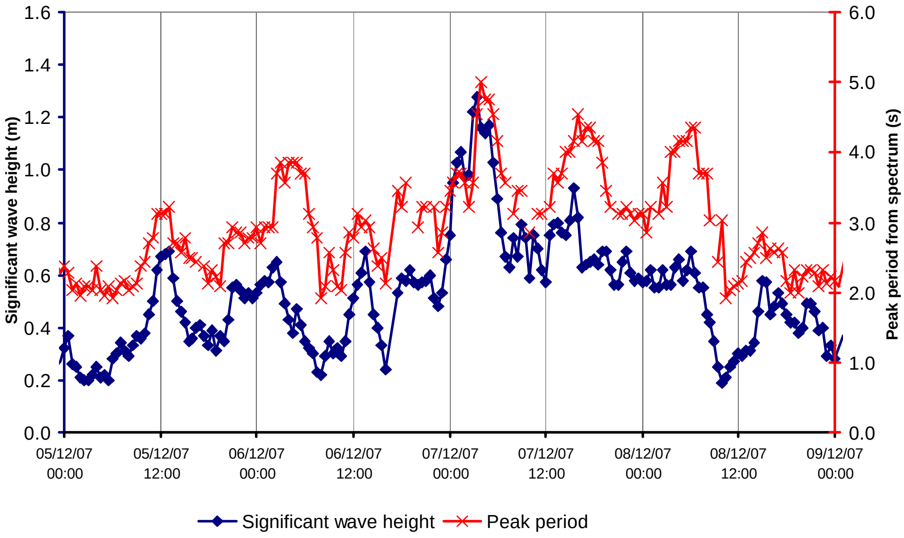


Figure III.17
Wind setup.

Figure III.18

Significant wave height and peak period.



Pilot Petten – storm of January 7th, 2008:

Figure III.19
Wind speed and direction from January 5th to January 8th.

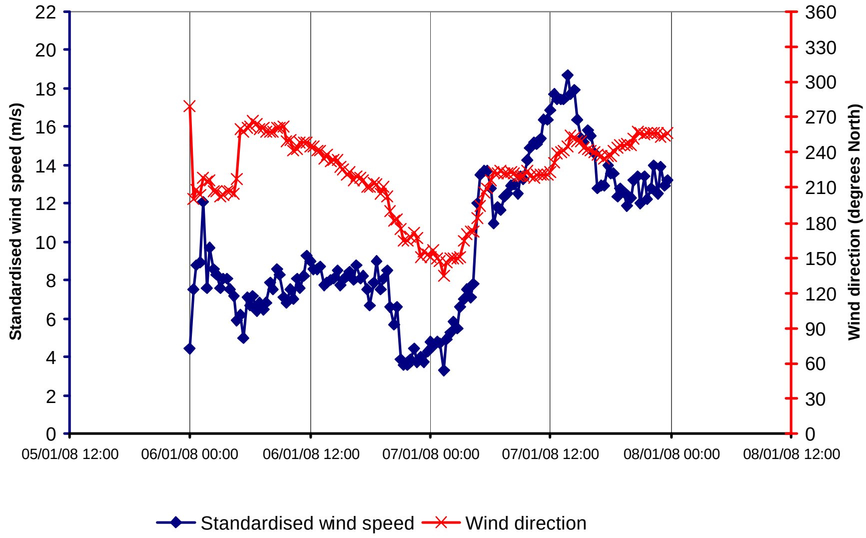


Figure III.20
Predicted water level for Petten Zuid and actually observed water levels at the pilot.

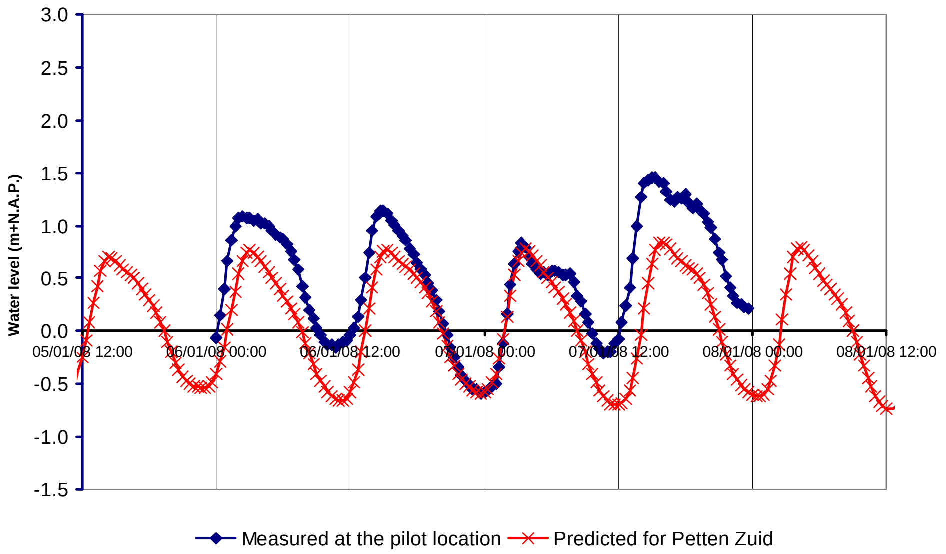


Figure III.21
Wind setup.

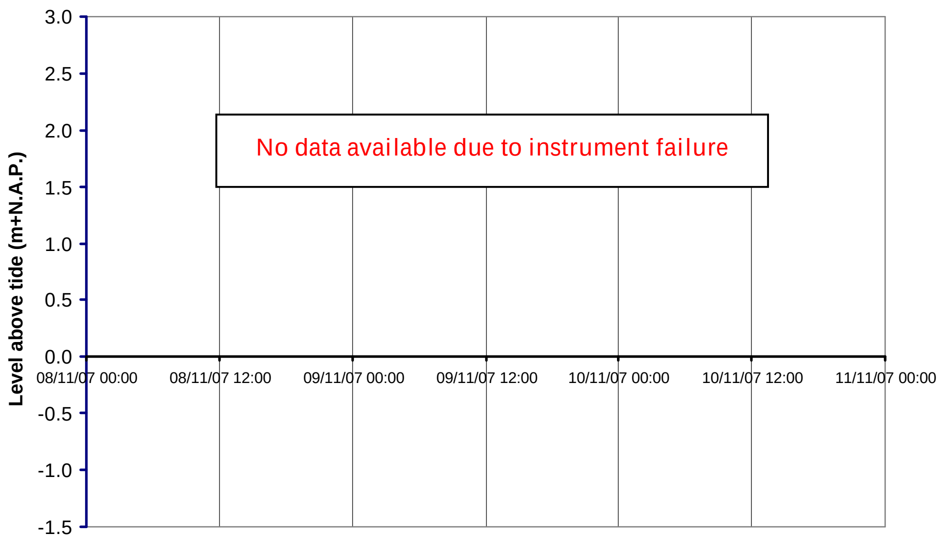
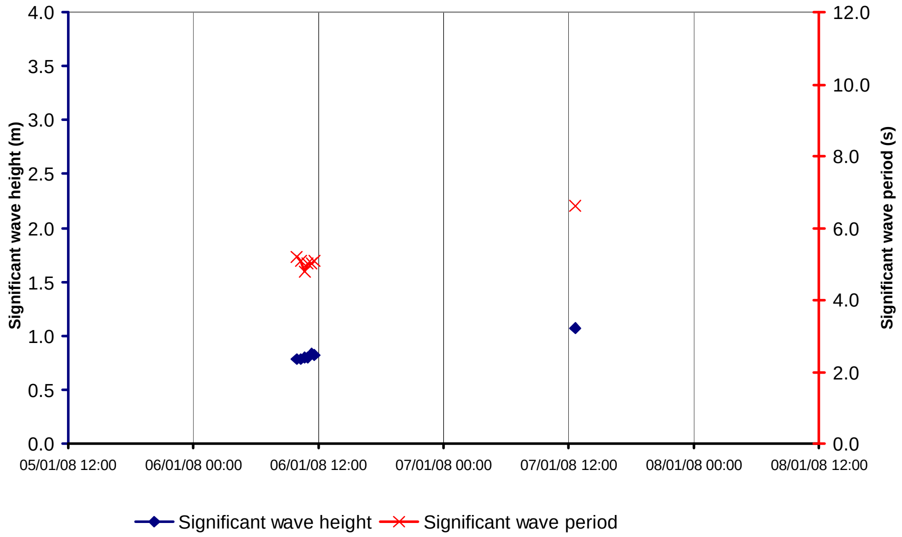


