CT 5318 FIELDWORK HYDRAULIC ENGINEERING

Varna, December 2010

Delft University of Technology

Preface

This report is made for the fifth years course CT5318 "Fieldwork Hydraulic Engineering" of the faculty of Civil Engineering at the Delft University of Technology. During the study civil engineering the students mainly follow theoretical courses and learn to describe and study all kind of physical phenomena with help of mathematical expressions and models. The fieldwork of Hydraulic Engineering is one of the opportunities to get a 'real life' impression of the studied phenomena's and theories.

One week the students stay in the Bulgarian village St. Konstantin, near Varna, at the Black Sea. The main goal of the fieldwork is learn how to deal with problems occurring at data collection and the elaboration and interpretation of the collected data. Several coastal measurements are executed at a couple of beaches and their accompanying structures. Cross-shore profiles are measured, sand samples are taken, waterline positions are obtained and the existing structures are investigated. Also a visit is made to the quarries of Devnya and Tsonevo. The last day a so-called 'touristic tour' is made through the surroundings of the project area and among others an oil field is visited.

The fieldtrip is organized every year with a lot of enthusiasm by ir. H.J. Verhagen, with assistance in Bulgaria of ir. Boyan Savov. We would like to thank them firstly for organizing this very instructive week and of course also for their support and enthusiasm during the fieldtrip.

Delft, December 2010

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Executive Summary

The 2010 CT5318 Fieldwork for Hydraulic Engineering students of the Delft University of Technology took place in st. Konstantin i Elena, just like previous years. St. Konstantin i Elena is a small town to the North-West of the city of Varna. The purpose of this fieldwork was to provide students with an understanding and experience in practical aspects of hydraulic engineering and site work. During this trip several measurements were done:

- Measurements at Sirius beach (cross-section-, waterline- and wave measurements);
- Measurements at Azalea beach (cross-section and waterline measurements);
- Measurements at Asparuchovo beach (cross-sections, waterline-, vegetation line-, bathymetry- breakwater- and sediment sampling measurements);
- Measurements at Lake Varna (bathymetry measurements);
- Measurements in the quarry of Devnya.

Sirius- and Azalea beach

The measurements at Sirius- and Azalea beach are initiated by the Sirius- and Azalea hotels, because of the overall landward retreating coastline of Bulgarian beaches. A comparison of the coastal situation with previous years can be made.

The waterline of Sirius beach has shifted seaward, which would indicate accretion of the beach. This is misleading though, because the summer beach profile is still present. After taking this into consideration in combination with the outcome of the cross-section measurements, it can be concluded that no accretion or erosion of the beach in respect to the previous years is visible. With respect to the wave measurements, no comparison can be made with previous years, but it can be concluded that Sirius beach was experiencing heavy wave attack during the measurements this year.

At Azalea beach, the cross-sections show a lowering of the beach in respect to previous years. It should be noted that this comparison could be misleading because of different weather circumstances during measuring at Azalea beach. With respect to the waterline, a slight retreat of the coast can be observed.

Asparuchovo beach

The Asparuchovo beach is studied because of the possible development of a (small) marina in the northern part of the beach and because of the supposed erosion at the southern part of the coast. Because this is the first time measurements at this beach have been done, the results of cross-section-, waterline-, vegetation line- and bathymetry measurements cannot be compared with results from previous years.

Further, the breakwater of Asparuchovo is in a bad condition, because of a lack of maintenance in combination with constructional mistakes and bad quality material.

Also, with respect to the sediment sampling measurements, the results firstly show the calcium content varying in between 10 % and 43 % with an average of 19 %. The measurements also show that on average the $0.5 < d < 0.125$ mm fractions are best represented, that there is less of the $2 < d < 0.5$ mm fractions and that there is almost no sediment with a diameter larger than 2 mm or smaller than 0.125 mm.

Lake Varna

Lake Varna is a deep elongated lake near the city of Varna. Recently a plan was set-up to create several artificial islands in the lake. The purpose of these islands is to store dredged material from a navigation channel in the lake. Bathymetry measurements are needed for a study about the feasibility of the construction of these islands. The feasibility of the artificial islands could not be examined, because more information is needed for this. Next steps to be taken for the investigation of the feasibility of constructing these islands are, making an estimation of the amount of dredged material, the properties of this material and to measure the currents and the waves at the planned location.

Quarry of Devnya

During this fieldwork, also two quarries were visited. At the quarry of Devnya measurements were done to analyze the suitability of the rocks for the design of a fictitious breakwater. Measurements were done at both small rocks and heavy rocks.

First of all, 20 small rocks were selected for measurement. This number of rocks is large enough to get an impression of the sort of rocks in this part of the quarry and small enough to be able to take the measurements in the time available in the visit to the quarry. The mean blockiness of the measured small rocks is 0.37. The mean elongation of the small rocks is 2.37. The D_{n50} is 0.2748 m.

Second of all, the amount of heavy rocks was determined. It was estimated that 464 rocks were available. With an expected capacity of 30 tons per truck, 28 trucks loads would be required to transport these heavy rocks.

This resulted in a maximum wave height H_s = 2.33 m, which means that with use of the large stones of the Marciana quarry, an imaginary breakwater could be constructed with a maximum allowable significant wave height of 2.33 m.

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1 Introduction

The section of Hydraulic Engineering of the faculty of Civil Engineering of the Delft University of Technology organizes a yearly fieldwork in the surroundings of the Bulgarian city Varna, at the coast of the Black Sea. This fieldwork focuses on measurements of coastal processes and structures; therefore it is very useful for students interested in Coastal Engineering to participate in the fieldwork. In this introduction information about the project area is presented.

1.1 Project area

1.1.1 Bulgaria

The Republic of Bulgaria is situated in Southeast Europe, in the eastern part of the Balkan region. The country is bordered by Romania in the North, Greece and Turkey in the South, Serbia and Macedonia in the West and the Black Sea in the East (see Figure 1). The coastline is almost 400 km long, consisting of roughly 130 km with beautiful beaches which attract a lot of tourists in the warm summers. Since January 2007 the country is part of the European Union which makes it an even more attractive travel destination for the mainly European tourists.

Figure 1: Bulgaria, with the location of Varna encircled.

1.1.2 Black Sea

The Black Sea is an inland sea connected to the Atlantic Ocean via the Mediterranean and Aegean Seas and various straits. The Bosphorus strait connects it to the Sea of Marmara, and the strait of the Dardanelles connects it to the Aegean Sea region of the Mediterranean. Due to all these small connections, the tide, which is generated in the Atlantic Ocean, can hardly penetrate into the Black Sea and is therefore negligible. The Black Sea has an area of 436,400 km^2, a maximum depth of 2,206 m and a volume of 547,000 km^3.

The coastal management of the Black Sea in Bulgaria is not done by a central organization, but by the several land and hotel owners close to the coast. This policy resulted in the construction of a lot of very local structures, which in general are not of the best quality. Another consequence is that executing nourishment on the beach has not got the desired effect, because the longshore current will transport the sediment away. The longshore current is caused by the oblique incident waves, which mostly arrive from southern direction. The more severe storms in the Black Sea however arrive from the North.

1.1.3 Varna

Varna is located in the eastern part of Bulgaria, at the coast of the Black Sea (see Figure 1). The city, also being called the marine capital of Bulgaria, is the third largest city of the country and it houses the nation's biggest cargo and cruise ship harbour. The city with its beautiful beaches is a main tourist attractor, and having an airport nearby makes it even more attractive.

1.1.4 St. Konstantin i Elena

The town St. Konstantin i Elena lies a little north of Varna, at the coast of the Black Sea. The region is famous for its beaches and mineral water sources, and rapidly developing into a tourist hot spot. A lot of hotels are built on and very close to the beaches. These beaches are suffering from tenacious erosion, resulting in very small beach widths and on some locations even small landslides. These retreating beaches are endangering the very important tourist industry.

1.2 Scope of the project

In every coastal engineering project information is required about the boundary conditions of the project area. Data collection is an important aspect of the preparation of such projects. In some coastal areas data are collected by e.g. wave buoys and anemometers but these instruments are not present at all coastal areas and neither at the project area. The fieldwork is done to present an opportunity for students to execute coastal measurements and to experience the influence of e.g. weather conditions on such measurements. The data collected this way needs to be elaborated to be able to obtain the project boundary conditions.

Next to a yearly different project location, every year measurements are done at two particular beaches, so yearly data of these beaches are collected. With help of these data the morphological development over the years of the studied beaches can be evaluated.

1.3 Survey locations

Measurements will be done on three different beaches, from which one of these locations is new compared to earlier years. The surveyed beaches are all situated close to Varna. First the yearly measurements of the Sirius beach and the Azalea beach will be continued. These two beaches are situated northeast of Varna at the coast of St. Konstantin i Elena. The location of the third beach, the beach of Asparuchovo (Агпарухово), is just south of the entrance channel to the large port of Varna. The location of the surveyed beaches is presented in Figure 2; location 1 is Asparuchovo and location 2 represents the Azalea and Sirius beaches.

Figure 2: Location of the surveyed beaches.

1.3.1 Sirius beach and Azalea beach

Sirius beach and Azalea beach are white, sandy beaches positioned in the touristic coastal area of St. Konstantin i Elena. A lot of hotels are situated closely to, or even on the beaches. Especially in the summer these hotels are visited by a lot of tourists, which use the beaches extensively. It is therefore of great importance to preserve the beaches; not only for the tourist industry but as well for the protection of the hinterland. As a result of erosion, the coastline of the beaches is retreating and coastal works are damaged. Even the hotels themselves are endangered by the advancing sea.

Between Sirius beach and Azalea beach there are two small groynes located which are meant to interfere in the longshore sediment transport and to trap sediment, to ensure a minimum beach width. An overview of the two beaches is presented in Figure 3.

Figure 3: Overview of the location of the Sirius and Azalea beaches.

Sirius beach

This beach is approximately 300 meters long and runs from a jetty in the South to a small groyne in front of Hotel Sirius in the North, see Figure 4. Guests of Hotel Sirius use the northern part of this beach, located directly in front of the hotel, which is very small and suffers from erosion.

Figure 4: Overview of Sirius beach.

With the earlier mentioned measurements, it can be seen that in the past few years a landward shift of the coastline occurred, resulting in a decrease of the beach width, which is already quite small. The width is approximately 20 metres and at the hotel no more than 5 metres.

The small groyne in the northern part of the beach is built to prevent erosion of the beach in front of the Sirius Hotel. The smaller rocks used in the construction of this groyne can be found spread over a small area. From this observation it can be concluded that the size of the rocks was probably not sufficient to withstand the force of storm waves.

Because of the retreating coastline it is interesting to model the morphological behaviour of the coast. By executing new measurements and comparing them with the previous measurements it is possible to describe a trend line in the behaviour of the coast and to suggest a possible solution.

Azalea beach

Azalea beach is located directly north of Sirius beach and is approximately 1200 meters long and 40 meters wide. The beach runs from the small groynes in front of the Sirius Hotel in the South to the breakwater of a small harbour in the North. A jetty is positioned at a certain point perpendicular to the coast; this can be seen in Figure 5.

Hotel Azalea is located directly next to the beach, in the dynamic coastal zone. Because of its location in the dynamic coastal zone the Azalea Hotel has influence in the morphological processes in the coastal zone.

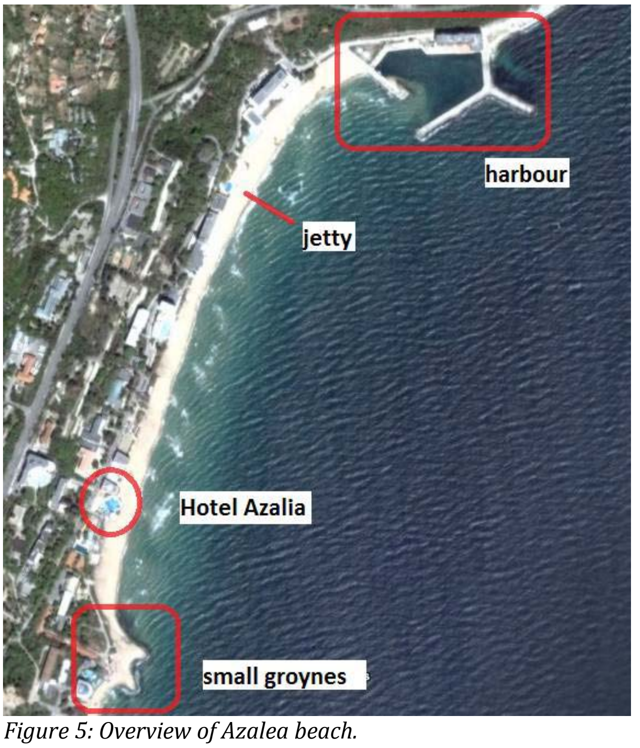


Figure 5: Overview of Azalea beach.

1.3.2 Asparuchovo beach

This beach has a length of approximately 1 km and it is bounded by a breakwater at the northern end. This breakwater is built around 35 years ago with the goal to prevent sedimentation of the entrance channel leading to the port of Varna, at the end of the Varna Lake. The breakwater has been adapted and extended multiple times because it was damaged clearly. The southern end of the beach is not defined so clearly, but the beach rotates a little and it changes into a more rocky area. All this can be seen in Figure 6.

Figure 6: Overview of Asparuchovo beach.

1.4 Structure of the report

The fieldwork will take place at several beaches. At each beach several, identical measurements are executed. Although some measurements are done on all the beaches, the report will treat the measurements per beach. All the information and data collected are presented per measuring location.

In chapter 1, the project area and its surroundings have been described. Further on will chapter 2 present all the measurements done at Asparuchovo beach. The Sirius beach is elaborated in chapter 3 and subsequently in chapter 4 the measurements executed at Azalea beach are presented. The measurements done at the Lake Varna will be discussed in chapter 5. An elaboration of the visit and local measurements done at the quarry of Devnya can be found in chapter 6. In chapter 7 some recommendations are made and conclusions are drawn. Finally, the used literature and internet sites can be found in chapter 8.

2 Asparuchovo Beach

2.1 Introduction

Asparuchovo beach is located at the south of Varna adjacent to the Black Sea, see Figure 7.

Figure 7: Location of Asparuchovo beach.

The Asparuchovo beach is studied because of two main reasons. The first reason being the possible development of a (small) marina in the northern part of the beach and the second being the erosion rates at the southern part of the coast. In order to be able to develop a marina, one should possess information about the beach profiles, the wave and wind climate, the bathymetry, the grain size etcetera. And further on, when one wants to interfere in the eroding process in the southern part of the coast, information should be gathered about the causes of this erosion.

2.2 Measurements Asparuchovo beach

It is the first time measurements at Asparuchovo beach are done. So these measurements are meant as the first in a series of measurements, because the beach will probably be monitored in upcoming years. Also no comparisons can be made at this point.

The measurements that have been done are:

- Water- and vegetation line measurements Asparuchovo beach using GPS;
- Cross-section measurements Asparuchovo beach;
- Bathymetry measurements Asparuchovo beach.

A detailed explanation of the cross-section measurements can be found in Appendix B.

2.2.1 Water- and vegetation line measurements Asparuchovo beach using GPS

In Figure 8 below a map with the positions of the water- and vegetation measurements has been given, but also the cross-section measuring data. The elaboration of the echo soundings can be seen in Figure 23. The coordinates are UTM coordinates.

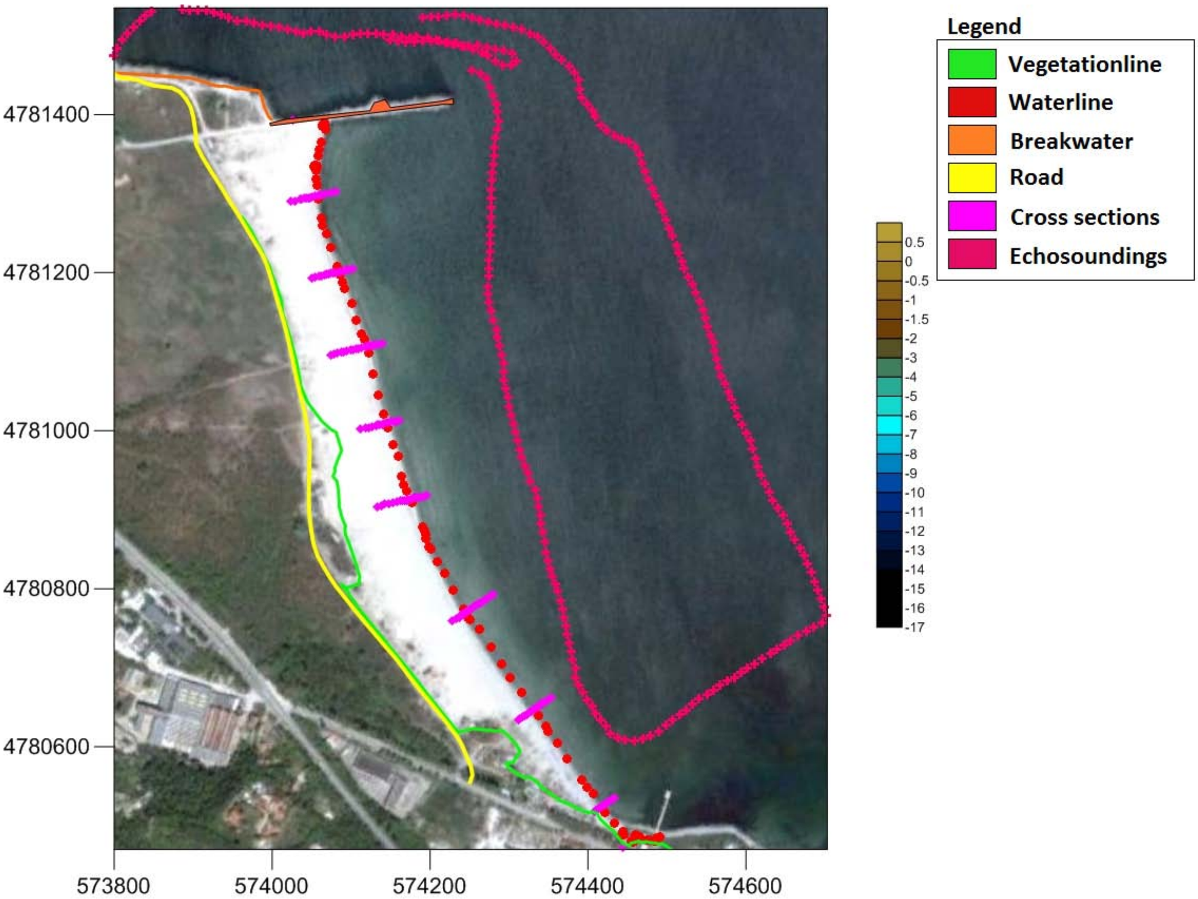


Figure 8: Water- and vegetation line Asparuchovo beach (Date Google Map: May 3rd 2007)

Conclusion water- and vegetation line measurements Asparuchovo beach

Because this is the first time measurements at this beach have been done, the results cannot be compared with results from previous years. What can be said about Figure 8 is that the map (used from Google Earth) is just an indication of the overview of Asparuchovo beach. The GPS coordinates are plotted onto this map, which is clearly visible for example at the waterline. The underlying map is showing a different waterline, which means that the waterline has shifted easterly, which would indicate accretion of the beach.

2.2.2 Cross-section measurements Asparuchovo beach

In this section the measurements of the cross-sections of Asparuchovo beach will be elaborated. First a summary of different points of action will be given:

1. Determine overall reference point for height;
2. Determine place to measure with theodolite;
3. Determine amount and place of baselines;
4. Determine places of cross-sections beach;
5. Measurements with theodolite and levelling rod.

Determine overall reference point for height (Asparuchovo)

In this project a white concrete building is chosen as reference point. The actual reference point on this building is marked with a red horizontal line. In Figure 9, this overall reference point is given.

GPS coordinates (UTM) of the overall reference point are: T 0573854 E / 4781339 N.

Figure 9: Overall reference point Asparuchovo beach.

Determine place to measure with theodolite (Asparuchovo)

In this project, the height of the theodolite compared to the reference point has been measured with the help of a levelling rod, placed on the red horizontal line on the white concrete building. The height of the theodolite compared to the reference point is + 0.18 m. Because the length of the beach is more than 1 km, the theodolite needed to change position a few times. The new heights of the theodolite compared to the reference points will not be given here, because they are not of importance for the outcome.

Determine amount and place of baselines (Asparuchovo)

In this project two baselines have been defined, which are presented in Figure 10. Each baseline lies between two reference points.

Baseline 1:

- Reference point 1.1 (near breakwater, denoted with 'BL Delft'): T 574027 E / 4781393 N. See Figure 11.
- Reference point 1.2 (yellow box on beach, the concrete plate on which the box is placed is marked with red paint with the text: '2010 CT5308'): T 574167 E / 4780749N. See Figure 12.

Baseline 2:

- Reference point 2.1: the left vertical side of the silos. See Figure 13.
- Reference point 2.2 (southern end of beach, marked with 'TU'): T 574444 E / 4780475 N. See Figure 14.

Figure 10: Overview reference points, baselines and cross-sections.

Figure 11: Reference point 1.1 (near breakwater, marked with 'BL Delft').

Figure 12: Reference point 1.2 (centre of yellow box, marked '2010 CT5318' on concrete plate). Photographed while standing on baseline.

Figure 13: Reference point 2.1 (left of silos, photographed while standing on baseline).

Figure 14: Reference point 2.2 (southern end of beach, marked with 'TU').

Determine places of cross-sections beach (Asparuchovo)

For baseline 1, it was decided that every 100 m (starting 100 m from reference point 1.1) a cross-section would be measured. For baseline 2, it was decided that only every 150 m (starting 100 m from reference point 2.1) would be measured. The explanation for this difference was that the project group was short on time at baseline 2 due to weather circumstances and failing measuring tools.

The 8 cross-section points are (5 on baseline 1, 3 on baseline 2):

- Cross-section 1: T 574052 E / 4781290 N
- Cross-section 2: T 574073 E / 4781196 N
- Cross-section 3: T 574095 E / 4781103 N
- Cross-section 4: T 574119 E / 4780984 N
- Cross-section 5: T 574151 E / 4780910 N
- Cross-section 6: T 574245 E / 4780770 N
- Cross-section 7: T 574327 E / 4780625 N
- Cross-section 8: T 574409 E / 4780515 N

Measurements with theodolite and levelling rod (Asparuchovo)

An overview of the points of cross-section measurement of Asparuchovo beach has already been given in Figure 10.

In Figure 15 to Figure 22, the cross-section profiles of the beach have been plotted. These profiles are plotted from the North to the South (from cross-section 1 till cross-section 8).

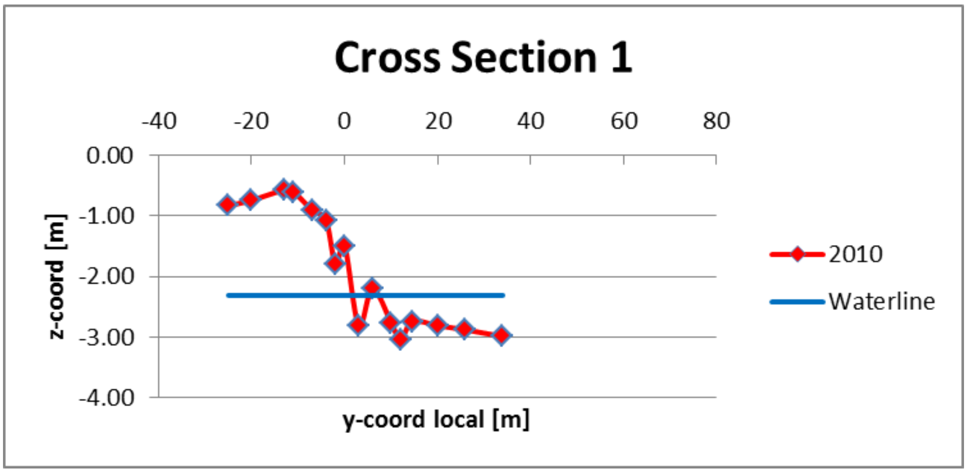


Figure 15: Cross-section 1 Asparuchovo beach.