Figure III.22

Significant wave height and significant wave period.



Pilot Zuidbout – storm of January 15th, 2008:

Figure III.23
Wind speed and direction from January 13th to January 17th.

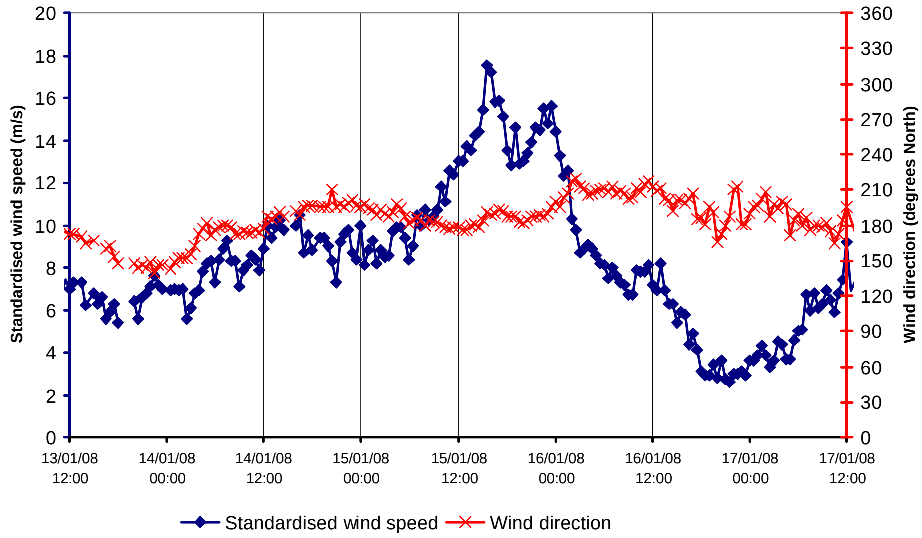


Figure III.24
Predicted and actually observed water levels at Stavenisse.

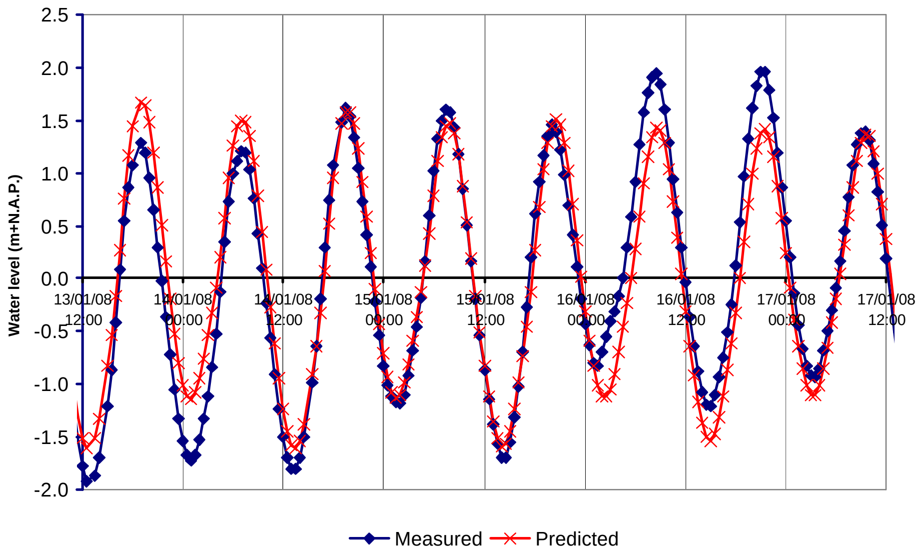


Figure III.25
Wind setup.

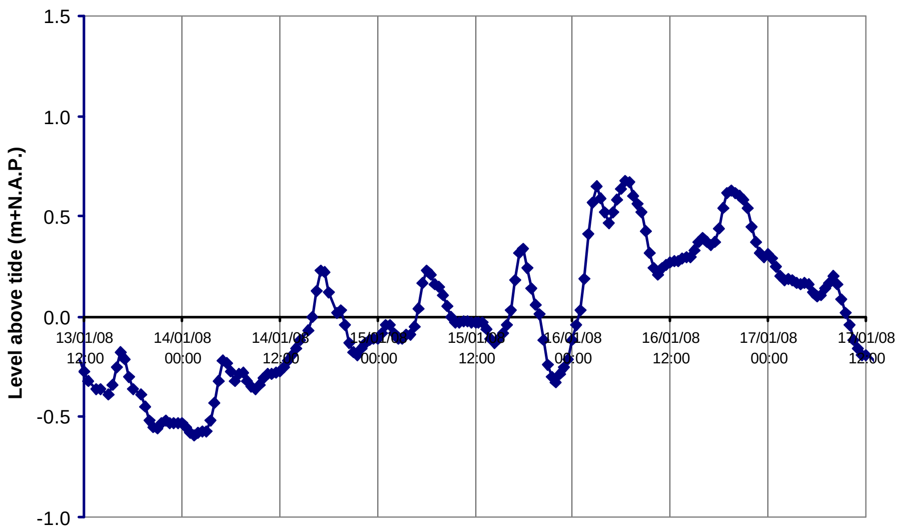
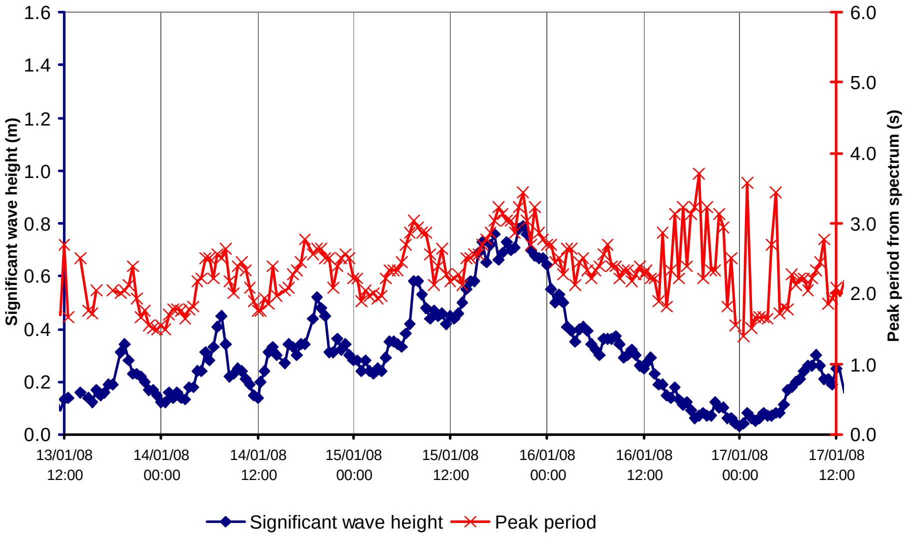