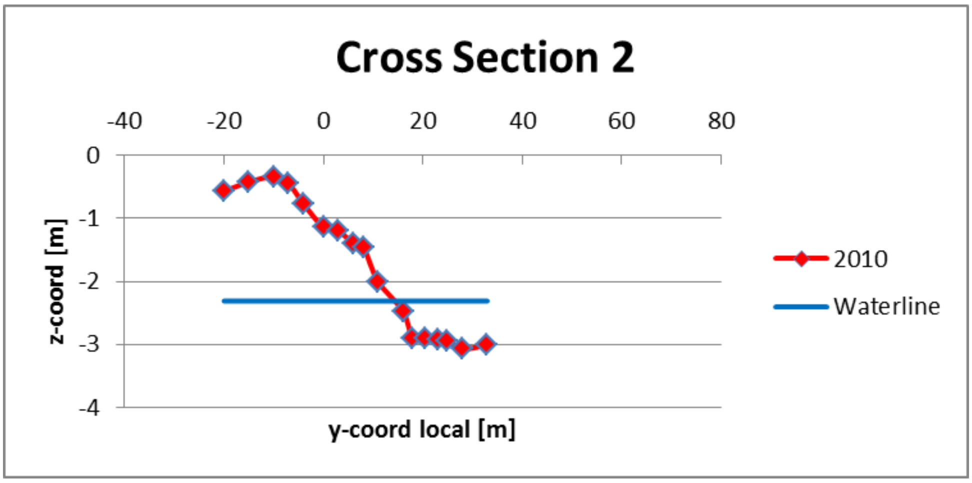


Figure 16: Cross-section 2 Asparuchovo beach.

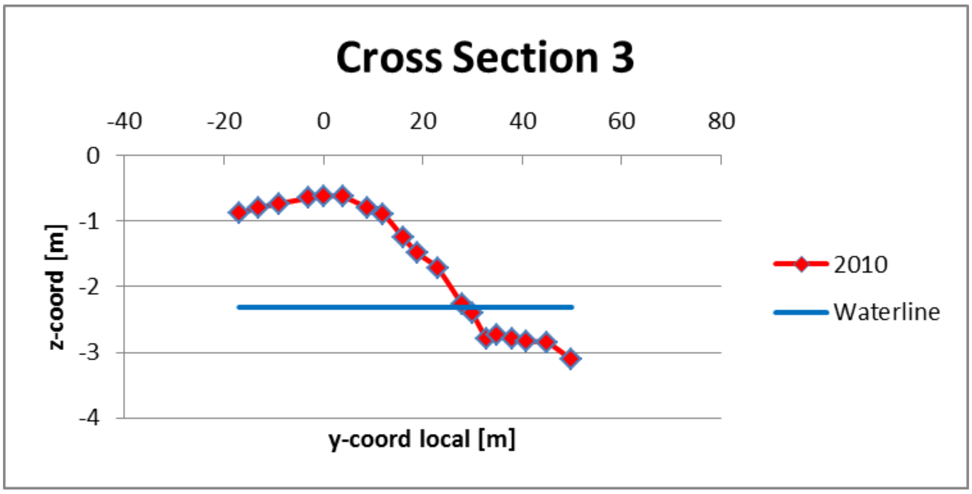


Figure 17: Cross-section 3 Asparuchovo beach.

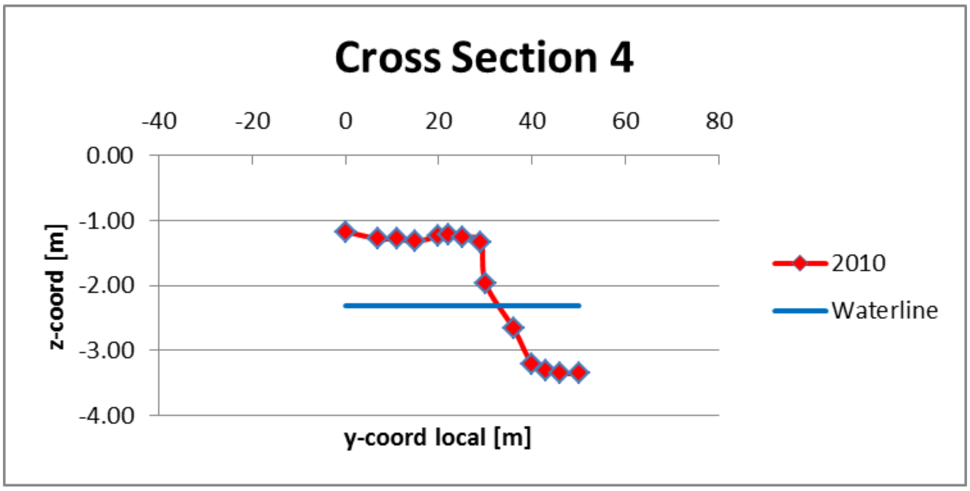


Figure 18: Cross-section 4 Asparuchovo beach.

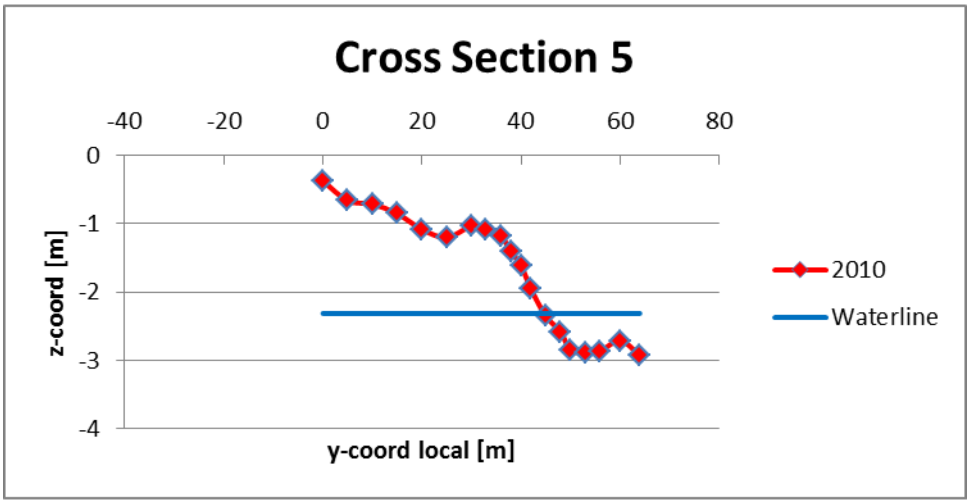


Figure 19: Cross-section 5 Asparuchovo beach.

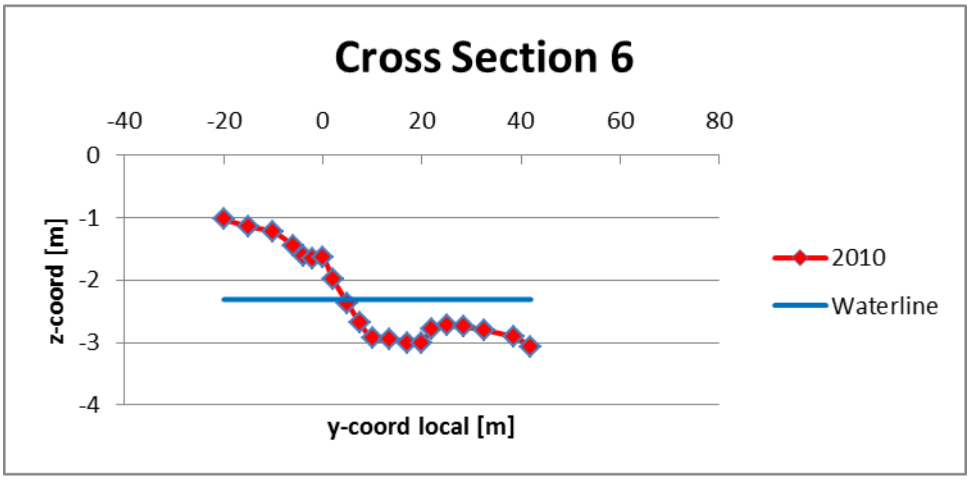


Figure 20: Cross-section 6 Asparuchovo beach.

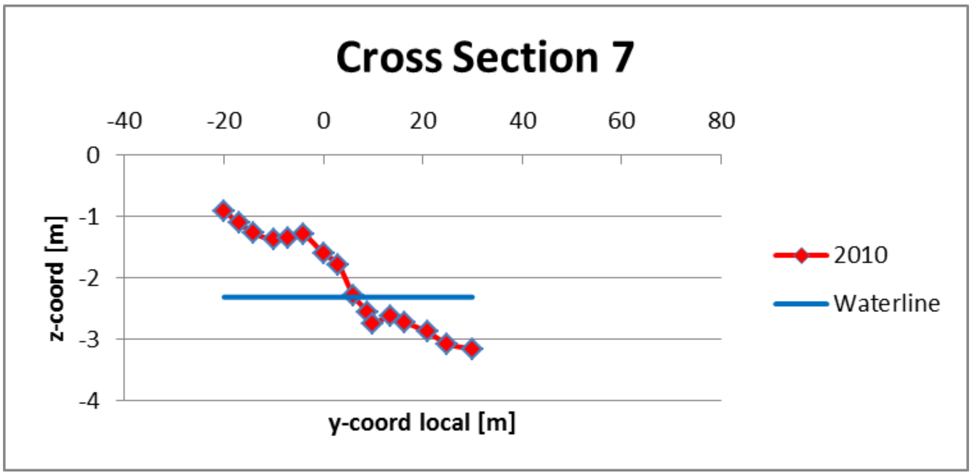


Figure 21: Cross-section 7 Asparuchovo beach.

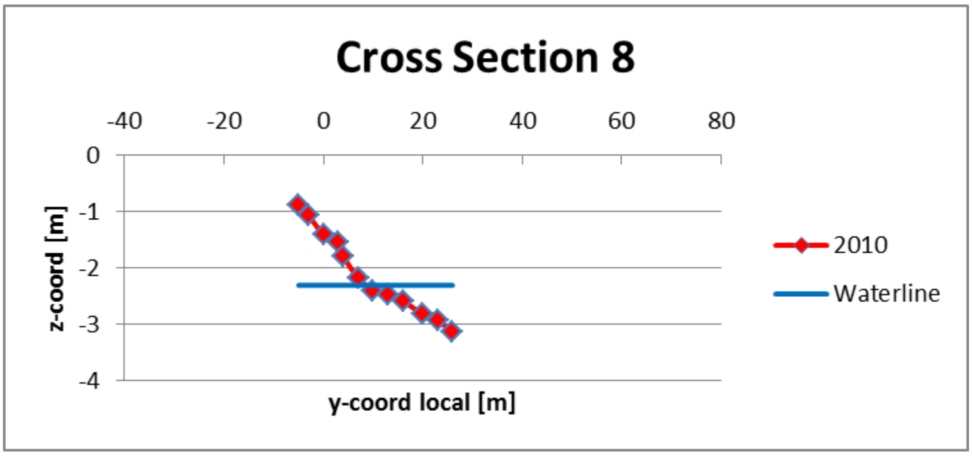


Figure 22: Cross-section 8 Asparuchovo beach.

These cross-section measurements can also be plotted into a map of contours. This has been done with the help of the program Surfer. The results are given in Figure 23. The pink bars are the different cross-sections that have been measured. The red dotted line near the water is the waterline. The pink dotted line in the sea is the line on which echo soundings have been done. The green line is the line of vegetation, while the yellow line is the road behind the beach. The coordinates are UTM coordinates. It should be noted that the deeper blue parts in the graph are nonsense because no data is available for those regions.

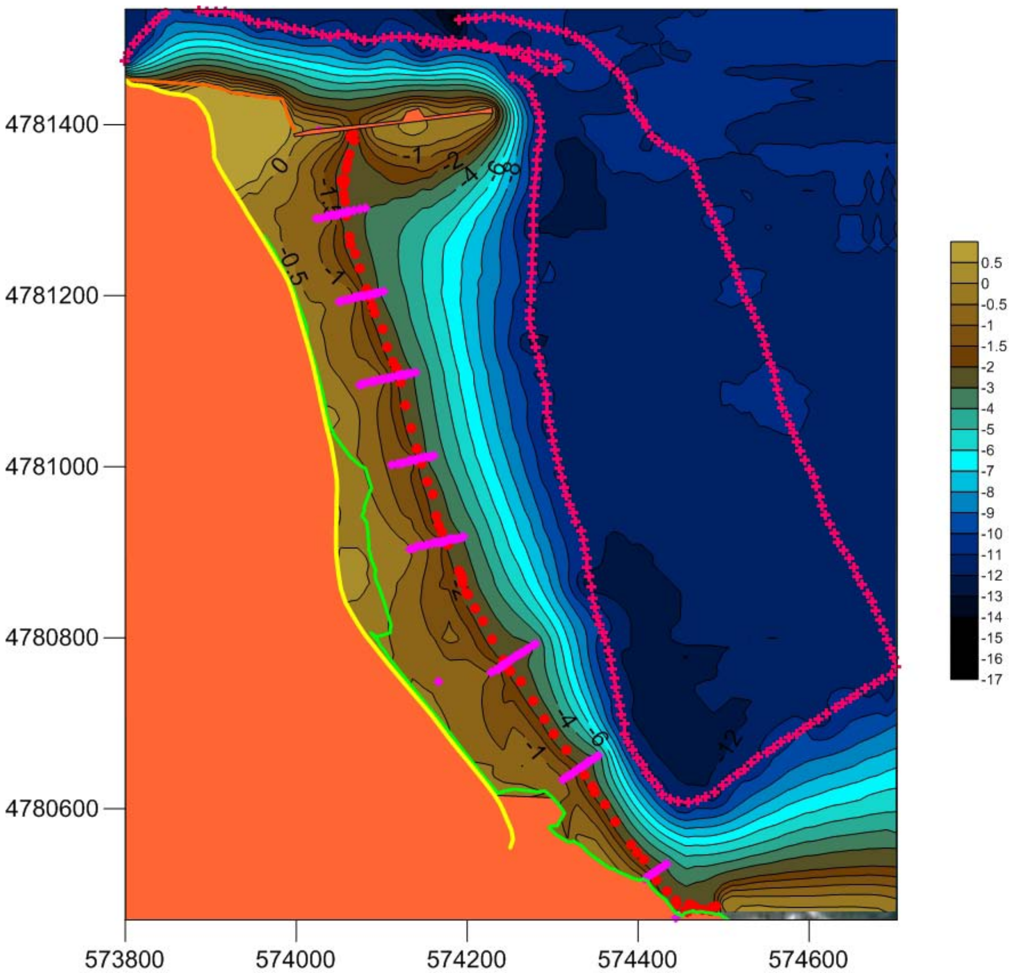


Figure 23: Map of contours (plotted with Surfer).

Conclusion cross-section measurements Asparuchovo beach

Observing the results of the measurements of the beach profile, it can be concluded that the profile differs a lot per cross-section. The cross-sections clearly show a sand bar in front of the beach. This sand bar has disappeared on the overview given in Figure 23, which has been constructed with the help of Surfer. Because of the scale, Surfer will simplify the results and erase any small differences. Since this is the first time measurements are done on this beach, so far nothing can be said about the erosion or accretion of the beach.

2.2.3 Bathymetry measurements Asparuchovo beach

Not only the profile of the beach, but also the profile of the seabed in front of the beach should be measured. This is called the bathymetry. The measurements on the bathymetry have been done by means of echo soundings. In Appendix A.4 is explained how these echo soundings have been done.

Because of bad weather circumstances, only one round of echo soundings have been done throughout the sea in front of Asparuchovo beach. The outcome of the measurements has already been processed into the map of contours, as shown in Figure 23 above.

2.3 Breakwater

2.3.1 Introduction

The breakwater of the beach of Asparuchovo is located at the northern end of the beach. North of the breakwater is the main entrance channel to the large harbour of West Varna. The mound type breakwater is built to prevent siltation of the channel and to protect the Asparuchovo beach from erosion. The breakwater is shown in Figure 24.

Figure 24: Breakwater Asparuchovo beach.

To get an impression of the dimensions of the breakwater, the used material (for the different materials of armour layer) and the state of the breakwater, the breakwater was observed and measured; in short the following points were investigated.

- The dimensions of the breakwater:
    - The length and width of the breakwater are measured with a tape measure; the width of the breakwater including the armour layer had to be estimated at the head of the breakwater because of the presence of tetrapods which made it impossible to walk on the breakwater head;
    - The height of the breakwater at several places in the length direction of the breakwater is measured with use of the theodolite.
- Different types of armour layer are determined and the dimensions of these types of armour are measured using a measuring tape;
- The state of the breakwater was observed and analysed by looking at the damages of the structure closely and by observing the bigger picture to try to find out what has caused the damage.

2.3.2 Dimensions breakwater

In appendix C an impression of the breakwater cross-section can be found; together with its main dimensions.

2.3.3 Armour layer

Second of all, the types of armour on the breakwater and their dimensions will be determined.

Types of armour

At the canal side (left) of the breakwater are 3 different types of armour present. Starting at the shore there are natural rocks and proceeding to the head of the breakwater there is a combination of natural rocks, different sizes of concrete blocks and tetrapods. This is shown in Figure 25 till 28. At the head of the breakwater only tetrapods are used as armour. At the beach side (right) of the breakwater the same types and combination of armour is used.

Figure 25: Natural rocks at the channel side of the breakwater.

Figure 26: Mixture of concrete blocks and natural rocks.

Figure 27: Mixture of tetrapods, natural rocks and concrete blocks.

Figure 28: End of the beach, start of the revetment with natural rocks at the beach side (right).

Dimensions of armour

With a measuring tape the diameter at the end of the tetrapod leg measured. The overall dimensions of the tetrapods were calculated [1]. This showed that the overall height of the element is 1.99 m and that the element has a volume of 2.2 m^3. The weight of the elements, assuming concrete with a density of 2400 kg/m^3, is 5.27 tons.

The parallelepipeds are 1.15 m by 1.30 m by 1.44 m. The volume of the block is 2.15 m^3 with a weight of 5.17 tons per element.

The smaller cubes have dimensions of 1 by 1 by 1 meter. The weight of the cubes is therefore 2.4 tons.

2.3.4 Damage

The breakwater is not in a good condition; probably the authorities do not accomplish structural conservation and repairing works. The lack of maintenance in combination with constructional mistakes and bad quality material led to this bad condition of the breakwater.

From the base of the breakwater till the head of the breakwater there runs a crack which can be seen in Figure 29, 30 and 31. Further investigation in this crack led to the outcome that exactly at the position of the crack, there is an iron pipe placed in the concrete surface plate.

Figure 29: Overview of the crack following the length of the breakwater.

Figure 30: At some points the size of the crack reaches a width of 5 cm.

Figure 31: The remaining of an iron pipe.

From the condition of the tetrapods and the broken pieces of the tetrapods, it is clear that these concrete units were not carefully constructed and placed at the structure. The lines which are clearly visible on the tetrapods originated from the casting procedure (see Figure 32); probably the casting was stopped halfway and continued the next day or even after the weekend which led to a bad cohesion between the different castings. These construction lines are weak links in the concrete volume of the tetrapods. Therefore more tetrapods are likely to break at the construction line.

Figure 32: Result of poor construction, construction line clearly visible in tetrapod.

Figure 33: Broken leg of a tetrapod.

Figure 34: Broken leg of a tetrapod, at construction line.

The surface plates are all connected with each other and are placed above a layer of natural rocks. This will cause large stresses when a wave comes in and generates an upward pressure underneath the surface plate. Because of the rigid structure of the linked surface plates, and the corroding iron pipes, the plates are badly damaged. This is shown in the figures below. Further, the design of the structure could probably not successfully react to the settlements of the subsoil of the structure.


Figure 35: Totally destroyed surface plates.


Figure 36: Large cracks in the surfaces plates.


Figure 37: A large piece of the surface plate is broken.

2.3.5 Design wave height

To calculate the design wave height, the size of the tetrapods located at the head of the breakwater is used. For calculation of the design wave height the Hudson formula for stability of breakwaters is used. After measurements the weight of the elements are obtained. The slope of the breakwater was very difficult to measure because of the rough wave conditions; therefore there are 3 different slopes compared in the calculation. Because of the fact that the tetrapods are placed at the head of the breakwater the value of 4.5 for K_d for breaking waves is used [1].

Hudson formula:

$$W = \frac{\rho_s g H_{1/10}^3}{Kd\Delta^3 \cot\alpha}$$

In which:			
	W	= Weight of the element	[ton]
	H	= Design wave height (0 damage)	[m]
	K_d	= Hudson coefficient	[-]
	Δ	= Relative density	[-]
	ρ	= Density of concrete	[kg/m^3]
	cot Alpha	= Slope of breakwater	[-]

After calculations with the tetrapods at the head the following results were found:

Slope [-]	H_{10} [m]	H_s [m]
1:1.5	2.15	1.69
1:2	1.79	1.41
1:3	1.56	1.23

Table 1: Results calculations design wave height at breakwater head.

The H_{10} is about equal to $1.27 \cdot H_s$.

The parallelepipeds at the trunk of the breakwater were estimated to have a K_d value of 6.5 for breaking waves. This results in the following design wave heights:

Slope [-]	H_{10} [m]	H_s [m]
1:1.5	1.89	1.49
1:2	1.57	1.24
1:3	1.37	1.08

Table 2: Results calculations design wave height at breakwater trunk.

After the calculation of the design wave heights another explanation of the overall damage can be found. The design wave height for the concrete elements seems to be rather low; this could initiate movement of the elements which in combination with bad quality concrete could lead to damage. However this is an intuitive feeling, bathymetric conditions could in some cases result in a low design wave height. Further analysis of wave- and bathymetric data is advised for a thorough analysis of the damages.

2.4 Sediment sampling

In order to be able to predict the amount of erosion at Asparuchovo beach the properties of the sediment must be known. The sieve curve is the most important property of the sediment. In this case also a significant amount of shells was found. It is useful to know the mass percentage of these shells.

In order to determine these properties, samples have to be taken. Soil samples are taken from various locations and at various depths in order to determine the sediment distribution of the beach. These soil samples are taken with a piston sampler which is explained in Appendix A.5. The sediment samples are brought to the Netherlands to be sieved and to determine the amount of shells (calcium) in the samples.

2.4.1 Sampling locations and depth

It is expected that there will be some variability in the sediment properties at various locations and depths on the beach. The amount of samples and the weight per sample were minimized because of restrictions on the flight to the Netherlands. Three samples were taken in the length profile of the beach: at the beginning, at the middle and at the end of the beach, to account for variability imposed by longshore transport. At each point three points were determined in cross-shore direction, to account for variability imposed by cross-shore transport. One point was set approximately 15 metres from the water line on the beach, one approximately 5 metres from the waterline in the sea and one approximately 30 metres from the waterline in the sea. Onshore and close to the waterline it was difficult to get samples from below the surface, only surface samples were taken there. In deeper water also samples from approximately 1.5 m below the bottom surface were taken. All samples weighed about 0.5 kg. Table3 and Figure 38 give the various locations where samples were taken.

	UTM easting	UTM northing	Depth
1	0574117	4781092	0 – 0.2
2	0574053	4781292	0 – 0.2
3	0574043	4781290	0 – 0.2
4	0574102	4781092	0 – 0.2
5	0574174	4780862	0 – 0.2
6	0574194	4780867	0 – 0.2
7	0574194	4780867	1.4 - 1.6
8	0574234	4780882	1.4 - 1.6
9	0574234	4780882	0 – 0.2
10	0574145	4781092	0 – 0.2
11	0574145	4781092	1.4 - 1.6
12	0574083	4781298	0 – 0.2
13	0574083	4781298	1.4 - 1.6

Table3: Coordinates of sample locations.