Figure III.26

Significant wave height and peak period.



Pilot Petten – storm of January 16th, 2008:

Figure III.27
Wind speed and direction from January 14th to January 17th.

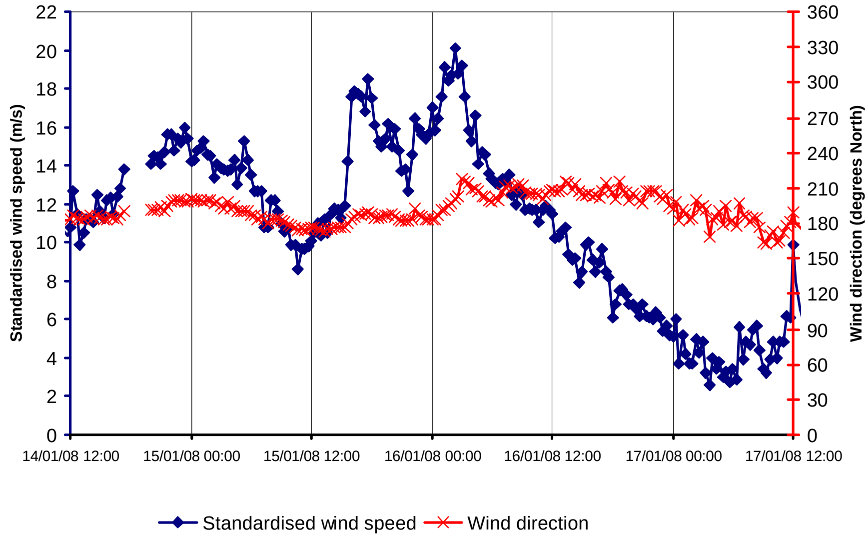


Figure III.28
Predicted water level for Petten Zuid and actually observed water levels at the pilot.

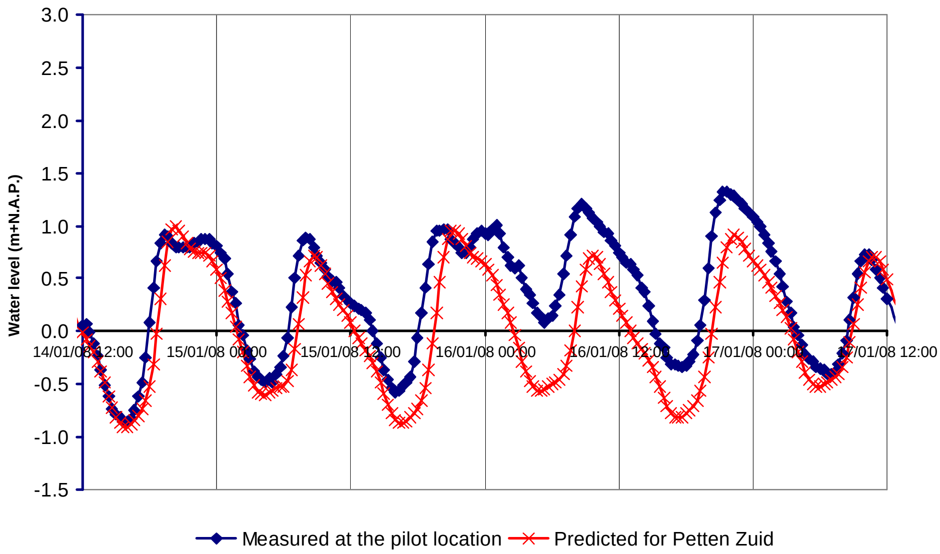


Figure III.29
Wind setup.

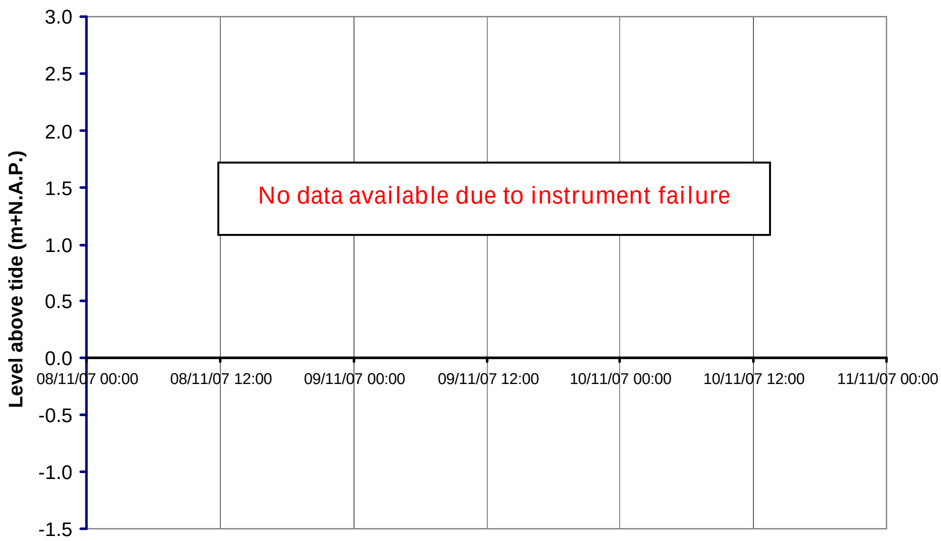
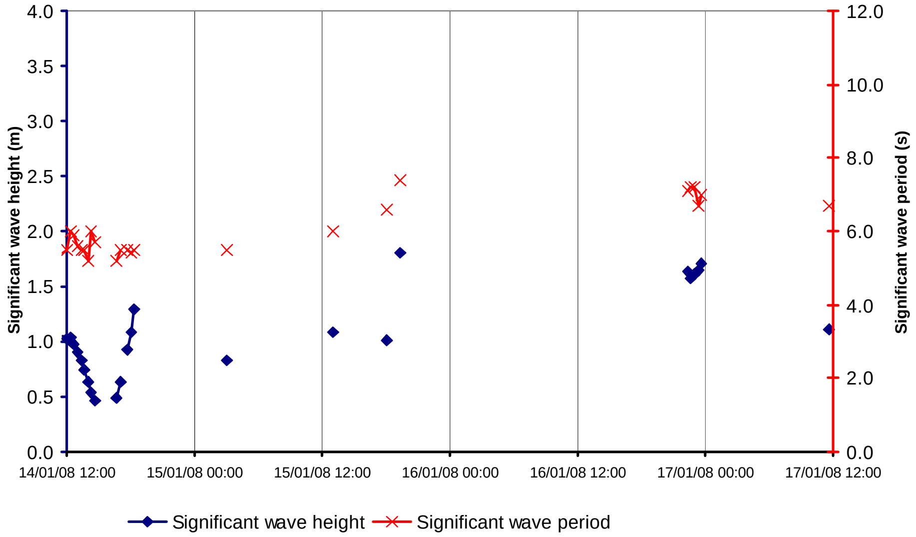