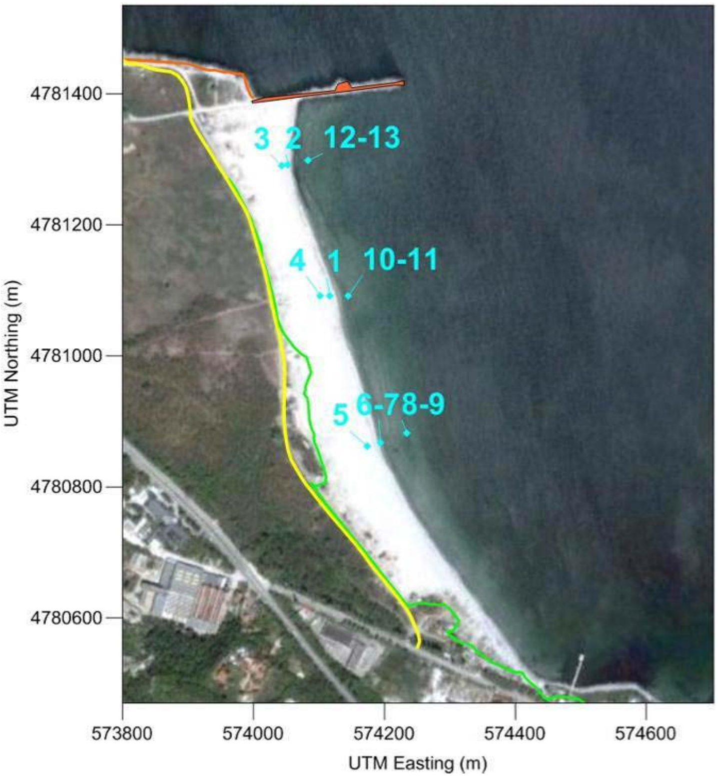


Figure 38: Locations of soil samples.

2.4.2 Sediment composition

There are multiple sediment properties that can affect the beach erosion process. In this case there is chosen to only qualify the most important properties. The mass percentage shells and the sieving curves were determined. In this chapter it will be explained why these properties are that important, the calcium carbonate extraction process and the construction of the sieving curve will be explained, the level of accuracy will be given and the final results will be explained together with their potential impact.

Organic material
Some organic material can be found in the samples. In order to get an accurate sieving curve these organic materials should be filtered from the samples. This can be done in various ways. One of these ways is to dissolve the organic materials using H_2O_2. In this case the organic material is expected only to represent a small percentage (< 1 %) of the samples, since a beach environment usually does not contain a lot of organic material. Because of the small percentage and the time consuming filtering process it was chosen not to do this.

Calcium Carbonate
When the beach erodes shells will break down into small pieces. Because these shells are lighter and break down to fine particles they are washed away quickly. Making a sieving curve including these shells will give a distorted view on the sediment properties because the large fractions will appear larger than they actually are. Therefore the shells will have to be filtered from the samples. In order to do this all calcium carbonate is dissolved with hydrochloric acid.

To determine the amount of calcium carbonate the samples were weighed. The biggest shells were taken out by hand and the samples were mixed with distilled water. 10 ml of hydrochloric acid was inserted in the mixture and the samples were stirred frequently. The hydrochloric acid started a reaction with the calcium which produces gasses. When this reaction stopped, another 10 ml of hydrochloric acid was inserted. When the hydrochloric acid was inserted, but no immediate reaction with the calcium could be seen, it was concluded that all calcium carbonate was extracted and that the sample was ready. The sample was then sieved and washed in a very fine sieve, only letting the water particles through, in order to wash away the hydrochloric acid. Finally the samples were put to dry in the oven. When completely dry the samples were weighed again and the mass percentage of shells could be determined.

Sieving curve
On an eroding beach the sieving curve is the most important sediment property because fine particles are washed away more quickly than coarse grains. In order to determine the sieving curve the following steps were taken:

After all the shells were removed with hydrochloric acid the samples were dried again in the oven. The samples were crushed in order to loosen the particles and samples of approximately 100 g were taken. In order to take an unbiased sample of 100 g, a special separation device was used. Not using this sampling device could result in an over- or under- representation of the fine particles. Subsequently the sample was put in a sieving machine. Seven sieves were used in order to produce an accurate sieving curve; sieves with an opening width of 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.18 mm, 0.125 mm and 0.063 mm were used. In order to provide a more accurate view, it was also required to measure sediment with a diameter smaller than 0.063 mm, but these sieves were not available. The sediment was put in the top sieve; these sieves were put on top of a vibrating machine to help the sediment through the sieves. Then the weight per sieve had to be determined. With this information (the weight percentages per sieve,) the weight percentages and the cumulative could be calculated and the sieve curves were produced, see Figure 39 and Figure 40.

2.4.3 Accuracy
During the various sampling processes some inaccuracies occurred. In this paragraph it is tried to explain all (in) accuracies.

Overall
- Moving samples: during the whole sampling process the samples were moved from storage cup or bag to another. During these movements some losses usually occurred, most of it being fine material losses.
- Machine accuracy: weighing machines and sieves are expected to work very precise, but there are some inaccuracies in the weighing and the sieving diameters.
- Human error

During sampling

During the sampling process on Asparuchovo beach the first inaccuracies occur.

- In order to minimize the amount of samples that will have to be taken to the Netherlands only a few spots could be measured. A few points were chosen, but in between these points or deeper into the surface a different sediment composition could be found.
- The piston sampler does not work equally well on all places. It especially works well on wet places, because it makes use of vacuum to suck the soil. Therefore only in the water samples from 1.5 m beneath the surface were taken.

During the dissolving of the shells

During this method a small percentage of sediment was lost:

- Because of the heavy reaction caused by adding too much hydrochloric acid to the sediment, part of the sediment was spilled.
- During the filtering a filter broke and some sediment was lost.
- After the filtering process the filter had to be cleaned with water, some sediment was left on the filter, predominantly fine sediment.

During the sieve curve measurements

When measuring the sieve curve multiple faults could occur.

- The sediment could “clog”; therefore an overestimation of the coarse particles could occur.

In order to quantify some of the inaccuracies the following control measures where performed:

- The measured mass of the sample at the start of the sieving process is in all cases not the same as the cumulative masses from the separate sieves. These differences are measured and are have a maximum inaccuracy of 1.05 % with an average of 0.22 % of the total weight of the sample.
- From the first two samples, sample 11 and 12, two samples were sieved. This was done in order to establish if the sieving process was accurate. As shown in Table 4 and Figure 39, the differences in the resulting sieving curves of sample a and b are relatively small and in the order of 1 - 20 % with the largest inaccuracies in the smaller fractions.

	Weight cumulative [%]						
Sieve width [mm]	**2**	**1**	**0.5**	**0.25**	**0.18**	**0.125**	**0.063**
11a	100	99.64	98.76	96.82	80.96	43.08	7.56
11b	100	99.69	98.96	97.02	80.88	44.72	7.71
12a	100	99.94	99.65	97.30	86.83	55.68	11.71
12b	100	99.967	99.31	97.06	86.17	52.91	9.07

Table 4: Cumulative weight of two soil samples with different sieve widths.

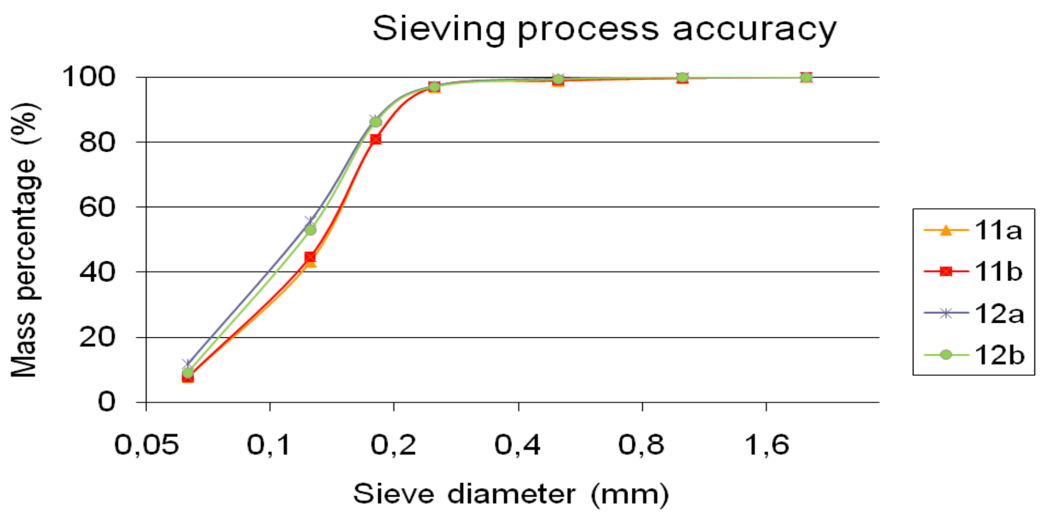


Figure 39: Sieving curves of two soil samples.

Conclusion

The sampling process is a process in which a lot of errors can be made. A rough estimation of the overall errors, when all these steps are performed with care, would be in the order of 10-30 %. It is doubtful that an exact sieve curve is needed for erosion analyses of Asparuchovo beach. Therefore this inaccuracy is accepted.

2.4.4 Results

In this section the results of the tests, mentioned in the section above, can be found.

Calcium carbonate

Table 5 shows the mass percentages of calcium. It shows that the calcium content varies in between 10 % and 43 % with an average of 19 %. Because of the limited amount of samples that were taken no clear pattern can be found. The patterns described below should therefore be used with caution.

- Sediment taken from the northern side of the beach contains slightly more shells than in the middle and on the southern side.
- Sediment from the waterline contains the largest amount of shells, followed by sediment taken from the beach. The least amount of shells was found deeper in the water.
- Samples taken from the surface contain approximately 50 % more shells than samples taken at 1.5 m depth.

#	Total weight sample [g]	Weight sample after dissolving calcium [g]	Difference = Weight Calcium [g]	Calcium [%]
1	352.84	318.27	34.57	9.80
2	498.83	283.37	215.46	43.19
3	247.09	211.17	35.92	14.54
4	503.83	343.33	160.5	31.86
5	430.04	376.30	53.74	12.50
6	475.69	349.63	126.06	26.50
7	434.61	345.49	89.12	20.51
8	482.34	428.35	53.99	11.19
9	322.06	273.28	48.78	15.15
10	586.84	522.68	64.16	10.93
11	477.63	404.39	73.24	15.33
12	377.86	334.11	43.75	11.58
13	628.65	501.76	126.89	20.18

Table 5: Calcium content of soil samples.

Sieving curves

The results following from the sieving process can be found in Table 6: Table 6 and Figure 40. These results show that on average the 0.5 mm < d < 0.125 mm fractions are best represented, that there is less of the 2 mm < d < 0.5 mm fractions and that there is almost no sediment with a diameter larger than 2 mm or smaller than 0.125 mm.

Also now a spatial pattern was hard to detect. Therefore the statements below should be used with caution.

- The samples taken from the deeper water contain more fine grains than the samples taken from the beach. The samples taken from the waterline contain the coarsest particles.
- Samples taken from the North of the beach are coarser than those taken from the middle and Southern part of the beach.
- Samples taken from a larger depth contain finer sediments than samples taken from the surface.

	Sieve diameter [mm]							
#	**2**	**1**	**0.5**	**0.25**	**0.18**	**0.125**	**0.063**	**< 0.063**
1	0.05	2.26	18.28	51.82	22.33	4.53	0.55	0.18
2	7.07	52.46	12.93	12.03	13.66	1.73	0.13	0.00
3	0.87	9.72	27.85	48.47	10.61	1.96	0.40	0.11
4	6.19	25.89	19.63	17.46	20.49	9.40	0.83	0.11
5	0.53	22.82	4.01	15.01	15.31	36.65	5.51	0.15
6	7.24	10.97	7.64	26.14	33.86	13.23	0.83	0.09
7	2.36	8.85	20.60	38.72	19.01	8.84	1.38	0.24
8	0.25	1.43	2.83	15.47	39.59	36.45	3.79	0.18
9	0.46	3.75	20.43	50.07	20.91	3.69	0.57	0.11
10	0.47	1.88	2.04	11.94	42.09	35.82	5.60	0.16
11	0.36	0.88	1.93	15.87	37.87	35.52	7.28	0.28
12	0.06	0.29	2.35	10.47	31.15	43.96	11.51	0.21
13	3.90	15.19	12.14	13.58	25.61	25.15	4.27	0.17
Average	2.29	12.03	11.74	25.16	25.58	19.76	3.28	0.15

Table 6: Mass percentage per diameter per soil sample.

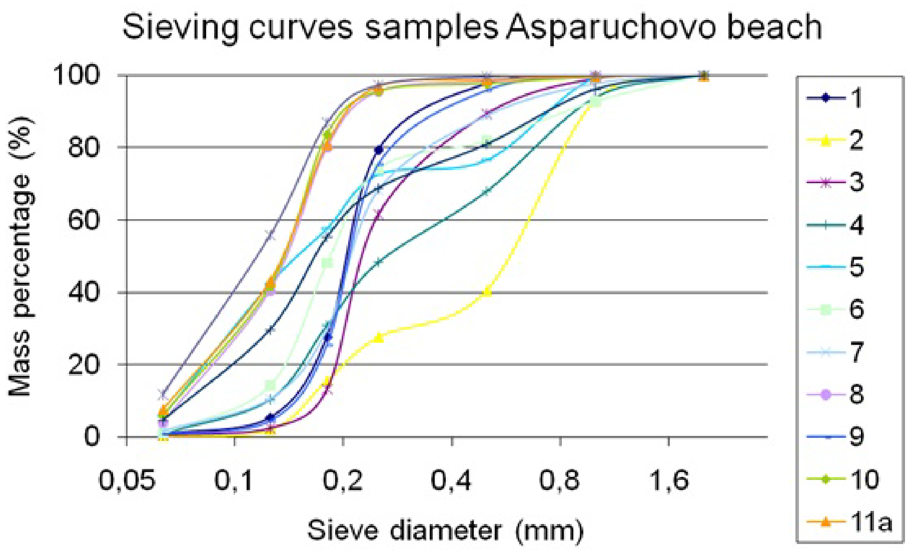


Figure 40: Sieving curves soil samples Asparuchovo beach.

3 Sirius beach

3.1 Introduction

In Figure 41 below the location of Sirius beach is presented again:

Figure 41: Location of Sirius beach.

To save the touristic purpose, endangered by the erosion processes as described in section 1.3.1, beach nourishments at Sirius beach were executed in 2003. Measurements of the previous years suggest that the volume of nourishments has completely disappeared. In order to get a better insight of morphodynamics at Sirius beach, a set of measurements is created since 2002. This set is extended by measurements of several following years. The waterline and cross-shore profile measurements are elaborated and compared with previous years' results.

3.2 Measurements Sirius beach

The measurements that have been done on Sirius beach are:

- Waterline measurements using GPS;
- Cross-section measurements.

A detailed explanation of the cross-section measurements can be found in Appendix B.

3.2.1 Waterline measurements Sirius beach using GPS

Like previous years the waterline has been measured at Sirius Beach with a GPS receiver. The results from this year and those from previous years are shown in Figure 42 below.

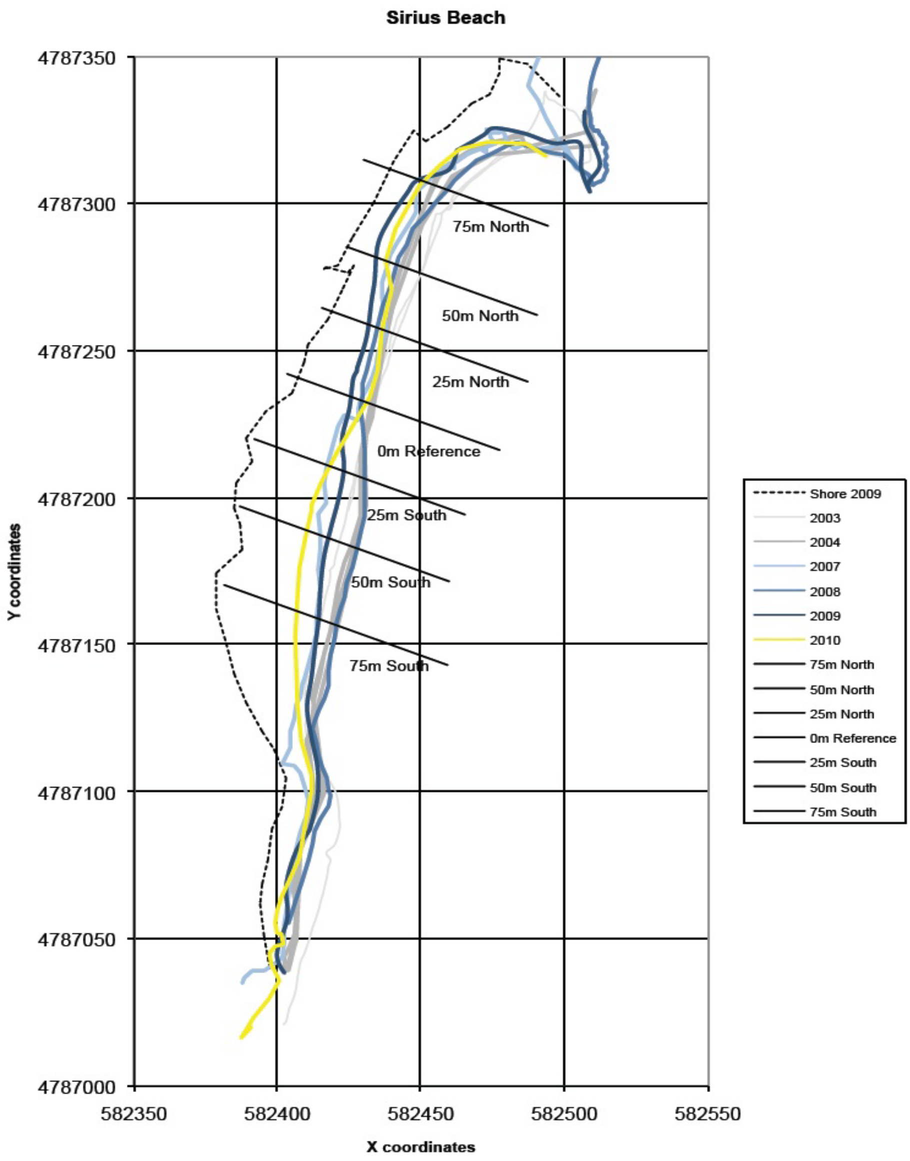


Figure 42: Development of the waterline from 2003 till 2010.

It can be seen that the trend of previous years has been interrupted. In the North, the waterline moves seawards while in the previous years it has moved landwards. At the southern side of the beach the waterline moves landwards while this used to be more or less stable.

The measurements are executed in October, between the summer and the winter. In such a period the beach profile changes a lot in a short time, from summer to winter profile. The date of the measurement was 4th of October 2010. A second measurement has been elaborated on the 9th of October 2010 in order to compare both and indicate the variability. In Figure 43 below both results are presented.

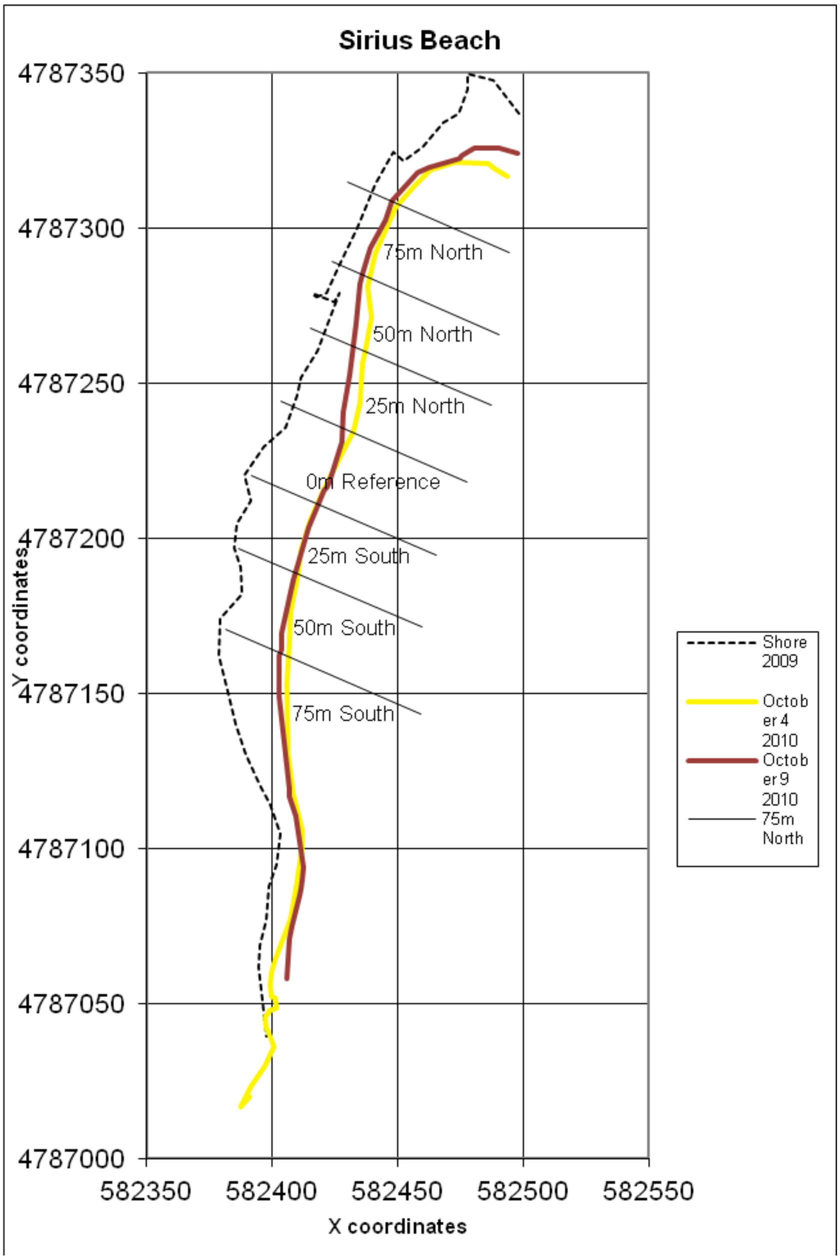


Figure 43: Waterline at Sirius Beach on October 4 and October 9 of 2010.

In just five days the waterline moved a lot, especially at the northern side of the beach. The waterline has been moved landwards. It could be possible that the beach is changing from a summer profile towards a winter profile. During the measurements the sea state was wild; wave heights up to two meters and more were observed. Due to these conditions the waterline has moved landwards. The photos taken at arrival and departure days show a different beach profile (see Figure 44).

Figure 44: Left: Sirius Beach on arrival (03-10-2010). Right: on day of leaving (09-10-2010).

At the waterline the beach profile is steep, which indicates a summer profile being attacked by bigger waves. On the photos, shown in Figure 45, you can see a different kind of beach, at the left (2009) you can see a step where the beach drops down, indicated with a black line. On the other photo (2010) you can see that there is still no step, the beach is high compared to last year and has a steep slope at the waterline.

Figure 45: Beach profiles in front of Sirius Hotel in 2009 (left) and 2010 (right).

The idea that this year a summer profile is still visible, while last year a more of a winter profile was visible, is confirmed by wind data. In Table 7 and Table 8 the amount of days with wind over 13 knots from the first of August 2009 and 2010 can be seen. Also the wind direction is shown (always North-West or North) because the northerly winds and waves will create a more northerly facing beach. This year there were only two days of wind with a speed of more than 13 knots, compared to ten days last year.

Date	**Wind speed [knots]**	**Wind direction**
07-08-09	15	NW
01-09-09	14	NW
06-09-09	15	N
07-09-09	18	N
08-09-09	18	N
09-09-09	14	N
11-09-09	14	NW
12-09-09	18	NW

19-09-09	16	NW
27-09-09	16	NW

Table 7: Wind speeds and directions Sirius beach 2009.

Date	Wind speed [knots]	Wind direction
22-08-10	14	NW
10-09-10	17	NW

Table 8: Wind speeds and directions Sirius beach 2010.

3.2.2 Conclusion waterline measurements Sirius beach

The GPS data are good indicators of the state of the beach profiles. Different from last year is that this year a summer profile is present. This is also confirmed by wind data that has been found [2]. Due to the summer profile it looks like the beach accreted this year, but this could be misleading. After some storms the profile will become a winter profile and a lot of sand will be transported in cross-shore direction. Therefore the waterline will move landward and may be a bit more northerly orientated. This could already be seen in five days with heavy waves, like shown in Figure 44 on the previous page.

3.2.3 Cross-section measurements Sirius beach

In this section the measurements of the cross-sections of Sirius beach will be elaborated. First a summary of different points of action will be given:

1. Determine overall reference point for height;
2. Determine place to measure with theodolite;
3. Determine amount and place of baselines;
4. Determine places of cross-sections beach;
5. Measurements with theodolite and levelling rod.

Determine overall reference point for height (Sirius beach)

In previous years reference points and levels are defined. The overall reference point, chosen in 2003, is near the stairs to the swimming pool, as shown in Figure 46. The top of the concrete floor is determined as reference height. The reference height of this overall reference point is marked as being the zero height. The GPS coordinates (UTM) of the overall reference point are: T 582380 / 4787140.

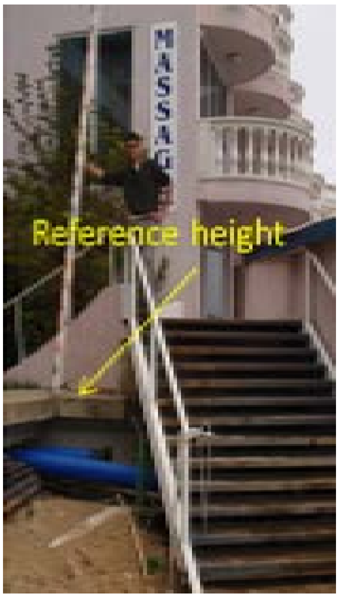


Figure 46: Overall reference point with the reference height or zero height.

Determine place to measure with theodolite (Sirius beach)

A tactical place for the theodolite is chosen in the middle of the length of the beach. Because the beach is relatively short, compared to other measured beaches, the theodolite did not have to be replaced. After placing the theodolite the height is compared with the reference height. The height of the theodolite compared to the reference point is + 0.18 m.

Determine amount and place of baselines (Sirius beach)

At Sirius beach one baseline is defined at which cross-sections have been measured. The baseline is defined as being the line between two reference points. The same reference points as the report of 2009 [3] was used. This baseline was determined and marked by beacons.

Baseline:

- Reference point 1 (same as overall reference point, see Figure 46):
  GPS (UTM) coordinates: T 582380 / 4787140. See Figure 47.
- Reference point 2 (Stairs at southern end of Sirius Beach):
  GPS (UTM) coordinates: T 582450 / 4787340. See Figure 48.

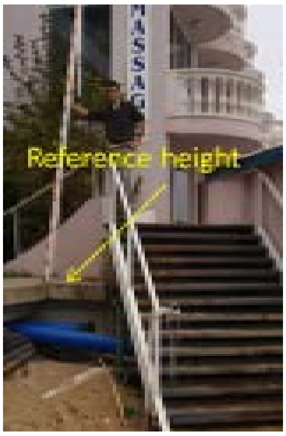


Figure 47: Reference point 1, stairs to swimming pool Sirius hotel. This is also the overall reference point mentioned before.

Figure 48: Reference point 2, stairs at southern end of Sirius beach.

Since both reference points cannot be used to determine a perpendicular line, an extra reference point is introduced for cross-section 0. This zero reference point is not used for heights but only to determine the first cross-section. Figure 49 below shows the zero reference point for Sirius beach, indicated with an arrow. It is the same zero reference point that was used in the report of 2009, although in this report the text and the picture did not correspond [3]. Further, the zero reference points from 2003 and 2008 are indicated in this figure.

N.B. After lining the cross-section, a measured difference of 75 meters to the South compared to the report of 2009 is observed [3]. This can be seen when comparing Figure 50 on the next page (with UTM coordinates) with figure 4-14 in the report of 2009.

Figure 49: Zero reference points from previous years 2003, 2008, 2009 and this year 2010.

Determine places of cross-sections beach (Sirius beach)

The cross-sections are elaborated three times either to the North and the South with an interval of 25 meters. To indicate the locations of these cross-sections, the GPS coordinates of the intersection with the baseline are mentioned below.

The 7 cross-section points on the baseline are:

- Cross-section 75N (North): T 582439 / 4787311
- Cross-section 50N: T 582431 / 4787286
- Cross-section 25N: T 582423 / 4787263
- Cross-section 0: T 582415 / 4787239
- Cross-section 25S (South): T 582406 / 4787215
- Cross-section 50S: T 582398 / 4787192
- Cross-section 75S: T 582390 / 4787168

Two extra cross-sections are introduced in 2009 namely perpendicular to the baseline on both reference points:

- Cross-section RP1: T 574409 / 4780515
- Cross-section RP2: T 582450 / 4787340

These extra cross-sections are neglected in the rest of the report.

In Figure 50, an overview of the baseline with the reference points and cross-sections is given. One should keep in mind with this figure that the cross-sections are not accurately projected onto the map.

Figure 50: Baseline with reference points Sirius beach.

In Figure 51, an overview of the baseline with the different cross-sections is given. The coordinates are given in UTM.

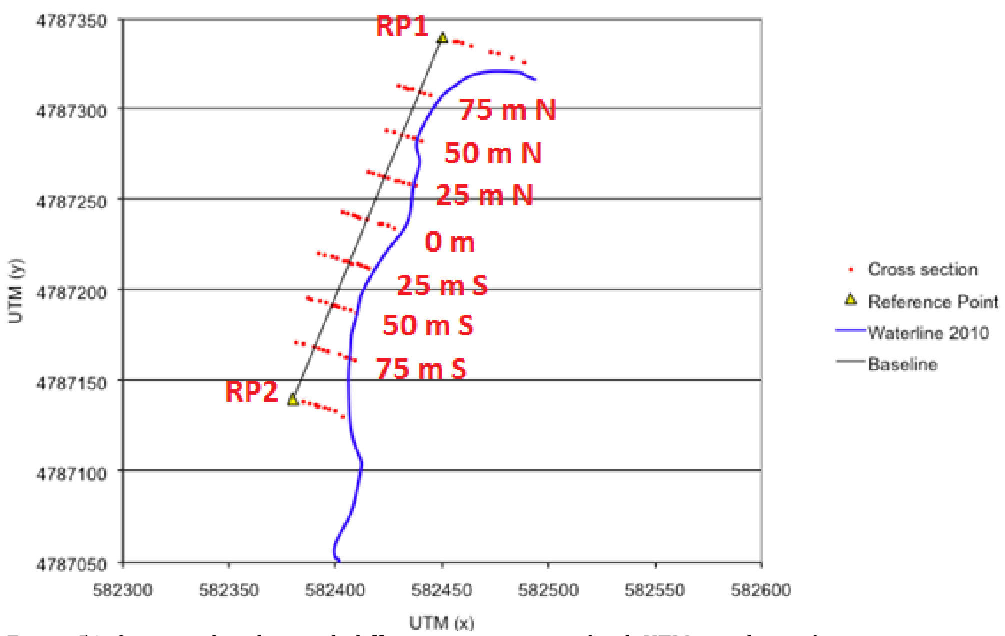


Figure 51: Overview baseline with different cross-sections (with UTM coordinates).

Measurements with theodolite and levelling rod (Sirius beach)

In order to monitor Sirius beach, yearly measurements have been carried out. In this manner a trend could be noticed, allowing future conclusions. The change in beach profiles can give an indication of the degree of erosion. A continuation of the erosion upon previous years is expected.

As described before, the beach profiles follow from measurements at seven cross-sections, which are equally distributed on the baseline, as is shown in Figure 51. The cross-sections at the two reference points were neglected. Every year the same location of the seven cross-sections is used. Hereby, developments of the beach profiles can be plotted in time. An important boundary condition is that the same location is taken as the zero reference point throughout the years. This appeared to be difficult, so an error of approximately 10 meters was introduced (as stated in [3]). This is assumed not to influence the overall picture of the beach.

In Figure 52 until Figure 58 the beach profiles are depicted. These profiles are ordered from North to South. In the beach profiles it is assumed that the change in waterline can be neglected.

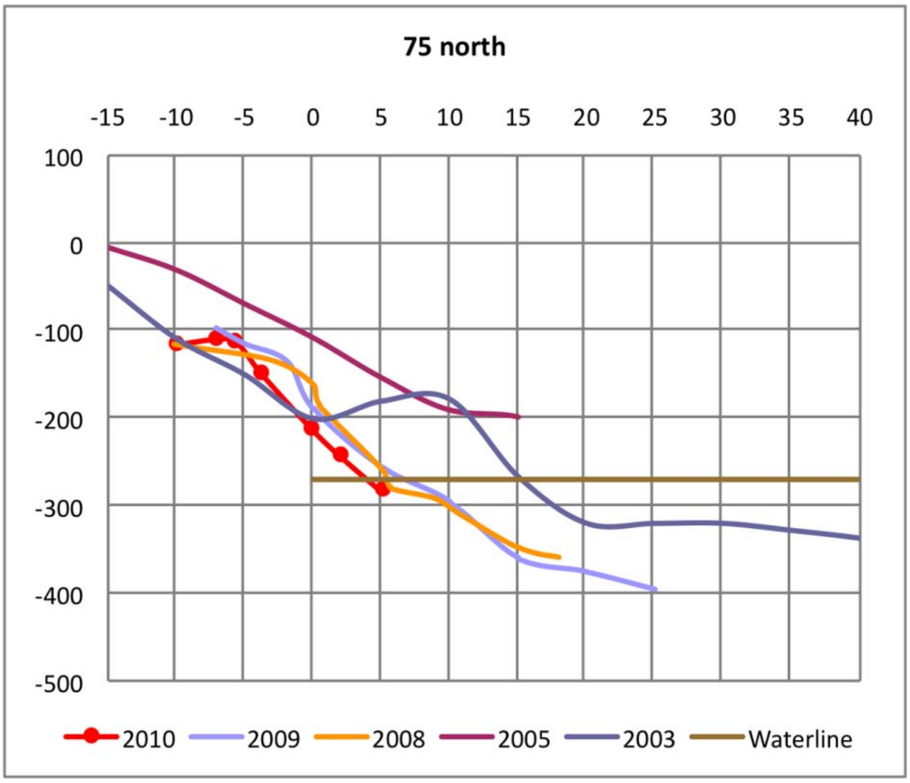


Figure 52: Beach profile 75 m north of zero reference point.

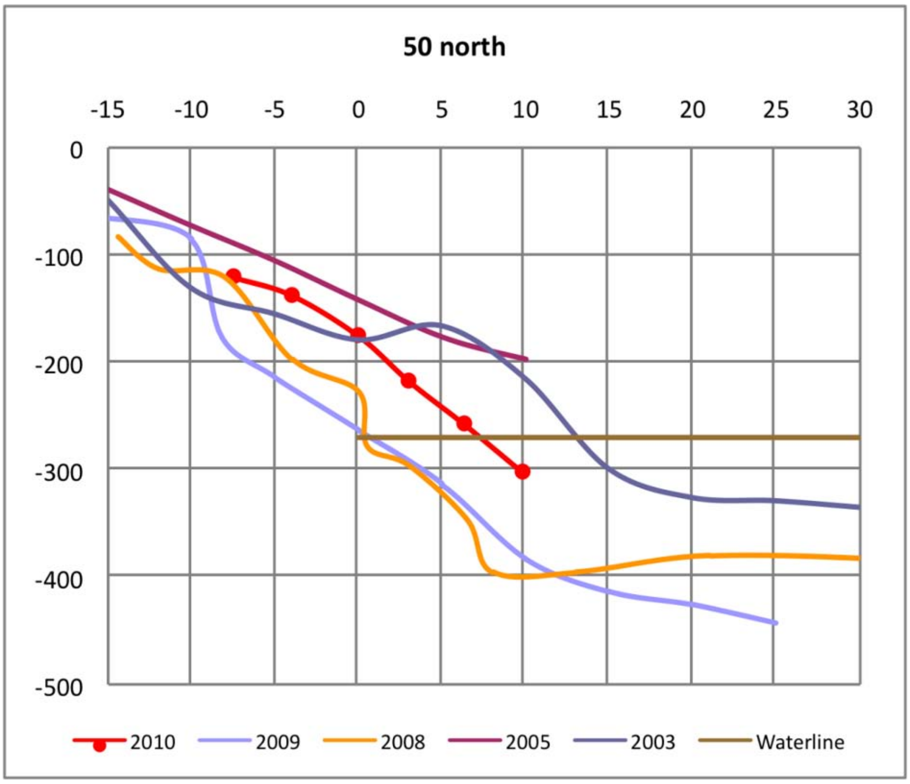


Figure 53: Beach profile 50 m north of zero reference point.

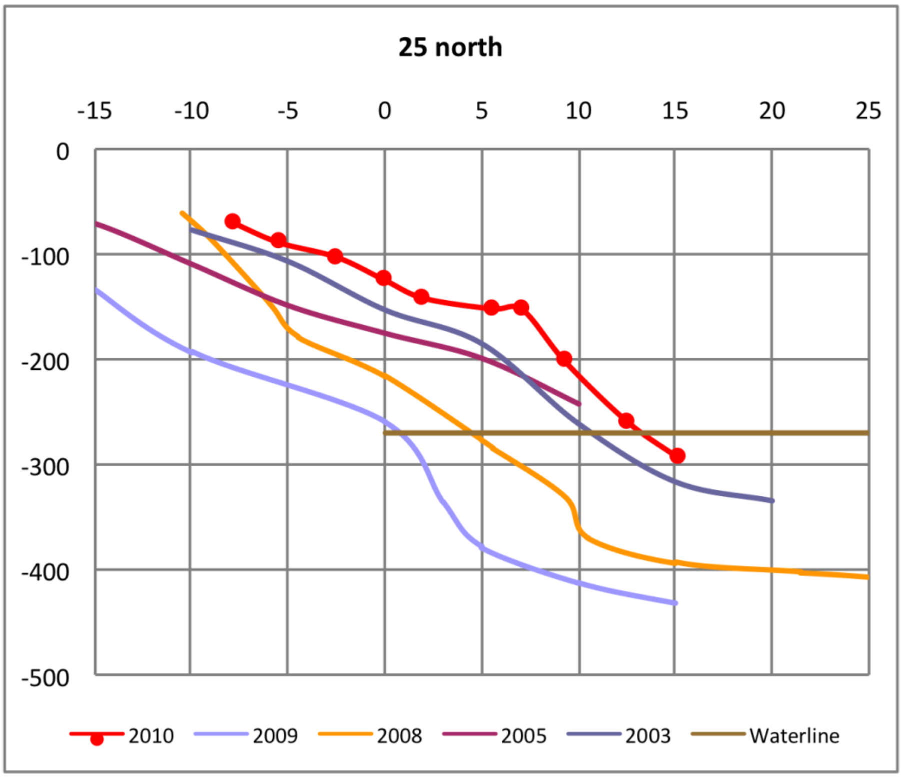


Figure 54: Beach profile 25 m north of zero reference point.

Figure 55: Beach profile at zero reference point.

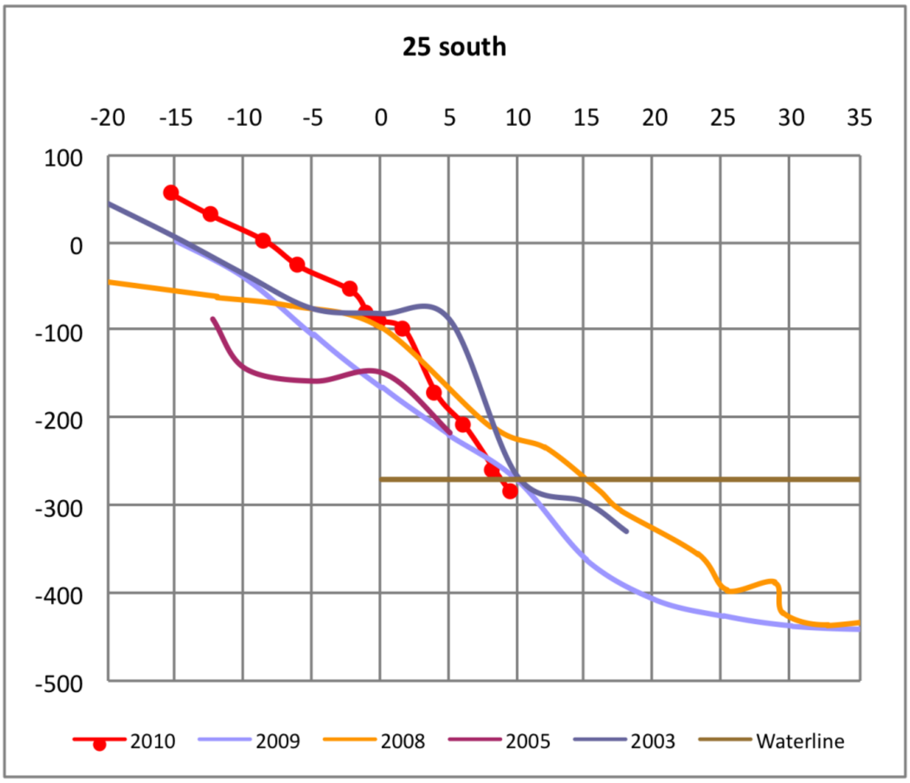


Figure 56: Beach profile 25 m south of zero reference point.

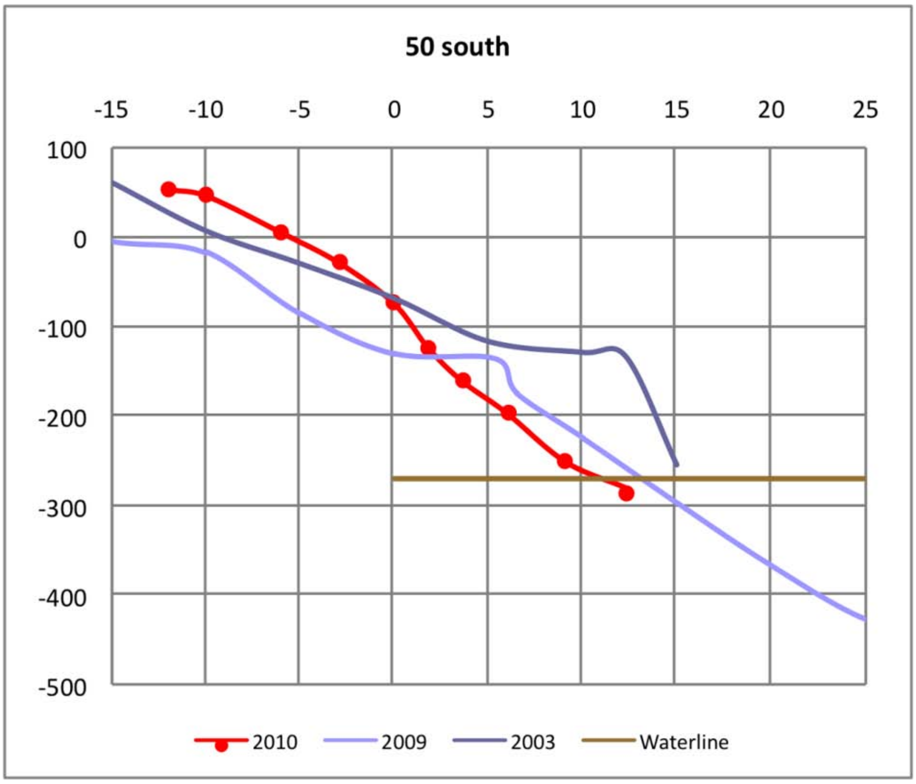


Figure 57: Beach profile 50 m south of zero reference point.

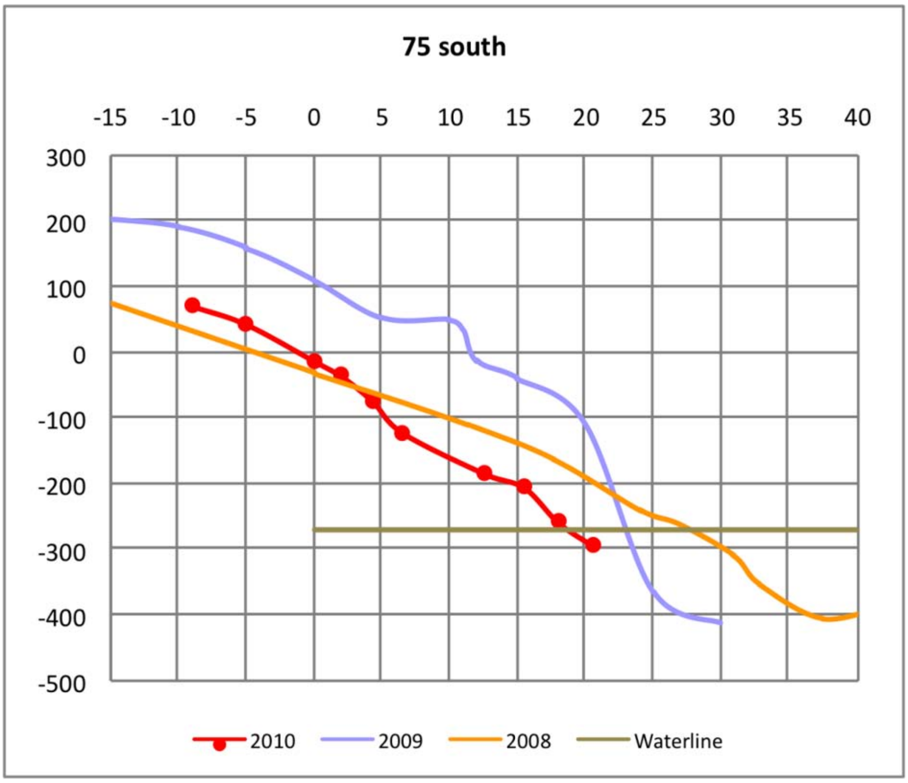


Figure 58: Beach profile 75 m south of zero reference point.

When the beach profiles are observed from North to South, a couple of interesting conclusions can be drawn. At 75 m north of the reference point, it is clear that the beach is retreating. This is confirming the trend of the previous years, especially when the results of 2010, 2009 and 2008 are compared. In the next three profiles to the South, the opposite is found though. Therefore the beach accreted here, even more than the two previous years. At 25 m north of the reference point, the beach appears to have even more accreted than in 2003 just after the nourishments. At 25 m until 75 m south of the reference point there actually is erosion, which seems to fit the timescale of a retreating beach.

3.2.4 Conclusion cross-section measurements Sirius beach

Elaboration of the profiles does not immediately show erosion of the beach in respect to the previous years. And the plots are also not pointing out a clear continuation of the eroding trend in 2010.

As mentioned in the section about the waterline at Sirius beach, the state of the beach was not similar to previous years. This can be explained by the seasonal differences in winter and summer profiles. In combination with the fact that the beach profile was highly variable during the week of the measurements and did not experience heavy weather until the week of the measurements, points also in this direction. The profiles were measured early in the week, before the heavy wave attacks that changed the beach profile throughout the week. Because in previous years completely different circumstance were encountered, a comparison cannot be made.

Note on the Sirius beach measurements:
There were doubts about the validity of the measurements. The measurements seemed to be completely out of range and therefore appeared not to have any meaning relative to the previous measurements. It was assumed that a mistake was made with the use of the measuring equipment. After some time still the above conclusions were drawn. Either way, it does mean that the measurements made this year should to be used with care.