Figure III.30

Significant wave height and significant wave period.



Pilot Petten – storm of January 31st, 2008:

Figure III.31

Wind speed and direction from January 30th to February 3rd.

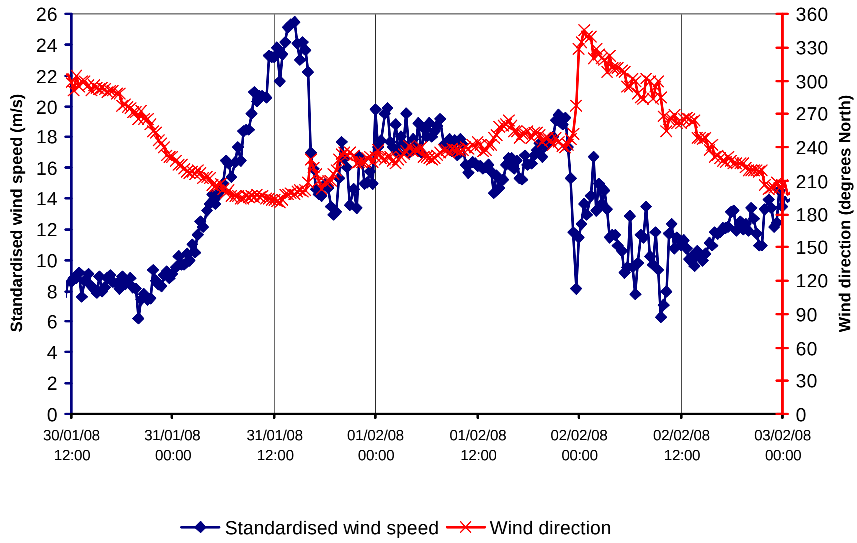


Figure III.32

Predicted water level for Petten Zuid and actually observed water levels at the pilot.

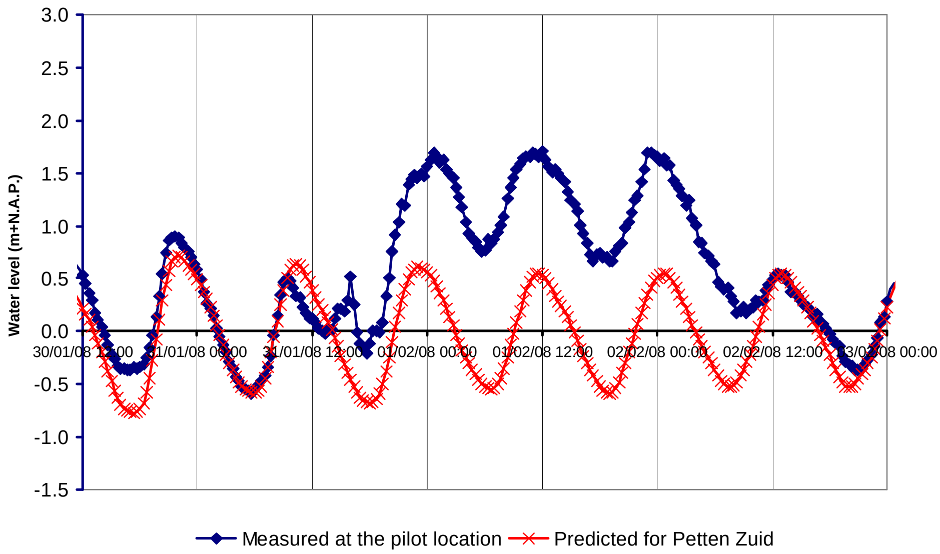


Figure III.33

Wind setup.

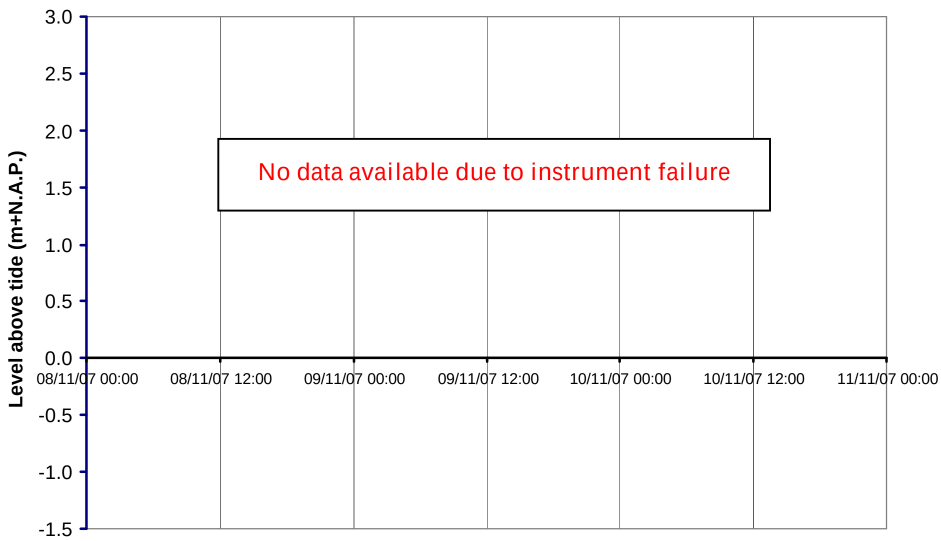
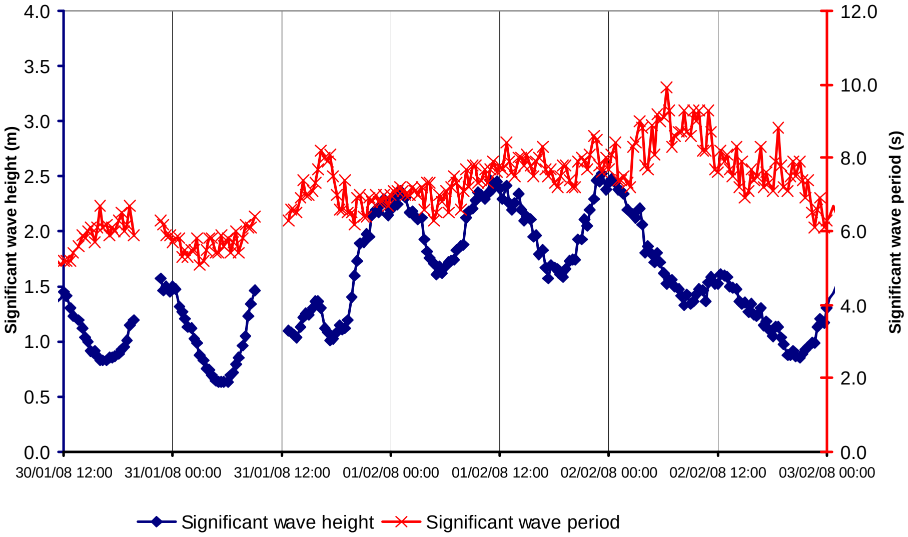


Figure III.34

Significant wave height and significant wave period.



Pilot Zuidbout – storm of February 2nd, 2008:

Figure III.35

Wind speed and direction from January 29th to February 3rd.

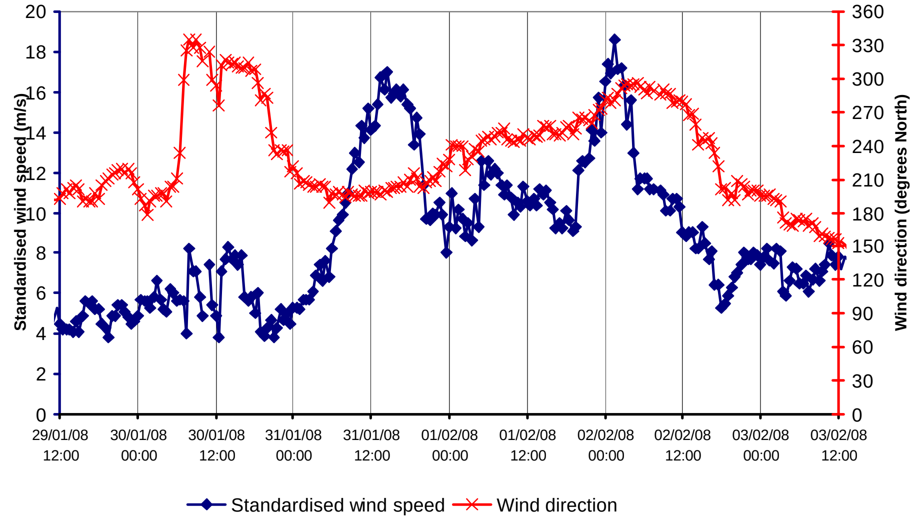


Figure III.36

Predicted and actually observed water levels at Stavenisse.

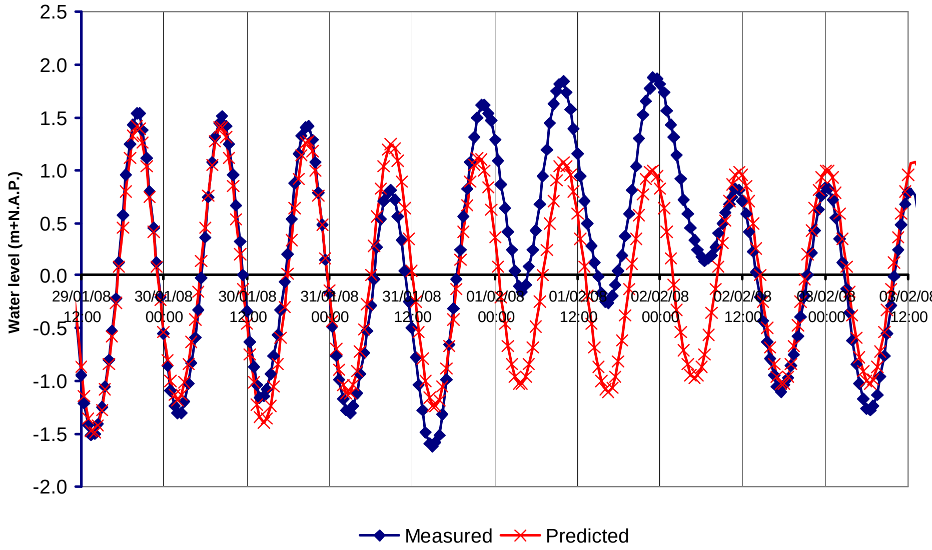


Figure III.37

Wind setup.

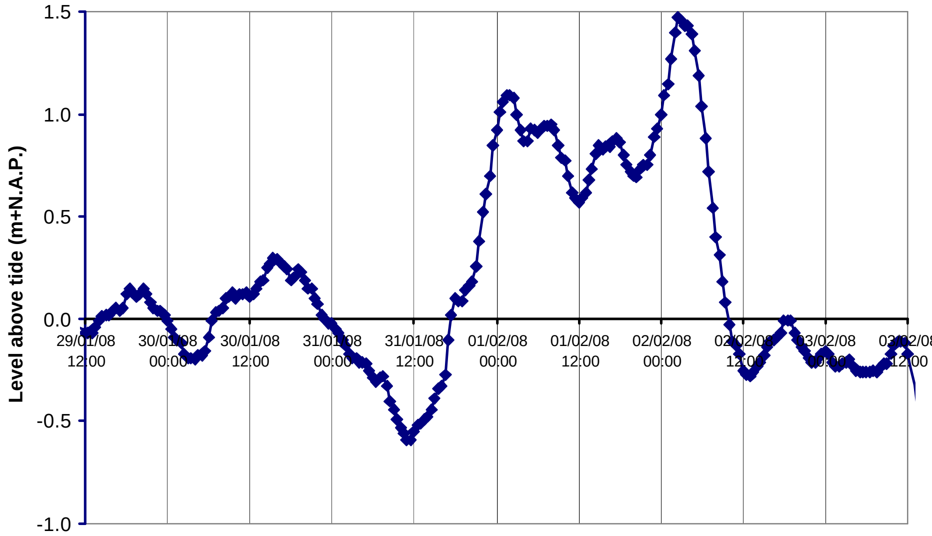
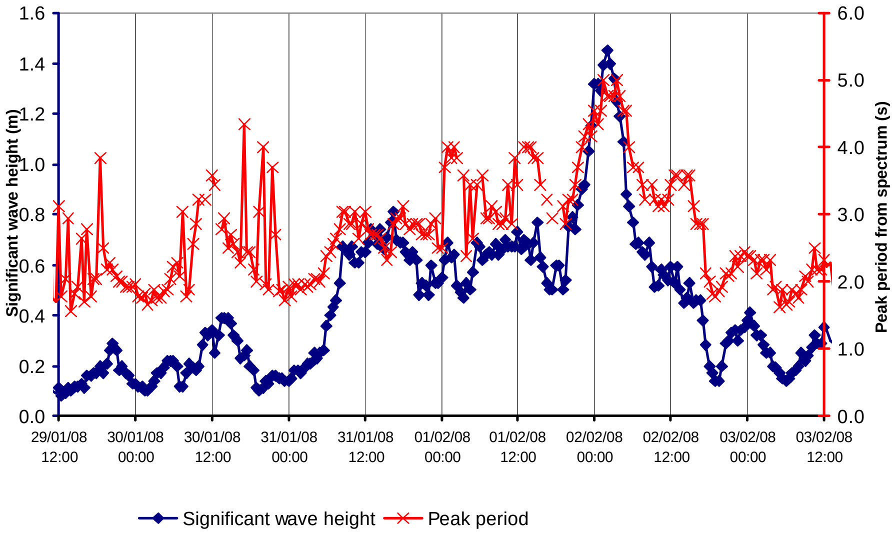