3.3 Wave observations

In this part of the fieldwork, visual wave measurements have been done to determine the wave height and period near the Sirius Beach Hotel. A few hundred waves have been observed and analysed according to the Battjes Groenendijk method, and afterwards they have been compared to the theoretical Rayleigh distributions for non-broken waves.

3.3.1 Observation method

To determine the wave height visually, non-breaking waves are required. Therefore the waves had to be observed as much outside the server zone as possible. To come up with reliable measurements the wave height had to be observed with respect to a reference point. Therefore the jetty next to Sirius beach has been chosen as the observation point. This location could be observed with a theodolite from the sixth floor of Sirius beach Hotel. The theodolite has been used as a binocular so that the whole jetty could be seen in detail.

Two measure locations at the pier were chosen to see the deformation of the waves, one at the tip of the pier and one halfway. At the two locations three reference points have been chosen. At the end of the pier, a bulb of shells, a hole in one of the columns and the top of the pier were used as reference points. In the middle of the pier two horizontal beams at the top of the pier are used.

After measuring the height of the waves with respect to the reference points, the heights of the reference points itself were measured. So first all the wave heights were measured in fictitious units between two reference points. Then the real length of such a fictitious unit is measured and the two values are multiplied with each other.

In this way the approximate mean water level could be calculated and the real wave height in meters. The further analyses are described in the next chapter.

3.3.2 Wind measurements

During the wave observations also the wind speed has been measured at Sirius beach. In relation to the wave observation this is not of much value, because it is very likely that the waves which have been measured were formed at a wind field positioned far away from Varna. The wind speed at the location itself is unrelated to the wave heights which have been observed. Nonetheless it gives a complete picture about the wave and wind climate at the moment of measuring at Sirius beach.

A few wind speed measurements have been done at different locations, one at the end of the pier and three more on shore. They more or less gave the same value, except the measurements at the end of the pier was a little bit higher. At the shore the wind speed was around 7 m/s and at the end of the pier it was 9 m/s, both from North-Eastern direction.

3.3.3 Observations in relation to Rayleigh

The results of the observations were collected and compared to the theoretical distributions of the wave height. In deep water, the individual wave heights should be Rayleigh distributed and for waves in shallow water Battjes and Groenendijk successfully tested a composite Weibull distribution which is elaborated in the next paragraph.

First in Figure 59 the distribution of the measured waves is shown. For this first dataset out of four, 48 individual waves were measured. From these data several expressions for the wave height were derived. In Appendix D the measured data are included, which are converted into wave heights in meters. From these data the theoretical Rayleigh distributions were calculated and compared to the measured data, scaled to compare to the Rayleigh distribution.

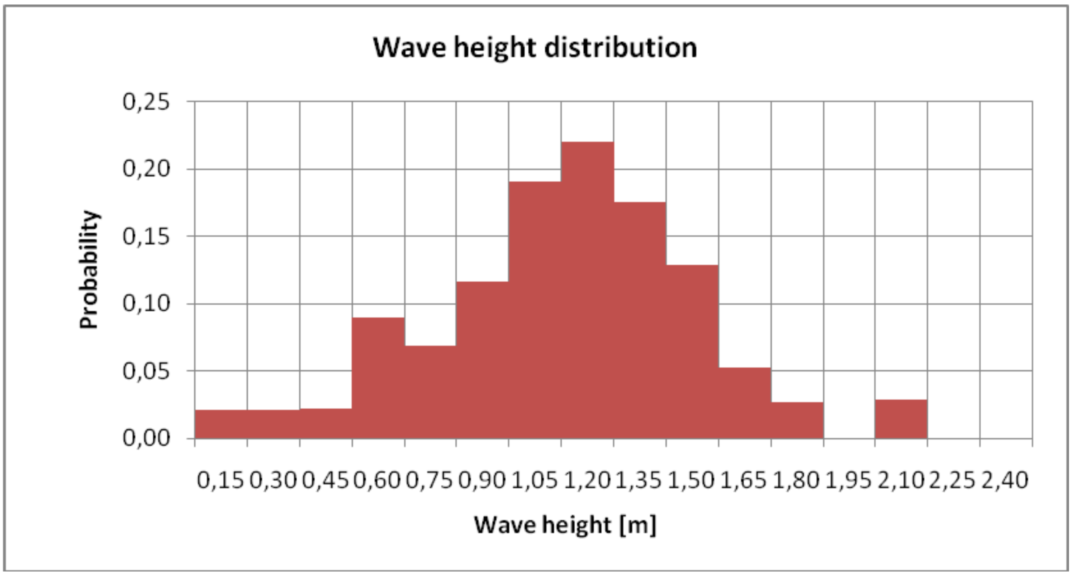


Figure 59: Wave height distribution of measured waves.

Next to the wave height observations, the average wave period was calculated. The result of 4 measurements on one day is elaborated in Table 9.

Number of waves in 10 min	T [s]
136	0.227
127	0.212
126	0.210
119	0.198
Average period in seconds	0.212

Table 9: Measured wave periods.

In order to compare the observed wave heights to the theoretical Rayleigh distribution, the observed wave heights are plotted on a scaled axis. To calculate the theoretical Rayleigh distribution the following formula is used:

$$P(H) = P(\underline{H} < H) = 1 - \exp\left(-\left(\frac{H}{H_{rms}}\right)^2\right)$$

The theoretical Rayleigh distribution was scaled by taking: $\sqrt{-\left(\ln\left(1 - P(\underline{H} < H)\right)\right)}$

In Figure 61, 62 and 63 the measured wave height distribution is plotted together with the theoretical Rayleigh distribution. As one can see, there is a deviation from the theoretical Rayleigh distribution. This deviation can be explained, because at the location where the wave height was observed the waves were already breaking.

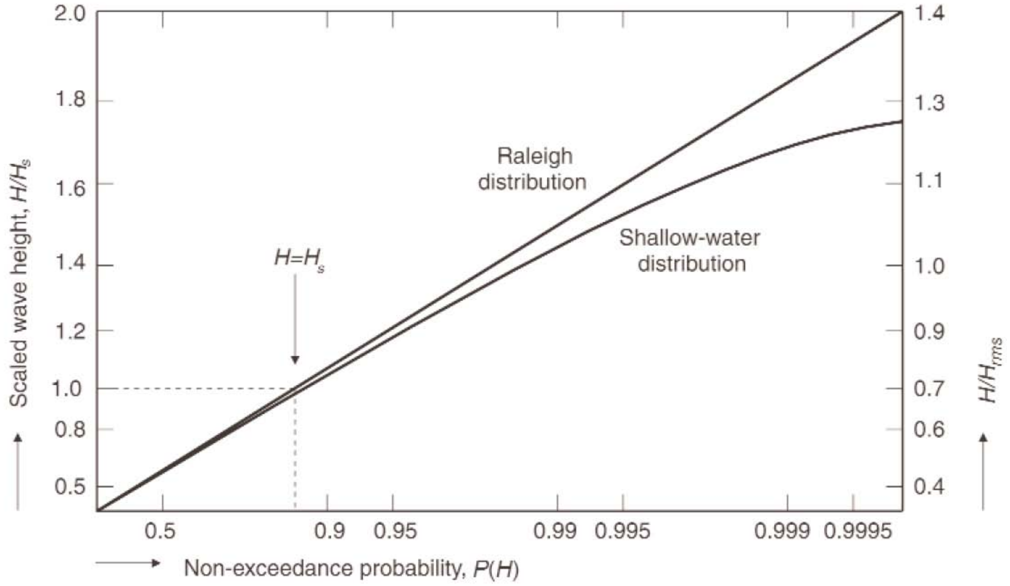


Figure 60: Example of a shallow water observed distribution [4].

When Figure 61, 62 and 63 are compared to Figure 60, there is clearly a relation. At the higher wave heights, the deviation from the Rayleigh distribution is getting larger. This deviation in shallow water can be explained by the nonlinear phenomena in shallow water, with breaking of the waves as an example.

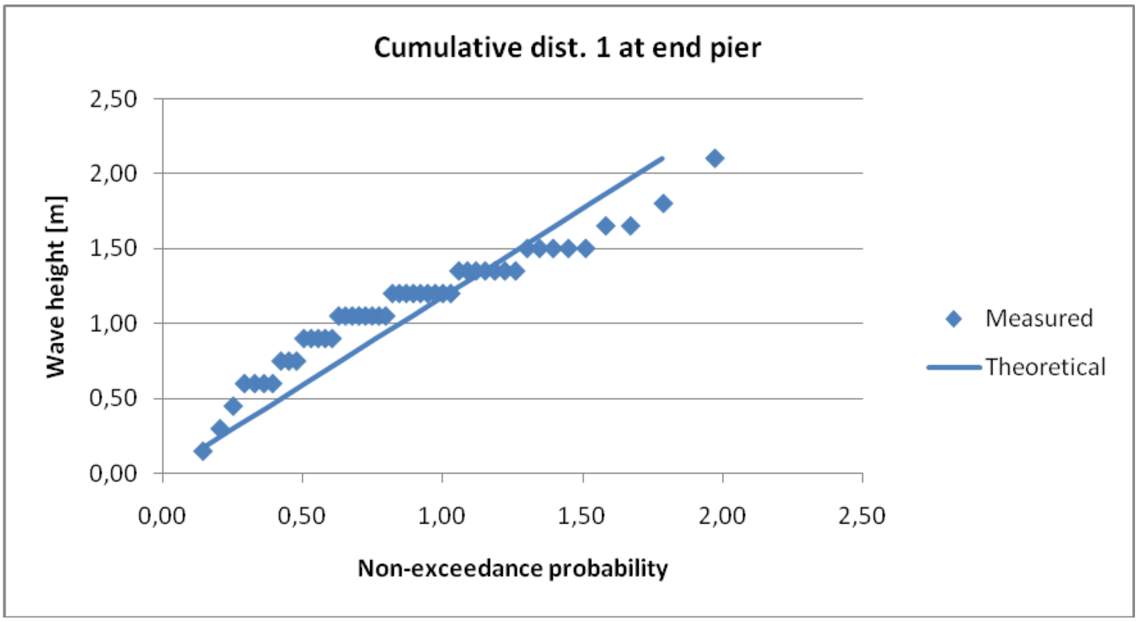


Figure 61: Distribution of the wave heights in relation to theoretical Rayleigh distribution.

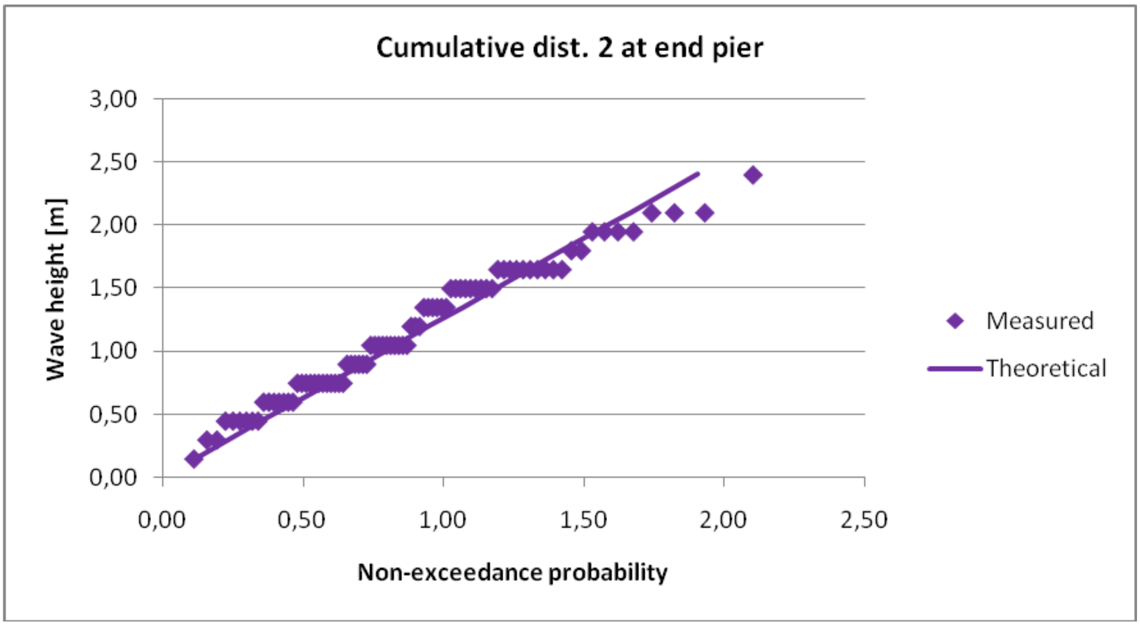


Figure 62: Distribution of the wave heights in relation to theoretical Rayleigh distribution

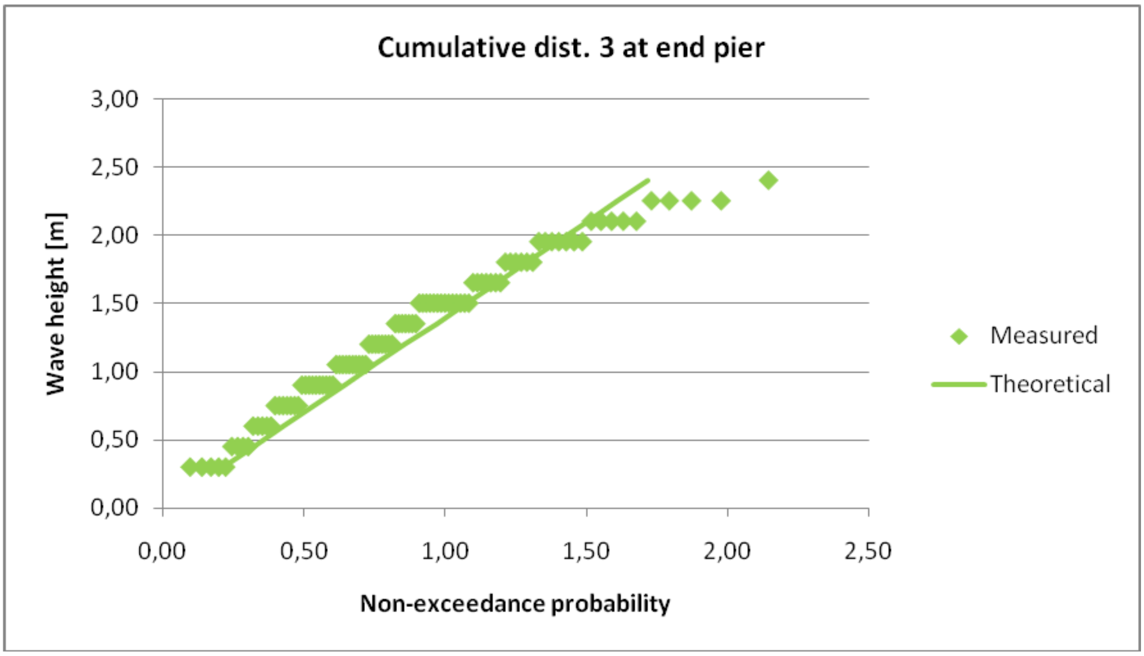


Figure 63: Distribution of the wave heights in relation to theoretical Rayleigh distribution.

Figure 63 is compared to Figure 61 and 62 the best representation of Figure 60. The measured wave heights follow almost the same 'line' as the wave heights in Figure 60.

3.3.4 Observations in relation to Battjes Groenendijk

In shallow water the wave height distribution is affected by non-linear interactions and by breaking of the waves. Because of these effects, the Rayleigh distribution is no longer applicable. Battjes and Groenendijk have tested a composite Weibull distribution in order to work with these effects.

In Figure 64 this theory is visible. The highest waves will break first and lower waves at that point will not (yet) break. At that point a normal Rayleigh distribution can be used for the lowest part of the distribution and a Weibull distribution for the upper part of the distribution.

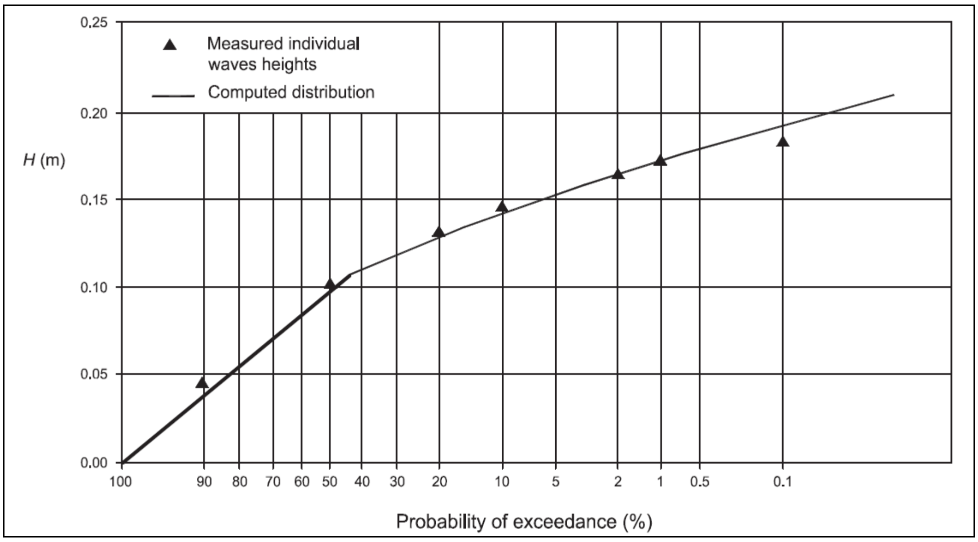


Figure 64: Figure from Battjes and Groenendijk 2000 [4].

There is a transitional wave height, which represents the wave height at the meeting point of these two distributions. Around this transitional wave height the following distributions are applied:

$$P(H) = P(\underline{H} < H) = \begin{cases} 1 - \exp\left(-\left(H/H_1\right)^2\right) \text{for } H < H_{tr} \\ 1 - \exp\left(-\left(H/H_2\right)^{3.6}\right) \text{for } H \geq H_{tr} \end{cases}$$

With $H_{tr} = \left(0.35 + 5.8 \tan\alpha\right) h$

Here alpha represents the slope and 'h' represents the local water depth.

From the pier also the local water depth was measured. At the end of the pier a water depth of 2.8 meters was measured and in the middle of the pier a depth of 2.1 meters was measured.

In Appendix E a table with calculated values is included, from where Figure 65 is the result. Here one can observe the four datasets that were acquired, in relation to the theory of Battjes and Groenendijk. As visible in Figure 65, dataset 3 fits in the best way to the theory. A reason for that could be that in dataset 3 a total of 100 individual waves were measured, compared to only 48 individual waves in dataset 1.

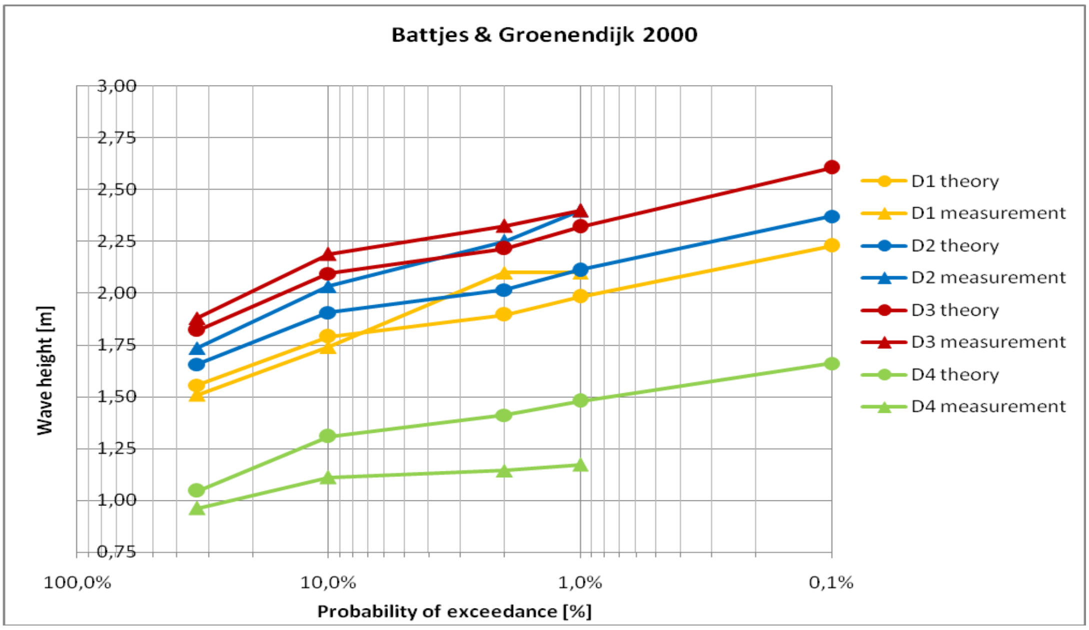


Figure 65: Measured wave heights compared to Battjes and Groenendijk 2000.

Another explanation for the differences between the measured and calculated values is the inaccuracy in the measurements of the local water depth. When one decreases the local water depth for example with dataset 4 from 2.1 to 1.5 meters, the two lines are almost on top of each other. It is very well possible that near the piles of the pier a local scour hole is present, what means that the measured depth is too large. Of course this inaccuracy is also applicable for the other three datasets.

3.3.5 Recommendations for further research

One may conclude that the measurements fit pretty well to the calculated values. On the other hand, there are some uncertainties like the local water depth that cause a relative big error. In order to improve the results next years, here are some recommendations to take into account for following measurements.

Water depth

In order to calculate the distribution for the Battjes Groenendijk theory right, the water depth and slope are needed. This year these values were measured at one point and it is not sure if these were accurate enough. These measurements should be made more extensive.

Number of observations

To elaborate the data and compare it to for example a theoretical Rayleigh distribution or composed Weibull distribution, more individual waves should be measured. A record of half an hour would be better than the 10 minutes of less that were recorded this year.

Measuring method

When also another way of measuring waves is used, the visual observations can be compared to the observations by another instrument. For instance the waves could also be measured by a pressure meter or by a wire piercing the surface.

4 Azalea beach

4.1 Introduction

In Figure 66 below the location of Sirius beach is presented again:

Figure 66: Location of Azalea beach.

4.2 Measurements Azalea beach

The measurements that have been done on Azalea beach are:

- Waterline measurements using GPS;
- Cross-section measurements.

A detailed explanation of the cross-section measurements can be found in Appendix B.

4.2.1 Waterline measurements Azalea beach

In 2008 the first measurements of (a part of) Azalea beach have been executed (in the report of 2008 it is referred to as Sirius North Beach). Last year the conclusion from the waterline data was drawn that the beach is eroding, but this is hard to say with only one set of measurements to compare with.

The fieldwork this year was done during a week with strong winds and bad weather. Therefore it was chosen to measure the waterline with a GPS several times in this week. Because the fieldwork is planned at the start of the period in which the summer profile of the beach is transitioning into the winter profile, there can be a big difference between the data in consecutive days and years. One has to keep in mind that the profile of the beach is continuously changing, and that these data are only a snapshot of the situation.

First the GPS waterline data, collected during the fieldwork 2010, is elaborated. These data give information about the changes which can occur during a week. It is interesting to compare these changes to yearly changes. This is done later on.

Changes during the fieldwork

During the fieldwork, the waterline has been measured at two different days, see Figure 67.