Figure III.38

Significant wave height and peak period.



Pilot Zuidbout – storm of March 1st, 2008:

Figure III.39

Wind speed and direction from February 29th to March 3rd.

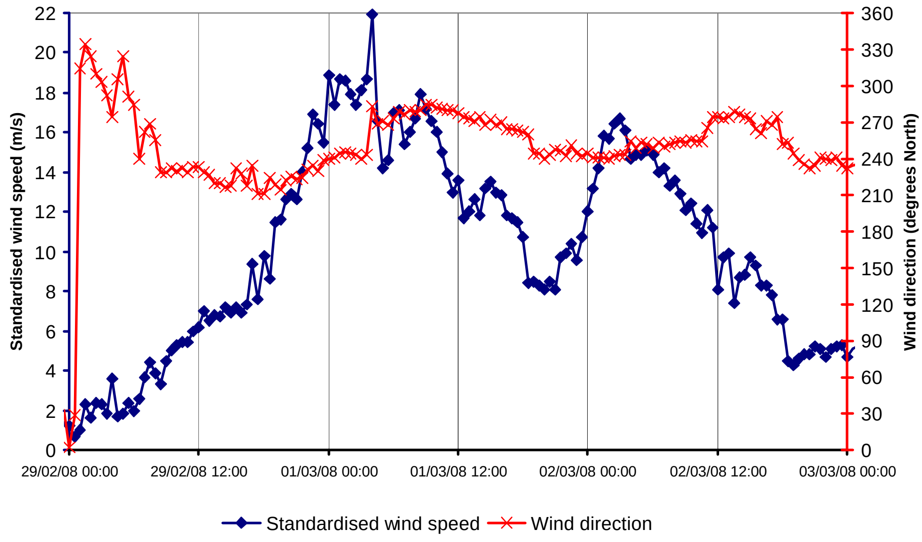


Figure III.40

Predicted and actually observed water levels at Stavenisse.

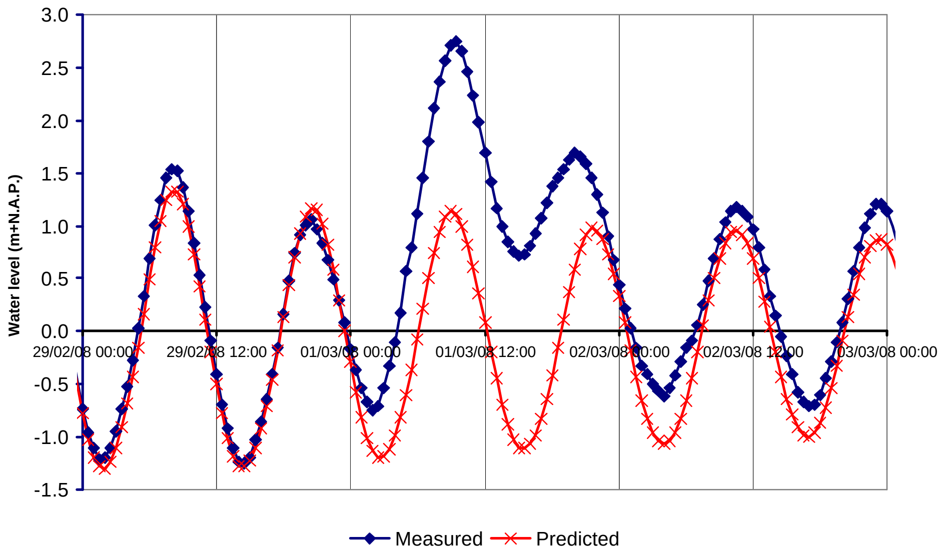


Figure III.41

Wind setup.

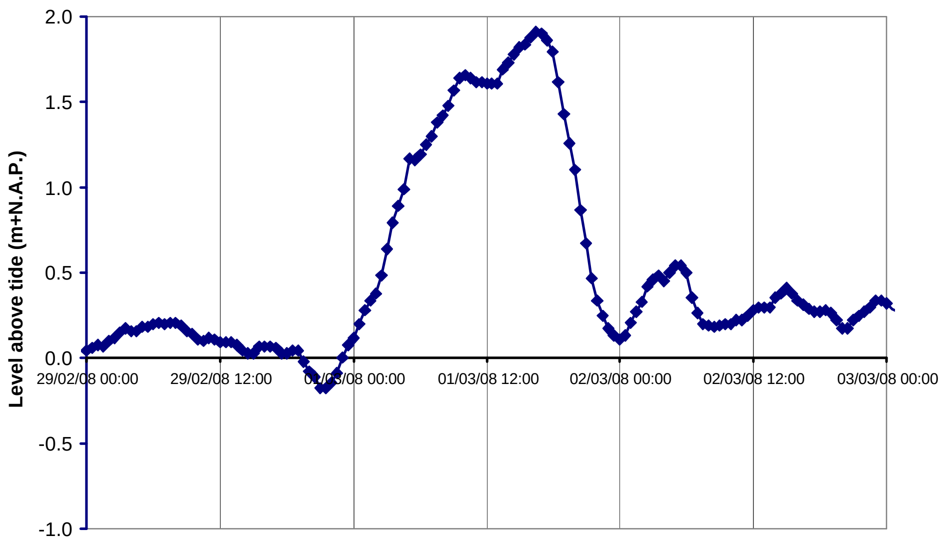
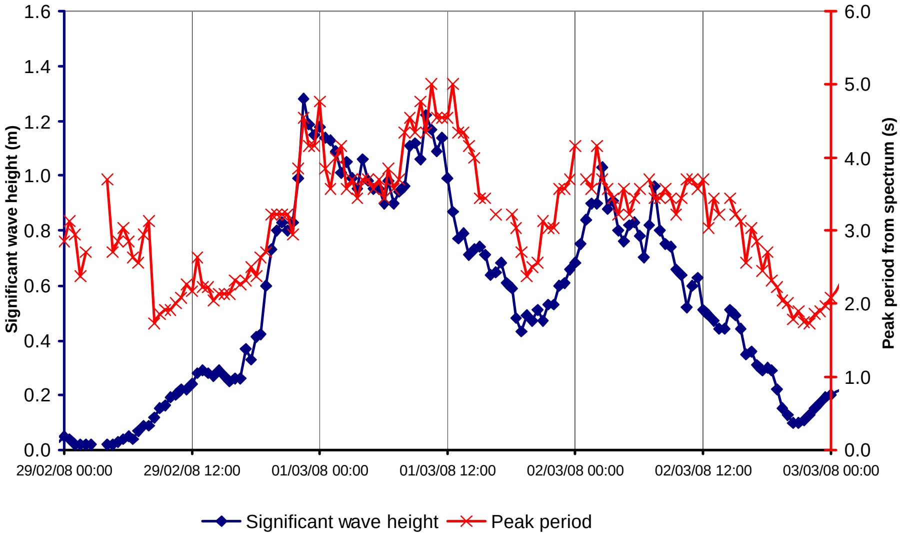


Figure III.42

Significant wave height and peak period.



Pilot Zuidbout – storm of March 12th, 2008:

Figure III.43

Wind speed and direction from March 10th to March 14th.

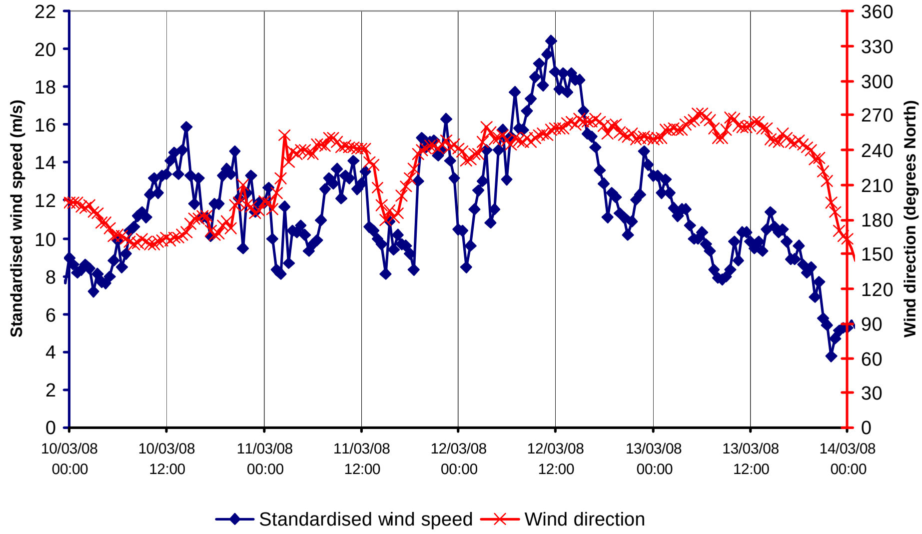


Figure III.44

Predicted and actually observed water levels at Stavenisse.

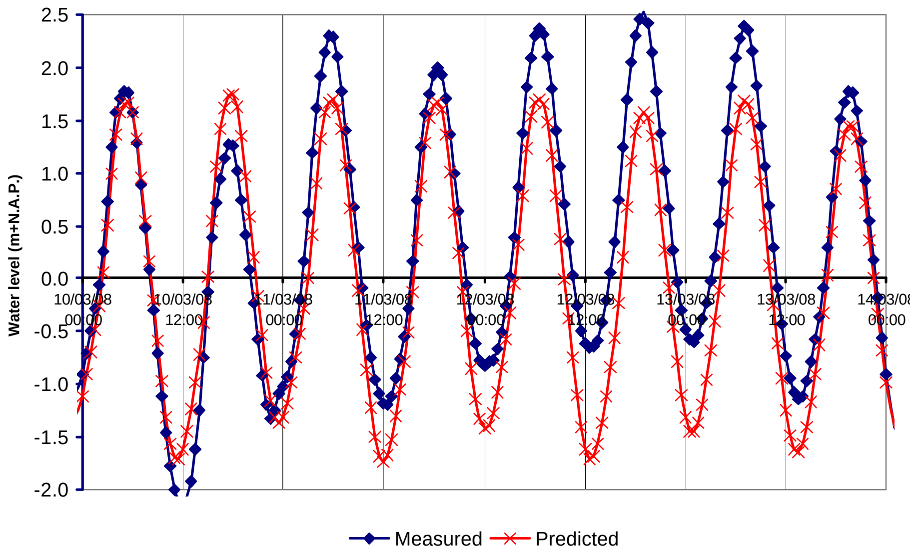


Figure III.45

Wind setup.

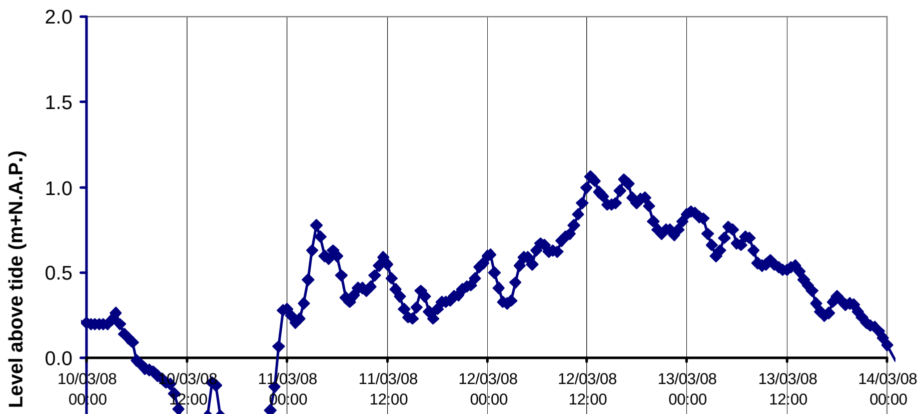
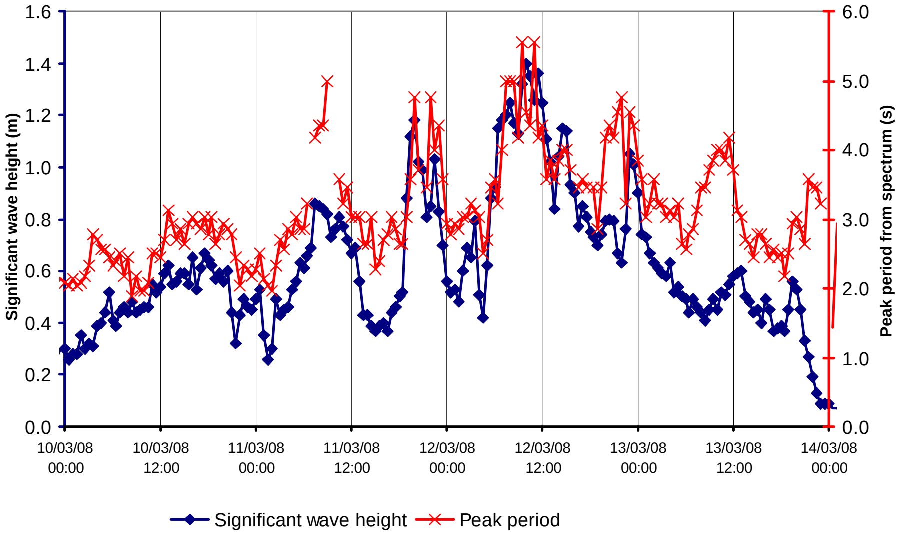


Figure III.46

Significant wave height and peak period.