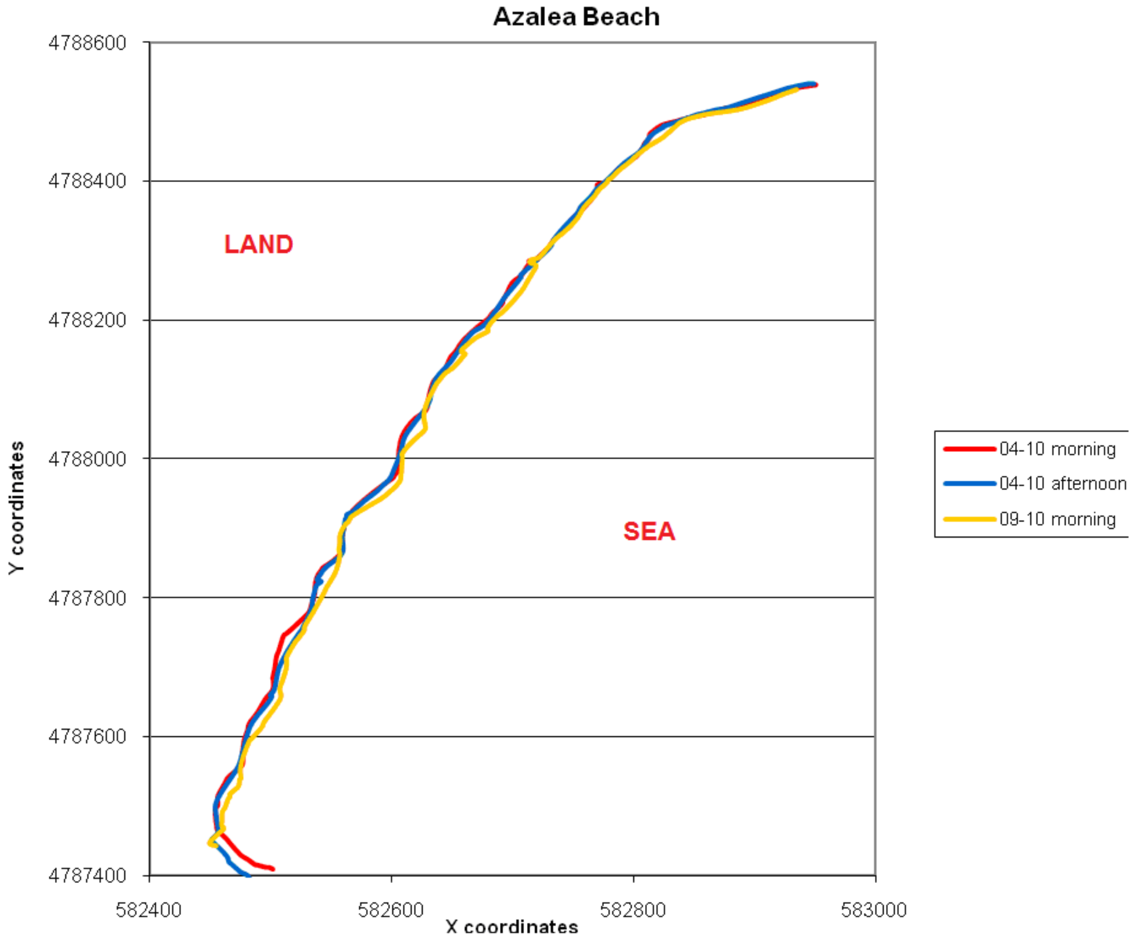


Figure 67: Waterline position at different days in 2010.

Figure 67 shows quite large differences in the position of the waterline between October 4th and 9th. The two measurements at October 4th are almost the same. Five days later, the measurement of October 9th, shows a waterline that shifted seawards. In the intermediate five days, high waves and strong winds have changed the profile of the beach. From the transition from the summer profile into the winter profile, a landward shift is expected. The shift of the waterline has a maximum value of about 15 m at some places. The seaward shift of the waterline can be explained with wind set-up and set-down, wave run-up and measuring errors.

N.B. The measuring method can give substantial errors. The GPS receiver is accurate within a range of 5 meters. Also where the person holding the GPS defines the waterline is changing from person to person. This can give differences of approximately 10 m.

In the next paragraph also physical processes are considered and their contribution to the shift of the waterline.

Moment of measuring	Wind conditions at Varna	Angle of incidence φ
04-10-2010 morning	North-Eastern wind, ca. 5.5 m/s	60^o
04-10-2010 afternoon	East-South-Eastern wind, ca. 5.5 m/s	7.5^o
09-10-2010 morning	North-Western wind, ca. 8.3 m/s	30^o

Table 10: Wind conditions at Varna.

Related to the wind conditions, wind set-up or set-down can vary. The wind set-up or wind set-down depends on the fetch, the wind speed and direction and the depth of the water body. Because the wind blew landward on October 4th, a wind set-up will occur. On October 9th, the wind was directed offshore, resulting in a set-down of the water surface. Because the Black Sea is a deep basin, the overall wind set-up or set-down is negligible. Near the shoreline, a shallower part is present, where a small set-up and set-down can be present. Because the slope of the beach is relatively steep (about 1:6), the horizontal shift of the waterline will be small, even if there is a variation in wind set-up or set-down. The difference in set-up and set-down is estimated to be max. 20 cm[1], resulting in a waterline shift of about 1 m.

Also wave run-up can change due to different conditions. The wave run-up can be defined as $8 \cdot H_s \cdot \tan(\alpha) \cdot \gamma_b \cdot \gamma_\beta$. Due to stronger winds, the wave run-up would have been larger on October 9th compared to October 4th, which would result in a larger wave run-up. But the angle of incidence is larger on October 9th, which reduces the run-up. Also it could be that during the week the winter profile has developed in such a way that the underwater part of the beach (foreshore) has flattened and functions like a kind of berm, reducing the wave height and run-up, see Figure 68.

The above mentioned factors all contributed to the shift of the waterline. The measuring errors are supposed to have given the largest contribution.

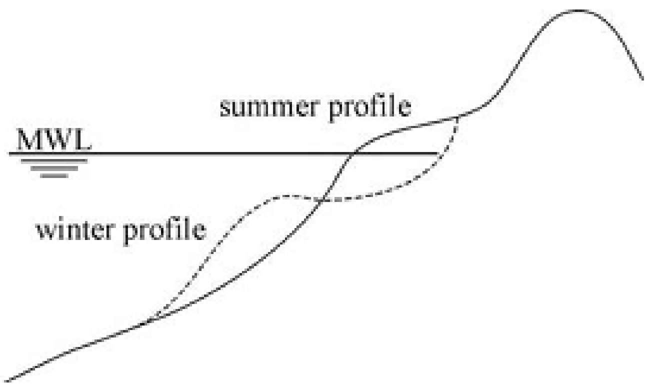


Figure 68: The transition from a summer profile into a winter profile.

Changes over the years

It is clear that the differences during a week are in the same order of magnitude as the differences in consecutive years. This means that the comparison of data of different years has to be done with great care. The data is very sensitive for weather circumstances and the transition from the summer to the winter profile. Only if measurements over a longer period are available, more reliable conclusions can be drawn.

For this moment it can be concluded that a slight retreating behaviour of the coastline can be noticed. The waterline of the last measuring day, October 9th, which is positioned most seaward if all measurements in 2010, is even positioned more landward than the waterline of 2009 en 2008.

[1] $\Delta h = c \cdot u^2/(gd) \cdot F \cdot \cos\varphi$, with $c \approx 2.35 \cdot 10^{-5}$, u = wind speed, d = depth of shallow area ≈ 17 m, F is width of shallow area ≈ 20 km and φ = angle of incidence. [5]

Unfortunately, no information about the weather conditions in the last two years is available. Next groups can compare the results of 2010 with their own results with the knowledge of the weather circumstances as described in Table 10.

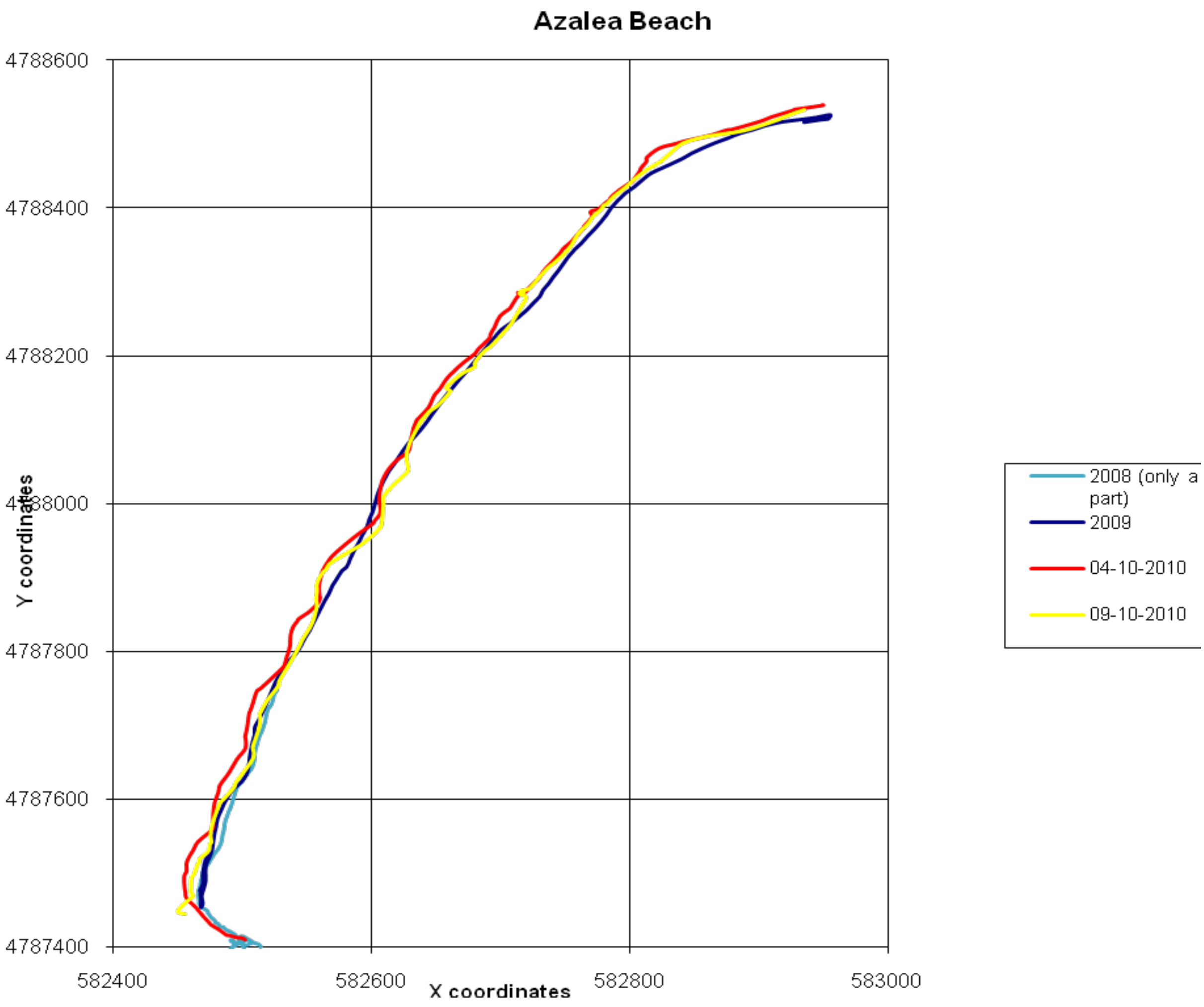


Figure 69: Waterline data 2008, 2009 and 2010.

4.2.2 Cross-section measurements Azalea beach

In this section the way of measurement of the cross-sections of the beach will be elaborated. First a summary of different points of action will be given:

1. Determine overall reference point for height;
2. Determine place to measure with theodolite;
3. Determine amount and place of baselines;
4. Determine places of cross-sections beach;
5. Measure with theodolite and levelling rod.

Determine overall reference point for height (Azalea beach)

On this beach the chosen reference point is the upper side of a concrete under beam in front of Azalea hotel. This is the first round tower when coming from Sirius beach (and not the second!). The overall reference point is marked red in Figure 70.

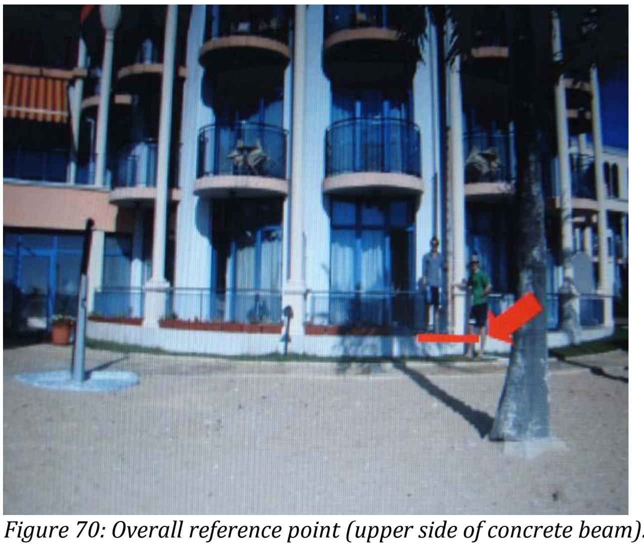


Figure 70: Overall reference point (upper side of concrete beam).

Determine place to measure with theodolite (Azalea beach)

In this project, the height of the theodolite compared to the overall reference point has been measured with the help of a levelling rod, placed on the concrete beam showed in Figure 70. The height of the theodolite compared to the overall reference point is – 0.73 m.

Determine amount and place of baselines (Azalea beach)

In this project, one baseline is used. This baseline lies between two reference points which are marked with red/white or grey poles. About this reference points:

Baseline:

- Reference point 1 (outside swimming pool of the Azalea Hotel): T 582476 E / 4787668 N. See Figure 71.
- Reference point 2 (at the concrete semi-circular platform of the outside bar of the Sunny Day hotel): T 582588 E / 4788005 N. See Figure 72.

Figure 71: Overall reference point (upper side of concrete beam).

Figure 72: Reference point B (baseline).

Since both reference points cannot be used to determine a perpendicular line, an extra reference point is introduced for cross-section 0. This zero reference point is not used for heights but only to determine the first cross-section. The same zero reference point as in the report of 2009 is used in this report of 2010. Figure 73 below gives the zero reference point for Azalea beach, which lies on the bottom of a concrete pile of the southern wing of the Azalea hotel.

Figure 73: Zero reference point Azalea beach.

Determine places of cross-sections beach (Azalea beach)

Just like the measurements that were done last year, this year it was decided to measure three cross-sections, with mutual distances of 50 and 100 meter. At the zero reference point, cross-section 0 m was created, perpendicular to the baseline.

In Figure 74, an overview of the baseline with the reference points and cross-sections is given. One should keep in mind with this figure that the cross-sections are not accurately projected onto the map.

Figure 74: Overview baseline and cross-sections.

N.B. The GPS coordinates (UTM) of the cross-sections on the baseline at Azalea beach are unfortunately not known. Of course these coordinates are not necessary for measurements next year, but they could be of some help when determining the three cross-sections on Azalea beach.

Measure with theodolite and levelling rod (Azalea beach)

A summary of the measurements of the cross-sections can be given in a graph, see Figure 75.

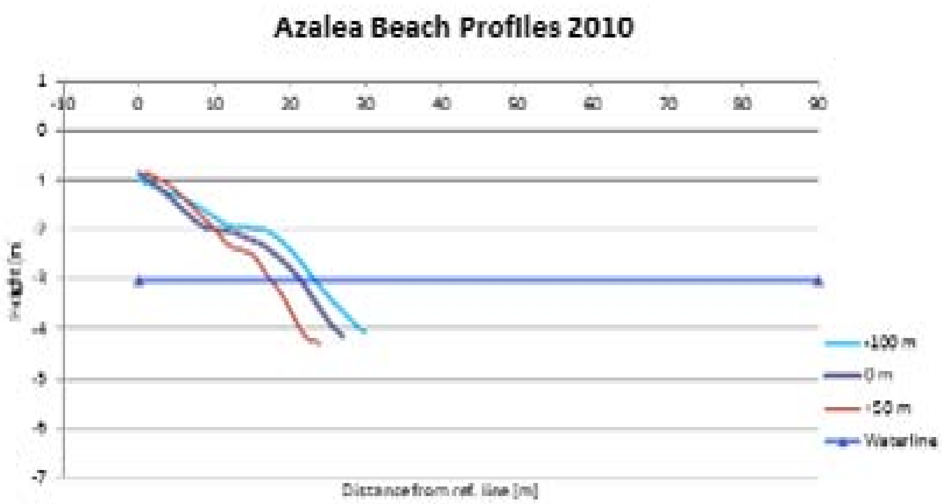


Figure 75: Beach profile Azalea 2010.

Unfortunately, the data from the beach profile measurement of previous year, the first year that the beach profile at Azalea has been measured, has been lost. Therefore last year's profiles cannot be plotted in one graph with this year's data. The graphs of last year are given in Figure 76.

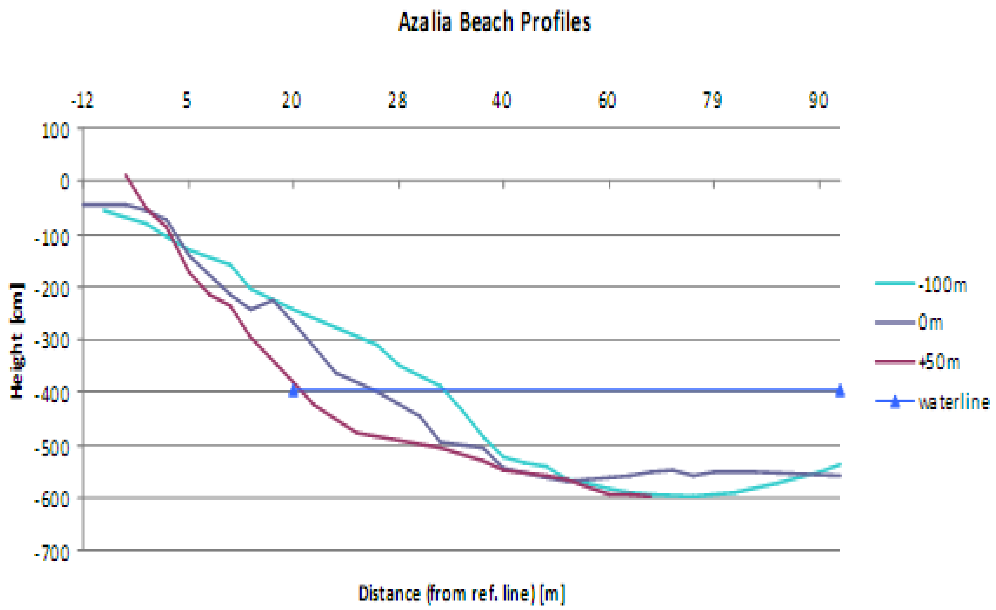


Figure 76: Beach profiles Azalea 2009.

Conclusion cross-section measurements Azalea beach

Because last year the weather circumstances were a lot better, the previous group was able to extend their measurements far into the sea. This year the circumstances were so bad, that measuring further in sea was too difficult with the levelling rod. This can also be seen in the difference in water level in 2009 and 2010. If a comparison of the dry beach profile is made, it can be noticed that near the zero line all cross-sections moved downward, which is an indication of erosion. The 'order' of the different cross-sections is the same for 2009 and 2010, which means that the overall profile of the beach has not changed. The beach has only lowered.

5 Lake Varna

5.1 Introduction

Lake Varna is a deep elongated lake near the city of Varna, see Figure 77. The lake is a river valley, which was drowned due to sea-level rise near the end of the Pleistocene. At the beginning of the 20th century, a connection between Lake Varna and the Black Sea was made for navigational purposes, resulting in a lowering of the water level in Lake Varna and turning the water in the lake into a brackish environment. In the seventies, the construction of Port Varna West required a bigger entrance channel to Lake Varna and the dredging of a shipping lane inside the lake. These activities have changed the currents, water quality and ecosystem of the lake. In former times the lake used to be a recreational area, popular for sailing, swimming and fishing. Nowadays, recreation has moved to the Black Sea coast, and the lake is mainly used as shipping lane to the port. [6], [7].

Figure 77: Overview of Lake Varna.

Recently a plan was set-up to create several artificial islands in the lake. The purpose of these islands is to store the dredged material from the navigation channel in the lake. This would be an easy way to get rid of the dredged material and it has the possibility to create a recreational area on the southern side of the islands. The islands would function like barrier islands and create a sheltered area, suited for sailing matches and other recreational activities. Furthermore the islands would form a physical border between the industrial (northern) side of the lake where the large container ships sail and the southern side with the marina and possibilities for recreation. The islands itself would probably become protected areas for birds, to compensate for the loss of Natura2000 area at the northern side of Lake Varna. The location of the islands is presented in Figure 78.

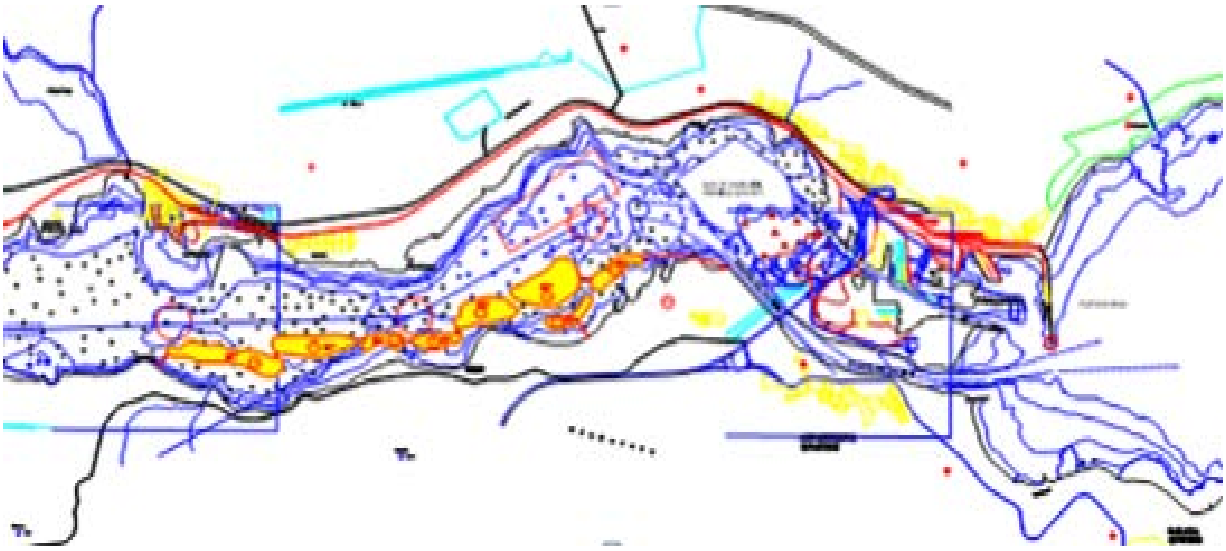


Figure 78: East side of Lake Varna with artificial islands indicated in yellow.

To make a study about the feasibility of the construction of these islands, more information about the bathymetry of the lake should be collected. Most of the available information contains data of the depth near the shipping lane or it is dated. To collect the required data, echo soundings were made at the location where one of the islands is planned. The outline of the measured area is indicated with a red line in Figure 79.

Figure 79: Overview of measuring location in Lake Varna.

5.2 Measurements

Measuring the bathymetry of Lake Varna at the earlier mentioned location was done with echo sounding equipment in combination with GPS in a small boat, with guidance of ir. Boyan Savov. The idea of this type of measurements is to sail in a regular way over the surface, in order to create a thick net of measurements with output in x-,y-, and z-coordinates. With this information it is possible to map the bed level using software like Surfer.

The collected data was processed and inserted in the program Surfer to obtain a visual simulation of the bed level of Lake Varna. Surfer interpolates the water depth measurements to a specified grid and is then able to form the contour lines in the measured area. There are multiple interpolation methods available and the best option depends on the density of the data points. The grid to be used is also dependent on the distance between the data points. The program gives the best results if multiple data points are used to determine the water depth in the intersection of grid lines. After comparing several interpolation methods, the best option seemed to be the natural neighbour method with grid cells of 20 x 20 m. This method does not create a lot of artefacts, it does not generate grid values in areas with no data, and it does not extrapolate z-grid values beyond the range of data. The natural neighbour method is assumed to be a good method for data sets containing dense data in some points and sparse data in other areas.

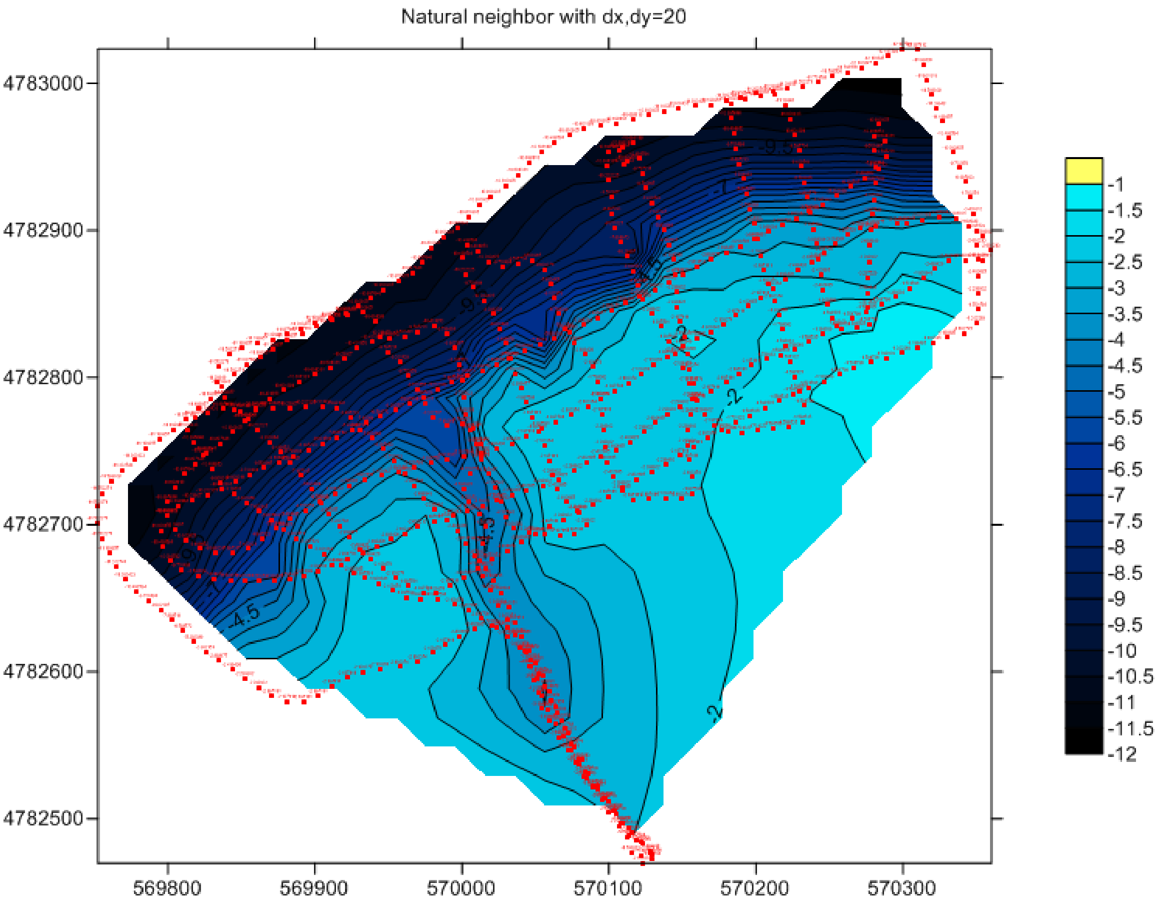


Figure 80: Map of bathymetry of measured area, created with Surfer.

Figure 80 shows the bathymetry in different shades of blue and the data points in red. It is clear that the area with a lot of data points, where the island is planned, gives no artefacts on locations without data points. At the areas where no data points are shown, the method gives an interpolation which is less accurate.

5.3 Conclusions and recommendations

The plans to create artificial islands in Lake Varna are in a very early stage. The feasibility of this plan depends on a lot of factors. The measurements give information about the amount of dredged material required to create an island at the measured location. A lot more information is needed to be able to investigate if it is possible to create these islands, for example information about waves and currents in this area. Also the amount of dredged material in a certain time span has to be known. It is no use to create an island by nourishing very small amounts of sand at a time, because then this sediment will be transported away. Also more information about the dredged material is needed, like information about the D_{n50} and about the (possible) pollution of the material. If the dredged material is polluted, there are strict requirements to fulfil when using this material. The islands may function like ‘the Slufter’ near the ‘Maasvlakte’, to store polluted material.

Next steps to be taken for the investigation of the feasibility of constructing these islands are, making an estimation of the amount of dredged material, the properties of this material and to measure the currents and the waves at the planned location.

6 Quarry measurements

6.1 Introduction

To investigate the available rock in the surroundings of Varna, two quarries near Varna were visited. At the Marciana quarry near Devnya some parameters of the rocks available for hydraulic engineering works were investigated. And at the Sini Vir quarry, south of Tsonevo, the quarry itself and the quarry processes as drilling holes near the edge to fill them with explosives and a stone crusher to crush the larger rocks were observed.

In section 6.2 there is a general introduction about the executed measurements. In section 6.3 the results of the different experiments and measurements are given for the small rocks and the heavy rocks. And in section 6.4 the design significant wave height of an imaginary breakwater is computed, when using the heavy rocks from the Devnya quarry.

Figure 81: A grab wagon at the Devnya quarry

6.2 Introduction to measurements

6.2.1 Small rock measurements

At the Marciana quarry 20 rocks were selected for the measurements. This number of rocks is large enough to get an impression of the sort of rocks in this part of the quarry and small enough to be able to take the measurements in the time available in the visit to the quarry. The measurements on these 20 rocks were done by 2 groups to get more reliable measuring data. The rocks were arbitrarily selected, under the only condition that the rocks could to be lifted by one person. For hydraulic engineering purposes the blockiness, elongation and the D_{n50} of the rocks needed to be determined. To obtain these parameters it was needed to measure the weight, dimensions and density of the rocks.

The weight of these rocks was measured with a simple weighing scale. In order to be able to calculate the blockiness, the dimensions of ‘the smallest box the rock could fit in’ were measured. For the elongation, the longest and the shortest length of the rock were measured. These measurements were done with a measuring tape. To determine the density of the type of rock at the quarry three little rocks were brought to Delft, where an additional experiment had to be done.

6.2.2 Heavy rock measurements

At the Marciana quarry there was also a heap of rocks which could not be lifted on a weighing scale because the rocks where far too heavy. For a hydraulic engineer it is handy to know the number of rocks in a heap. This number of rocks was determined by measuring the general dimensions of the heap of rocks, the volume of the rocks and the porosity of the heap of rocks. The general horizontal dimensions 'x' and 'y' were measured with a measuring tape; the average vertical dimension z (height) was estimated. The porosity of the heap of rocks was also estimated by the naked eye.

6.2.3 Design significant wave height

With the outcome of the experiments done at the quarry, it is possible to compute the design significant wave height of a breakwater built with rocks of the quarry. For this imaginary breakwater it is more realistic to take the heavy rocks as revetment material, to withstand large waves.

6.3 Outcome of general measurements

6.3.1 Specific density

The execution of the experiment for determination of rock density is described in NEN 5186 and uses the following formula:

$$\rho_s = \frac{m_3 \cdot \rho_w}{m_2 - m_1}$$

ρ_s	= the density of the stone	[kg/m^3]
ρ_w	= the density of the water, at test temperature	[kg/m^3]
m_1	= apparent weight of the stone submerged	[kg]
m_2	= weight of the wet stone	[kg]
m_3	= weight of the dry stone	[kg]

	Stone submerged	Wet stone[2]	Dry stone[1]
Stone	m_1 [kg]	m_2 [kg]	m_3 [kg]
1	1.097	1.880	1.880
2	0.607	1.068	1.068
3	0.388	0.665	0.665

Table 11: Measured results of the different weights of the three stones.

The temperature of the water used for measuring the weight of the submerged stone was 20^o C, so the density of the water was ρ_w = 995 kg/m^3.

The resulting values of the calculated densities of the 3 stones are depicted in the following table:

Stone	Density ρ_s [kg/m^3]
1	2389
2	2305
3	2389

Table 12: Results for the density calculation of the three collected stones.

The mean value of the density is 2361 kg/m^3 and as the previous year's results vary from 2284 to 2405, a density of 2360 kg/m^3 (the rounded value) is a plausible result. This number will therefore be used for further calculations.

[2] In an approximation it was assumed that $m_2 = m_3$, which means the stones do not hold water.

6.3.2 Remarks on calculations of specific density

It should be noted that the stones behaved like sponges during the experiment: determining the mass under water, the value changed very quickly, because the porous dry stones gained mass by absorbing water. For this reason the mass measurement should be done as soon as possible after submerging the stones.

The value 2360 kg/m³ which was found is a little bit higher than the mean one for this limestone quarry (2300 kg/m^3) but it must be considered that the determination of the density is not very accurate, because of the large variation in the quality of the stones and the small amount of stones that were examined. In addition, it can be concluded that these stones are not dense enough for hydraulic engineering use as breakwaters can best be made from stones that have an average density of about 2650 kg/m^3.

6.4 Small rock measurements

6.4.1 Volume

The specific density is determined on ρ_s = 2360 kg/m^3. With this value and the measured weight of the smaller rocks at the Marciana quarry the volume of the several stones can be determined, like is done in Figure 82 below.

The results of the measurements of the two groups are averaged such that there are two measured values. Group 1, which was second in line of measuring the small rocks, broke the weighing scale when they were still in the process of weighing all the rocks. This explains the blanks in Table 13 for the weight values of some of the rocks measured by group 1. There are some reasonable differences between the measurements of the two groups because of the unreliable weighing scale. Figure 82 shows the measuring process of the small rocks.

Figure 82: Measuring small rocks with the weighing scale.

With the density of the rocks and the weight obtained in the above described experiment, the volume V is calculated by:

$$V = \frac{M}{\rho}$$

The results of these calculations can be found in Table 13.

Stone number	Weight [kg]			Density [kg/m^3]	Volume [m^3]
	Group 1	Group 2	**Average**		
1		47.5	**47.5**	2360	0.0201
2		55	**55**	2360	0.0233
3		130	**130**	2360	0.0551
4	95	85	**90**	2360	0.0381
5		62	**62**	2360	0.0263
6	75	71	**73**	2360	0.0309
7	50	48	**49**	2360	0.0208
8	35	34	**34.5**	2360	0.0146
9	65	60	**62.5**	2360	0.0265
10	26	22	**24**	2360	0.0102
11	30	24	**27**	2360	0.0114
12		50	**50**	2360	0.0212
13	45	50	**47.5**	2360	0.0201
14	19	26	**22.5**	2360	0.0095
15	80	75	**77.5**	2360	0.0328
16	34	40	**37**	2360	0.0157
17		135	**135**	2360	0.0572
18		90	**90**	2360	0.0381
19	37	38	**37.5**	2360	0.0159
20	12	10	**11**	2360	0.0047

Table 13: Results of the volume of the small rocks.

6.4.2 Blockiness

The blockiness is defined as the ratio of the volume of the rock divided by the smallest imaginary box the rock could fit in. For an impression of different values of blockiness of rocks, see Figure 83 below.

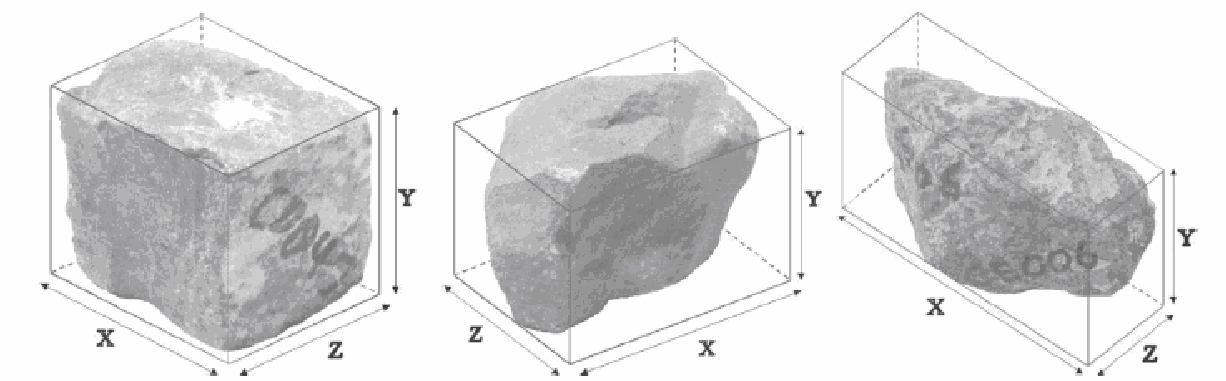


Figure 83: Several rocks and their boxes to calculate their blockiness [3].

The blockiness is calculated by:

$$B = \frac{V}{x \cdot y \cdot z}$$

For the dimensions of the boxes the rocks would fit in, the measured values for X, Y and Z of both groups have been averaged. With the calculated volume, the blockiness can be determined. The differences between the measurements of both groups are sometimes quite large; this is due to the subjective way of choosing the sides of the box. For the results of the blockiness of the measured 20 rocks, see Table 14.

	X			Y			Z			**Blockiness**
	Group 1	Group 2	**Average**	Group 1	Group 2	**Average**	Group 1	Group 2	**Average**	**B** [-]
1	0.62	0.5	**0.56**	0.35	0.22	**0.285**	0.6	0.3	**0.45**	0.28
2	0.57	0.48	**0.525**	0.25	0.24	**0.245**	0.42	0.31	**0.365**	0.50
3	0.52	0.6	**0.56**	0.6	0.55	**0.575**	0.47	0.4	**0.435**	0.39
4	0.58	0.65	**0.615**	0.48	0.45	**0.465**	0.34	0.38	**0.36**	0.37
5	0.65	0.65	**0.65**	0.46	0.54	**0.5**	0.28	0.22	**0.25**	0.32
6	0.68	0.72	**0.7**	0.4	0.48	**0.44**	0.42	0.26	**0.34**	0.30
7	0.45	0.45	**0.45**	0.34	0.35	**0.345**	0.28	0.35	**0.315**	0.42
8	0.4	0.4	**0.4**	0.3	0.32	**0.31**	0.43	0.3	**0.365**	0.32
9	0.54	0.55	**0.545**	0.25	0.28	**0.265**	0.18	0.42	**0.3**	0.61
10	0.4	0.4	**0.4**	0.32	0.2	**0.26**	0.2	0.34	**0.27**	0.36
11	0.35	0.38	**0.365**	0.38	0.36	**0.37**	0.36	0.2	**0.28**	0.30
12	0.52	0.48	**0.5**	0.32	0.32	**0.32**	0.35	0.36	**0.355**	0.37
13	0.4	0.48	**0.44**	0.42	0.3	**0.36**	0.13	0.36	**0.245**	0.52
14	0.61	0.6	**0.605**	0.37	0.38	**0.375**	0.36	0.12	**0.24**	0.18
15	0.63	0.66	**0.645**	0.4	0.42	**0.41**	0.43	0.36	**0.395**	0.31
16	0.4	0.48	**0.44**	0.27	0.4	**0.335**	0.5	0.34	**0.42**	0.25
17	0.7	0.72	**0.71**	0.4	0.54	**0.47**	0.3	0.36	**0.33**	0.52
18	0.6	0.6	**0.6**	0.55	0.54	**0.545**	0.3	0.3	**0.3**	0.39
19	0.42	0.4	**0.41**	0.32	0.31	**0.315**	0.3	0.3	**0.3**	0.41
20	0.28	0.3	**0.29**	0.16	0.2	**0.18**	0.23	0.26	**0.245**	0.36

Table 14: The blockiness of the small rocks.

The mean blockiness of the small rocks is 0.37, so the rocks are not really blocky.

6.4.3 Elongation rate

The elongation rate is defined as the longest side divided by the shortest side of the rock. Both sides should cross the rock centre. This is illustrated in Figure 84 below.

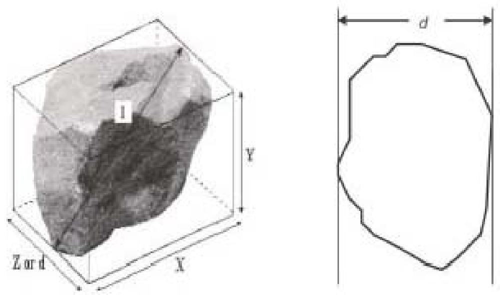


Figure 84: A rock and its longest (l) and shortest (d) side [3].

The measurements of the longest and shortest side of both groups have been averaged, and with the elongation rate determined as below, the elongation rate can be computed.

$$Elongation\ rate = \frac{l}{d}$$

The elongation of all the stones is given in Table 15.

	Longest side [m]			Shortest side [m]			**Elongation**
	Group 1	Group 2	**Average**	Group 1	Group 2	**Average**	l/d [-]
1	0.62	0.5	**0.56**	0.27	0.25	**0.26**	2.15
2	0.6	0.6	**0.6**	0.25	0.2	**0.225**	2.67
3	0.57	0.6	**0.585**	0.35	0.42	**0.385**	1.52
4	0.64	0.65	**0.645**	0.33	0.35	**0.34**	1.90
5	0.6	0.65	**0.625**	0.23	0.2	**0.215**	2.91
6	0.68	0.72	**0.7**	0.24	0.28	**0.26**	2.69
7	0.52	0.52	**0.52**	0.25	0.26	**0.255**	2.04
8	0.38	0.4	**0.39**	0.24	0.2	**0.22**	1.77
9	0.53	0.56	**0.545**	0.24	0.28	**0.26**	2.10
10	0.42	0.46	**0.44**	0.14	0.15	**0.145**	3.03
11	0.4	0.4	**0.4**	0.17	0.18	**0.175**	2.29
12	0.52	0.46	**0.49**	0.24	0.3	**0.27**	1.81
13	0.52	0.5	**0.51**	0.27	0.22	**0.245**	2.08
14	0.61	0.6	**0.605**	0.18	0.08	**0.13**	4.65
15	0.63	0.66	**0.645**	0.3	0.26	**0.28**	2.30
16	0.47	0.5	**0.485**	0.2	0.24	**0.22**	2.20
17	0.74	0.76	**0.75**	0.4	0.34	**0.37**	2.03
18	0.64	0.65	**0.645**	0.2	0.2	**0.2**	3.23
19	0.46	0.46	**0.46**	0.27	0.26	**0.265**	1.74
20	0.3	0.3	**0.3**	0.11	0.15	**0.13**	2.31

Table 15: The elongation rate of the small rocks.

The mean elongation of the small rocks is 2.37.

6.4.4 Nominal diameter and grading

To calculate the nominal diameter D_{n50}, the following formula and the outcome of the values above were used.

$$D_n = \sqrt[3]{V} = \sqrt[3]{M/\rho}$$

Using this formula for all the measured 20 stones delivers the nominal diameter for these stones, presented in Table 16.

Weight [kg]	Volume [m^3]	D_{n50} [m]	Cumulative frequency [%]
11	0.0047	**0.1670**	5
22.5	0.0095	**0.2120**	10
24	0.0102	**0.2167**	15
27	0.0114	**0.2253**	20
34.5	0.0146	**0.2445**	25
37	0.0157	**0.2503**	30
37.5	0.0159	**0.2514**	35
47.5	0.0201	**0.2720**	40
47.5	0.0201	**0.2720**	45
49	0.0208	**0.2748**	50
50	0.0212	**0.2767**	55
55	0.0233	**0.2856**	60
62	0.0263	**0.2973**	65
62.5	0.0265	**0.2981**	70
73	0.0309	**0.3139**	75
77.5	0.0328	**0.3202**	80
90	0.0381	**0.3366**	85
90	0.0381	**0.3366**	90
130	0.0551	**0.3805**	95
135	0.0572	**0.3853**	100

Table 16: Nominal diameter of the measured stones, sorted from low to high weights.

Sorting these nominal diameters and appointing the cumulative frequency following out of the measurements, it is possible to make a graph of the grading of the material.

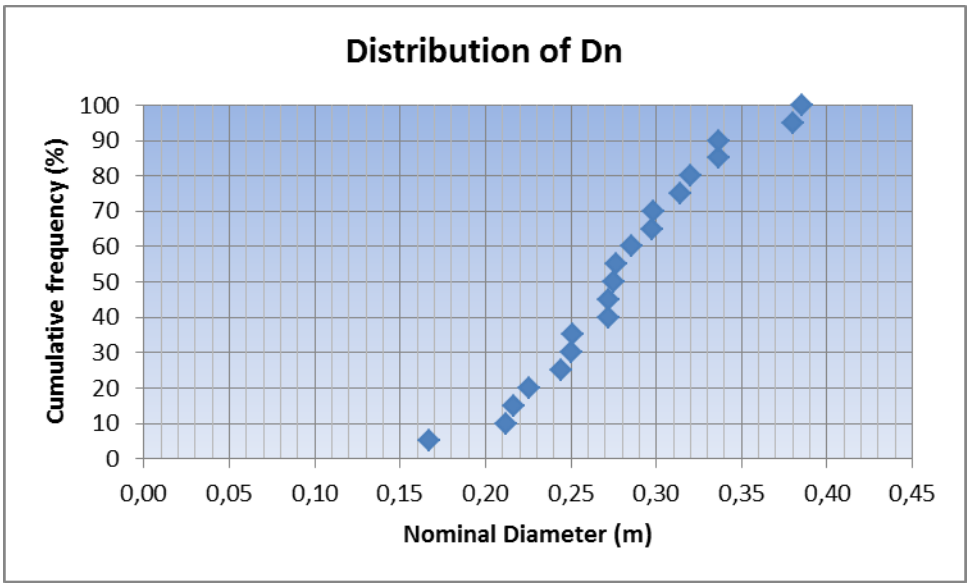


Figure 85: Distribution of the nominal diameter, grading of the material.

From Figure 85 it follows that this material is well graded. but it is not possible to say this with a lot of certainty, because the rocks were selected arbitrarily and the sample of rocks was quite small.

The D_{n50} follows from the cumulative frequency distribution of the nominal diameters: at the point where the cumulative frequency is 50 %. This means the D_{n50} is 0.2748 m.

6.5 Heavy rock measurements

6.5.1 Volume

Calculating the volume of rocks without being able to weigh the mass of a stone is less accurate, because an estimation of the blockiness has to be made. The estimation of the blockiness of the heavy rocks is based on the calculated blockiness of the small rocks and how blocky the small and the heavy rocks look on the pictures. From the pictures it can be concluded that the heavy rocks have a slightly bigger blockiness than the small rocks, i.e. about 15 % bigger. The blockiness of the heavy rocks can now be calculated: B (heavy rocks) = 1.15 · B_{mean} (small rocks) = 1.15 · 0.37 = 0.43.

Figure 86: The large rocks at the Devnya quarry.

With the blockiness and the measured values of length, width and height of the smallest boxes the rocks could fit in, the volume was calculated. And the nominal diameter D_{n50} follows from the volume. Knowing the density of the type of rock, the mass was calculated as well. An overview of the characteristics of the five large rocks considered at the quarry can be found in Table 17.

Rock	**Length** [m]	**Width** [m]	**Height** [m]	**B** [-]	**Volume of box** [m^3]	**Volume of rock** [m^3]	**Mass** [kg]	**D_{n50}** [m]
1	1.1	1.52	1.2	0.43	2.006	0.863	2036	0.95
2	1.62	0.56	1.05	0.43	0.953	0.410	967	0.74
3	1.15	0.9	1.05	0.43	1.087	0.467	1103	0.78
4	1.8	1.3	1.1	0.43	2.574	1.107	2612	1.03
5	1.76	0.95	1.25	0.43	2.090	0.899	2121	0.97
				Mean	1.742	0.749	1768	0.89

Table 17: Main characteristics of five large rocks at Marciana quarry.

Averaging of the obtained values from the five rocks will result in the mean volume, the mean weight and the average nominal diameter of the large rocks. It should be pointed out that these average values follow from a really small sample of rocks and with values that follow from an estimation of the blockiness.