ANNEX

Glossary

Abrasion	The mechanical wearing, grinding, scraping, or rubbing away of revetment components by friction or impact, or both.
Aggregate	The natural sands, gravels, and crushed stones used in the manufacture of concrete or asphalt.
Apron	Layer of stone, concrete or other material to protect the toe of a structure.
Astronomical tide	see tide
Bathymetry	The measurement of depths of water in oceans, seas, and lakes; also information derived from such measurements.
Breaker type	A wave breaking on a shore, over a reef, etc. Breakers may be classified into four types: surging, collapsing, plunging and spilling.
Burn-in	The process by which components of a system are exercised prior to being placed in service. The intention is to detect those particular components that would fail as a result of infant mortality. After the burn-in period, the system can then be trusted to be mostly free of further early failures once the burn-in process is complete.
Collapsing breaker	Breaking occurs over lower half of wave, with minimal air pocket and usually no splash up. Bubbles and foam present.
Crest height (dike)	Highest point on a beach face, breakwater, seawall, dam, dike, spillway or weir.
Erosion	The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal current or wind.
Estuary	The region near a river mouth in which the fresh water of the river mixes with the salt water of the sea.
Fetch	The area in which seas are generated by a wind having a fairly constant direction and speed. Sometimes used synonymously with fetch length, which is the horizontal distance, (in the direction of the wind) over which a wind generate seas or creates wind setup.
Grading (rock)	The proportions by mass of a soil or fragmented rock distributed in specified particle-size ranges.
Groyne	A shore protection structure built (usually perpendicular to the shoreline) to trap littoral drift or retard erosion of the shore. In US called a groin.
Inlet	1) A short, narrow waterway connecting a bay) lagoon) or similar body of water with a large parent body of water. (2) An arm of the sea (or other body of water) that is long compared to its width and may extend a considerable distance inland.
Lee	Shelter, or the part or side sheltered or turned away from the wind or waves.
Nominal rock size	Nominal diameter or rock proportional to the sieve size with D_n=0.84 D, a value used for characteristic size of armourstones.
Peak period	The wave period determined by the inverse of the frequency at

	which the wave energy spectrum reaches its maximum.
Plunging breaker	Crest curls over air pocket; breaking is usually with a crash. Smooth splash up usually follows.
Porosity	The ratio, usually expressed as a percentage, of (1) the volume of voids of a given soil or rock mass, to (2) the total volume of the soil or rock mass.
Revetment	A facing of stone, concrete, etc., built to protect a scarp, embankment, or shore structure against erosion by wave action or currents.
Semidiurnal tide	A tide with two high waters and two low waters in a tidal day with comparatively little diurnal inequality.
Significant wave	A statistical term relating to the one-third highest waves of a given wave group and defined by the average of their heights and periods. Experience indicates that a careful observer who attempts to establish the character of the higher waves will record values that approximately fit.
Slope	The degree of inclination to the horizontal. Usually expressed as a ratio, such as 1:25 or 1 on 25, indicating 1 unit vertical rise in 25 units of horizontal distance; or in a decimal fraction (0.04); degrees (20°18'); or percent (4 percent).
Spectral peak period	see peak period
Spilling breaker	Bubbles and turbulent water spill down front face of wave. The upper 25 percent of the front face may become vertical before breaking. Breaking generally occurs over quite a distance.
Still water level, SWL	The elevation that the surface of the water would assume if all wave action were absent.
Storm surge	A rise above normal water level on the open coast due to the action of wind stress on the water surface.
Stripping	Term used for asphalt structures. Separation and removal of asphalt binder from aggregate surface due primarily to the action of moisture and / or moisture vapour.
Surging breaker	Wave peaks up, but bottom rushes forward from under wave, and wave slides up beach face with little or no bubble production. Water surface remains almost plane except where ripples may be produced on the beach face during runback.
SWAN	Numerical software wave model, Simulating WAves Nearshore, a third-generation stand-alone (phase-averaged) wave model for the simulation of waves in waters of deep, intermediate and finite depth. It is also suitable for use as a wave hind cast model.
Tide, tidal movement	The periodic rising and falling of the water that results from gravitational attraction of the Moon and Sun and other astronomical bodies acting upon the rotating Earth. Although the accompanying horizontal movement of the water resulting from the same cause is also sometimes called the tide, it is preferable to designate the latter as tidal current, reserving the name tide for the vertical movement.
Toe	Lowest part of sea- and portside embankment slope, generally forming the transition to the seabed.
Turbulent flow	Any flow which is not laminar, i.e., the stream lines of the fluid, instead of remaining parallel, become confused and intermingled.

Uplift	The upward water pressure on the base of a structure or pavement.
Wave height	The vertical distance between a crest and the preceding trough. See also significant wave.
Wave period	The time for a wave crest to traverse a distance equal to one wavelength. The time needed for two successive wave crests to pass a fixed point.
Wave runup	The rush of water up a structure or beach on the breaking of a wave. The amount of run-up is the vertical height above stillwater level that the rush of water reaches.
wave spectrum	In ocean wave studies, a graph, table, or mathematical equation showing the distribution of wave energy as a function of wave frequency. The spectrum may be based on observations or theoretical considerations. Several forms of graphical display are widely used.
Wave trough	The lowest part of a wave form between successive crests. Also that part of a wave below still-water level.
Wind setup	On reservoirs and smaller bodies of water (I) the vertical rise in the still-water level on the leeward side of a body of water caused by wind stresses on the surface of the water; (2) the difference in still-water levels on the windward and the leeward sides of a body of water caused by wind stresses on the surface of the water. Storm surge (usually reserved for use on the ocean and large bodies of water).
Wind waves	Waves formed and built up by the wind.

COLOFON Elastocoast pilots in the Netherlands

STORM SEASON 2007 / 2008

OPDRACHTGEVER:

ARCADIS Nederland BV

STATUS:

Definitief

AUTEUR:

E. Bijlsma

GECONTROLEERD DOOR:

M. Visser
H.G. Voortman

VRIJGEGEVEN DOOR:

C. Lazonder

15 September 2008
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ARCADIS NEDERLAND BV
Piet Mondriaanlaan 26
Postbus 220
3800 AE Amersfoort
Tel 033 4771 000
Fax 033 4772 017
www.arcadis.nl
Handelsregister
09036504

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