6.5.2 Estimation of number of rocks

The heap of rocks had total dimensions of 26.5 to 19.9 meter of length and width to 2.2 meter in height. With the known density of the rocks and an assumed porosity of the heap of 70 percent, the total mass is about 26.5 · 19.9 · 2.2 · 0.3 · 2.36 = 821 tons. This would mean that the number of heavy rocks on the heap is approximately 821 / 1.768 = 464 rocks. And with an expected capacity of 30 tons per truck, 28 trucks loads would be required to transport the total heap.

6.6 The design significant wave height

As the necessary stone properties are known, it is possible to calculate the maximum allowable significant wave height for the design of an imaginary breakwater built of the large stones of the quarry.

At first, using the elongation and the blockiness, the void ratio (or porosity) of the placed blocks is determined. The characteristic values of the small rocks were used because their measurements have been done on a larger rate of rocks than the heavy rocks and therefore they are more reliable. The regression-equations from tests have as a general format:

$$\text{Param} = A + B \cdot BLc_m + C \cdot l/d_m + D\,\sigma(BLc)$$

BLc_m = mean value of blockiness = 37 [%]
l/d_m = mean value of elongation = 2.37 [-]
$\sigma(BLc)$ = standard deviation of blockiness = 10.3 [-]

Table 18 of Newberry follows with the coefficients and the resulted values.

Parameter	**Slope**	**A**	**B**	**C**	**D**	**Value**
Single layer porosity n_v	1:1.5	42.38	-0.2177	3.695	-0.4128	38.83041
	1:2	42.9	-0.2204	3.74	-0.4179	39.30463
	1:3	43.46	-0.2233	3.789	-0.4233	39.81784
Single layer thickness k_t	1:1.5	1.1375	-0.0026	-0.1588	-0.0003	0.661854
	1:2	1.0736	-0.0024	-0.1499	-0.0003	0.626447
	1:3	1.1038	-0.0025	-0.1541	-0.0003	0.642993
Double layer porosity n_v	1:1.5	34.53	-0.2137	3.446	0.1852	36.69768
	1:2	35.94	-0.2224	3.586	0.1928	38.19586
	1:3	36.2	-0.224	3.613	0.1942	38.47507

Table 18: Coefficients and results of the regression formula for porosity and layer thickness [9].

Assuming that the imaginary breakwater will be double layered and will have a 1:2 slope (most usual conditions for new breakwaters in the region), the Double layer porosity n_v = 38.2 [%] is calculated and the Single layer thickness k_t = 0.63 m.
Subsequently the stability parameters C_{pl} and C_{sur} defined as "6.2" and "1.0" in the Van der Meer formula are corrected according the table from Stewart below.

BLc-range	l/d range	Armour Porosity [%]	Placement method	"6.2"	"1.0"
40 - 50 %	1.3 - 3.0	38.7	Standard	7.09	-
40 - 50 %	1.3 - 3.0	36.1	dense	6.68	1.67
50 - 60 %	1.3 - 3.0	37.1	standard	6.44	1.51
50 - 60 %	1.3 - 3.0	35.2	dense	7.12	2.08
60 - 70 %	1.3 - 3.0	35.5	standard	7.71	2.63
60 - 70 %	1.3 - 3.0	34.4	dense	10.85	-
50 - 60 %	1.0 - 2.0	36.1	standard	8.50	1.45
50 - 60 %	1.0 - 2.0	34.6	dense	8.80	-

Table 19: Corrections of the coefficients"6.2" and"1.0" in the 'Van der Meer-equations [10].

With BLc_m= 37 and l/d_m = 2.37 and by using a standard placement method, the results are C_{pl} = 7.09 and C_{sur}=1.0.

As the Hudson formula is a simplified formula, the Van der Meer equations were used. The Van der Meer equations are:

$$\frac{H_s}{\Delta D_{n50}} = 6.2P^{0.18}\left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \xi^{-0.5} \qquad \text{(Plunging breakers)}$$

$$\frac{H_s}{\Delta D_{n50}} = 1.0P^{-0.13}\left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \xi^{P}\sqrt{\cot\alpha} \qquad \text{(Surging breakers)}$$

Moreover, a number of assumptions had to be made:

Permeability	P = 0.1	(impermeable core; concrete)
Number of waves	N = 7500	(damage considered to have reached an equilibrium)
Damage level	S = 10	(failure of the structure)

To determine the wave type, first we must calculate the transition from plunging to surging waves using a ξ_{cr}:

$$\xi_{cr} = \left[C_{pl}P^{0.31}\sqrt{\tan\alpha}\right]^{1/(P+0.5)}$$

With C_{pl} = 7.09, P = 0.1 and tan α = ½, the value ξ_{cr} = 4.47.

The Iribarren number for the imaginary breakwater:

$$\xi = \frac{\tan\alpha}{\sqrt{H/L_0}} \text{ with } L_0 = \frac{gT^2}{2\pi}$$

The usual value of the wave steepness in the region is H/L_0 is 0.04 so ξ = 2.5 < 4.47 = ξ_{cr}. This implies the use of the plunging breakers formula:

$$\frac{H_s}{\Delta D_{n50}} = C_{pl}P^{0.18}\left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \xi^{-0.5}$$

Table 20 contains all the used parameters in the formula.

p_s [kg/m^3]	2360
p_w [kg/m^3]	1000
$\Delta = (p_s - p_w) / p_w$	1.36
D_{n50} [m]	0.89
ξ	2.5
S_d	10
N	7500
P	0.1
C_{pl}	7.09

Table 20: Parameters for the Hs calculation.

The result is H_s = 2.33 m, which means that with use of the large stones of the Marciana quarry, an imaginary breakwater could be constructed with a maximum allowable significant wave height of 2.33 m. However, all the assumptions that have been done should be taken into account when analysing this result. A conclusion can be made that the large stones which were analysed, are not suited for creating a breakwater because the calculated maximum allowable wave height (H_s = 2.33 m) is low, when considering the fact that a high damage level (S = 10) was assumed.

7 Conclusions and recommendations

The goal of the course CT5318 “Fieldwork Hydraulic Engineering” was to collect a large range of data for coastal engineering purposes by doing field measurements. During a week the following type of data has been collected:

- Bathymetry of several beaches; cross sections, the waterline and underwater bathymetry;
- Hydraulic data in the form of the wave period and the wave height;
- Rock-related data; the blockiness, the mean elongation and the density;
- Sediment-related data; the calcium content due to shells and the sieving curve;
- A survey of the present situation; condition of a breakwater and several other coastal structures.

In the following, conclusions are drawn for every location.

Asparuchovo beach

At this location there are plans to develop a small marina in the northern part of beach and for that reason the boundary conditions are needed. Furthermore some erosion is presumed in the southern part of the coast and the condition of the breakwater needs to be investigated.

From the measurements it can be concluded that the cross sections show some variation along the beach and you can see clearly that a sandbar is present. With help of the program Surfer a contour map is created, which shows a total overview. However the accuracy of this map is not very high, within the interpolation process the results will be simplified and some small differences will erase due to the scaling. For this reason it is recommended to obtain more and large scale data, especially about the bathymetry.

The breakwater is in a very bad shape, a lot of broken tetrapod’s, cracks in the head of the breakwater and so forth. The cause is a lack of maintenance in combination with constructional mistakes and bad quality material. From design calculations it is concluded that the design wave height is rather low in comparison with the estimated wave height. It is recommended to carry out some wave measurements in order to do a thorough analysis of the cause of the damage.

Sediment samples are taken from different locations at Asparuchovo beach, for each sample the calcium content and the sieving curve is determined. The results show that the calcium content is the largest in the proximity of the waterline. This is logical, because in the surf zone the water has a lot of energy and can contain a lot shells. The samples taken at 1.5 m depth contain fewer shells than the samples on the beach. The sieving curve shows that the finest particles are found at the deeper water and then samples from a larger depth contain even more fine grains than at the sea bottom. The samples in the neighborhood of the waterline contain the coarsest materials. Also there is some small variation along the axis of the beach.

Since there is no historical data available, we cannot draw any conclusions on erosion/accretion.

Recommendations:
- To use another method to measure the underwater?? bathymetry, especially for shallow water it is not possible to do measurements with the fish finder-method. Besides this the fish finder method is very sensitive for bad weather conditions, so it would be interesting to use a less sensitive method;
- To carry out wave measurements at Asparuchovo beach in order to study to cause of damage of the breakwater more thoroughly.

Sirius Beach

The bathymetry measurements show results that are completely out of range when compared with the measurements from previous years. Also during the week the beach profile was highly variable, the waterline moved considerable in landward direction. The cause for this can be found by the seasonal difference in winter and summer profiles, most probably the beach is changing from a summer profile towards a winter profile at the specific moment the measuring took place. From this follows that firm conclusions about accretion or erosion cannot be drawn.

The wave analysis shows the distribution of the wave height, around 1,20 m, and the average wave period, 0.212 seconds. The measured data is comparable to the calculated results, though still some improvements can be made for accuracy reasons, especially the measuring of the water depth.

Recommendations:

- To investigate the process of change from summer profile to winter profile for Sirius beach and the effect on the measurements.

Further recommendations:

For the wave analysis several things can be improved:

- In order to calculate the distribution for the Battjes Groenendijk theory right, the water depth and slope are needed. This year these values were measured at one point and it is not sure if these were accurate enough. These measurements should be made more extensive;
- To elaborate the data and compare it to for example a theoretical Rayleigh distribution or composed Weibull distribution, more individual waves should be measured. A record of half an hour would be better than the 10 minutes of less that were recorded this year;
- When also another way of measuring waves is used, the visual observations can be compared to the observations by another instrument. For instance the waves could also be measured by a pressure meter or by a wire piercing the surface.

Azalea beach

The bathymetry results show some lowering of the beach, which is an indication of erosion. The shape of the beach profile is still the same. Since there is only one previous data set to compare with, clear statements about morphological processes cannot be made. During the week several waterlines have been determined and it seems like the waterline is moving with a maximum of 10 meters. However most probably this is due to the error of the measuring method. The GPS receiver is namely accurate within a range of 5 meters and more important, the measuring is done through different persons, with can lead to differences of approximately 10 m.

Recommendations:

- To create a more accurate method to determine the waterline.

Lake Varna

Lake Varna is a deep elongated lake near the city of Varna. Recently a plan was set-up to create several artificial islands in the lake. The purpose of these islands is to store dredged material from a navigation channel in the lake. For this purpose bathymetry measurements were collected for a study about the feasibility of the construction of these islands.

Recommendations:

- For engineering purposes more information is needed, for example the properties and amount of the dredged material and details about waves and currents.

Quarry

Several characteristic of rock have been determined in the quarry. The mean value of the density is 2361 kg/m3, the mean blockiness of the small rocks is 0.37, the mean elongation of the small rocks is 2.37 and this leads to a D_{n50} of 0.2748 m. The blockiness of the heavy rocks is 0.43. Afterwards the maximum allowable significant wave height is calculated for the design of an imaginary breakwater built of the large stones of the quarry, this results in a H_s of 2.33 m, when considering the fact that a high damage level (S = 10) was assumed.

Also the conclusion can be drawn, with respect to the second educational aim (to let the students experience the practice of doing measurements in the field), that the group experienced some difficulties due to the weather, a lack of tools and miscommunication.

8 References

[1]: Verhagen, d' Angremond, van Roode (2009); *CT 5308 Breakwaters and closure dams,* Delft, Table 7-3
[2]: www.windguru.com; consultancy date: 04-10-2010
[3]: (December 2009); *Preliminary Design of a Floating Marina*, Delft
[4]: CIRIA, CUR, CETMEF (2007); *The Rock Manual. The use of rock in hydraulic engineering (2nd edition)*, C683, CIRIA, London
[5]: http://www.kennisbank-waterbouw.nl/CressHelp/A1.1/Z1.htm
[6]: http://en.wikipedia.org/wiki/Lake_Varna
[7]: http://www.ilec.or.jp/database/eur/eur-35.html
[8]: Bresnahan, Dickenson (publishing year unknown), *Surfer Manual*, USA
[9]: NEWBERRY *ET AL* (2002); *The effect of rock shape and construction methods on rock armour layers*, proc. ICCE, Cardiff, pp 1436-1448
[10]: STEWART *ET AL* (2002); *The hydraulic performance of tightly packed rock armour layers*, proc.ICCE, Cardiff, pp 1449-1461

Appendices

A. Measuring equipment

A.1 Introduction

In addition to all the measurements done, a short description of the used equipment is given in this appendix. Also the errors in the use of the equipment are considered.

A.2 GPS

The Global Positioning System (GPS) is used to define locations in the horizontal plane of the field and to couple these points on a topographic map. The system uses a group of satellites which sends and receives signals. The accuracy depends on several factors, the most important being the number of satellites ‘visible’ by the receiver. Other sources of errors are the clock in the receiver, the reported location of the satellite, the relative position of the satellites in the group with respect to each other, etcetera. These factors together give the GPS a range of accuracy of 3-12 metres, depending on the above mentioned factors and the quality of the hand-receiver itself.

The GPS can express a position in Universal Transverse Mercator (UTM) units or in latitude/longitude. For the fieldwork the UTM system is used, which is an easy-to-use metric grid. The grid divides the earth in blocks with a finer grid consisting of lines perpendicular to each other. Positions are easy to determine on a map because the output is given in metres.

For the altitude (vertical; the z-direction) the GPS is not accurate enough, so therefore a theodolite is used.

A.3 Theodolite

A theodolite is a simple instrument to measure horizontal and vertical angles. The instrument consists of a binocular placed on top of a tripod. The position of the binocular has to be exactly levelled to prevent unnecessary measure errors; the location is determined with help of a GPS. Once the theodolite is placed accurately, the instrument is used to measure multiple points in the open view. With help of a levelling rod placed on the field, the relative altitudes of these points can be obtained (because the theodolite is not able to measure distances or absolute altitude). All altitude values are measured with respect to a certain reference point, which has to be defined first.

The errors in the use of a theodolite are the accuracy of the spirit level, how well the theodolite is levelled and the error in reading the values from the levelling rod. The levelling of the instrument is the most important, because once the instrument is not exactly levelled, the altitude error will be the vertical angle times the distance.

A.4 Echo sounder

The echo sounder is placed under a boat and it measures the water depth with help of sound signals. The depth is determined by the propagation speed of sound in water and the time interval between sending and receiving the acoustic signal. To obtain the water depth, the position of the echo sounder below the water level has to be added to the measured depth. The instrument sends out a bundle of sound which creates a ‘footprint’ on the bed. The echo sounder will automatically average a number of points. This average value is taken as water depth in a certain data point. The size of the footprint, determined by the width of the beam, influences the accuracy significantly.

For accurate results it is important that the wave heights are not too high, since the waves significantly influence the boat movement. A smaller boat will be more affected by waves, but on the other hand a small boat can measure closer to the beach. To get reliable results, it is also important that the boat is moving not too fast.

A.5 Soil sampler

The piston sampler is constructed from a thin-walled, 40-mm diameter, stainless steel tube with a length of approximately 2 meters. The bottom end is open, whereas the top has outflow openings and an opening through which a stainless steel extension rod (5) can be moved. At the bottom of the steel extension rod a piston (6) is located, see Figure 87.

The piston sampler works by creating a vacuum. Therefore the sampler performs best when under water. The bottom of the sampler is placed on the sediment and is push down as far as possible. By putting pressure on the sampler and pulling out the steel extension rod a vacuum is created and soil, together with the water, is sucked in the sampler.

When the extension is extended as far as possible the sample is complete and can be exerted (onshore) on a half open tube and is ready to be analysed.

Inaccuracies in soil data can be achieved because of several reasons. The piston encounters more friction when operated at dense packed sand or sand with a large diameter. Also water is needed to create a perfect vacuum. When the piston sampler is used on land, is used in densely packed sand or in sand with large diameter only minor sampling depths can be achieved. This could result in smaller depth profile or an underestimation of the large fractions. When finer materials are sampled they could easily flow out of the piston sampler. This could result in an underestimation of the finest particles.

Weather conditions and water height can restrict the operational use of the piston sampler.

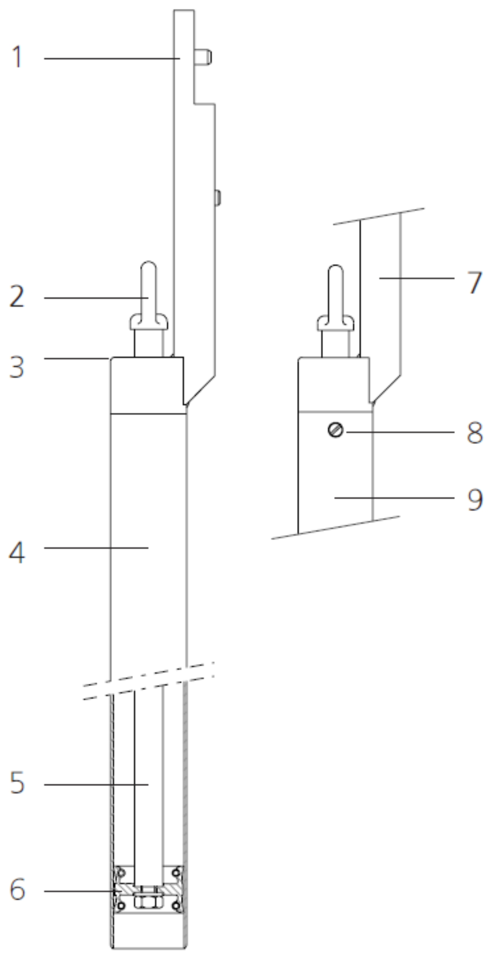


Figure 87: Soil sampler.

A.6 Sieving machine

The sieving machine consists of seven sieves on top of each other. All sieves have different opening widths; the biggest positioned on top. The soil is put in the top sieve of the machine which on its turn is positioned on a vibrating machine. The vibration helps the sediment to flow through the sieves.

Since there are only seven sieves used in the machine, there is a clear lower limit of the grain size. For a more accurate research use could be made of more (finer) sieves.

A.7 Calcium carbonate exertion process

In order to determine the amount of shells in the samples, the calcium carbonate particles can be dissolved with hydrochloric acid. First the bigger shells are taken out by hand and then the soil samples are mixed with distilled water and hydrochloric acid will be added. While stirring the mixtures frequently, the hydrochloric acid will react with the calcium in the soil. This reaction is accompanied by gas formation. At the moment the gas formation stops, more hydrochloric acid is inserted in the sample to be sure all calcium carbonate will dissolve.

B. Beach level measurements

General

In this section the way of measuring the cross-sections of the beaches will be explained. First a summary of different points of action will be given:

1. Determine overall reference point for height;
2. Determine place to measure with theodolite;
3. Determine amount and place of baselines;
4. Determine location of cross-sections beach;
5. Measure with theodolite and levelling rod.

Determine overall reference point for height

First of all, the most important action in measuring beach levels is to determine a reference point for the heights in the landscape, which will be available for several years. This is important because of two reasons:

- If by mistake, the measuring point of the theodolite is lost during measuring, a new one can be made with the help of this fixed reference point;
- If next year a new group of students wants to make the same measurements and wants to compare it with the measurements made this year, this reference point can be used.

Determine place to measure with theodolite

The second step in the process of measuring the beach levels is to determine the place to measure with the theodolite. This point should be on the beach, from which it is easy to observe the beach and to see the reference point. After placing the theodolite on this point, the height compared to the reference point must be measured first.

When dealing with a beach with a long length, the theodolite needs to change position sometimes because it is not possible anymore to read the levelling rod. In the list below the steps that need to be done to change the position of the theodolite are given:

- Place a levelling rod on a fixed point (the road for example);
- Measure what height this place on the road has compared to the current position of the theodolite;
- Replace the theodolite to a better position;
- Measure again what the height of the theodolite is compared to the fixed point on the road;
- Calculate what the height of the new point of theodolite is compared to the reference point.

Determine amount and place of baselines

The baseline is used to provide a straight line (between two reference points) to which all the cross-section lines can be positioned perpendicularly. In order to investigate and compare the position and lay out of the beach over the years, it is important to be able to measure the cross-sections on some fixed locations. The most important factors when determining the baselines:

- Baselines should be straight, because they are used in the calculations to determine the UTM points of the cross-section lines that cross the baselines;
- Baselines should be close and somewhat parallel to the waterline, because the most interesting profile of this beach is near the waterline;
- Baselines should not be running through the water, because it is very difficult to measure the distance of the measuring points on the cross-section line, that is perpendicular to the baseline;
- Fixed reference points should be used, so next year the same measurements can be made.

An example of a baseline defined in Figure 88 below.

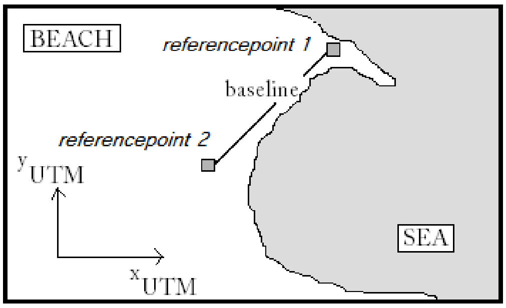


Figure 88: Example of a baseline.

Determine locations of cross-sections beach

Now that the baselines are defined, the next step in the process is to determine where the cross-sections of the beach should be measured. Determination of the places of the cross-sections has been done with a measuring tape (each 50 m). The list of actions in this process is:

- Someone is standing at reference point 1 holding the end of a measuring tape;
- A second person walks with the other end of the measuring tape in the direction of reference point 2 down the baseline. When the end of the measuring tape is reached, a pole is planted at this point;
- A third person walks further down the baseline in the direction of reference point 2, while the second person holds the end of the measuring tape at the pole that was planted;
- When the end of the measuring tape is reached, a pole is planted at this point. This point is defined as cross-section 1 and is (for this example) 100m away from reference point 1 down the baseline;
- This process will be continued till enough cross-sections on the baseline are defined;

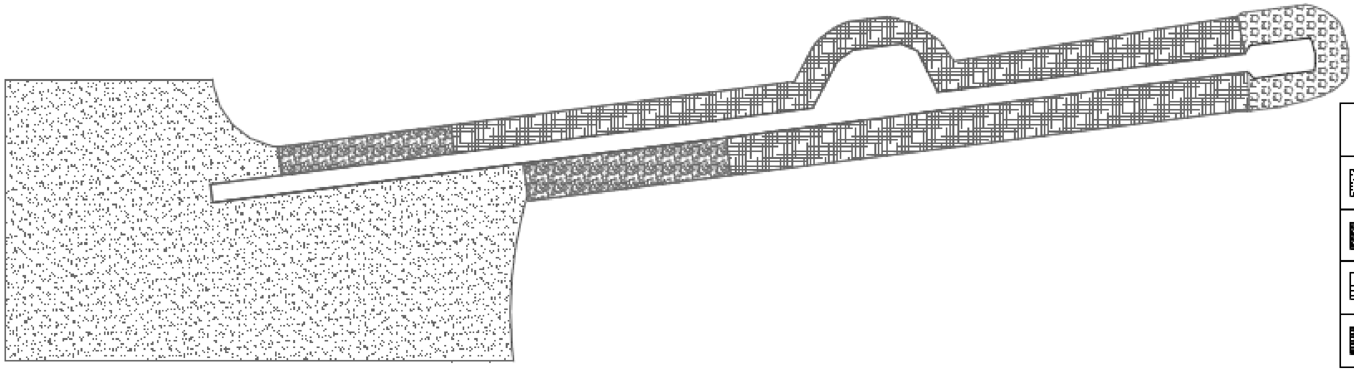
When the places of the cross-sections were defined on the beach, the cross-section lines (perpendicular on the baselines) could be constructed. This was done by means of a small prism with which a line perpendicular on the baseline could be defined. A pole was planted on this so called 'cross-section line'. After defining the cross-section line, a measuring tape was put down on the beach.

Measure with theodolite and levelling rod

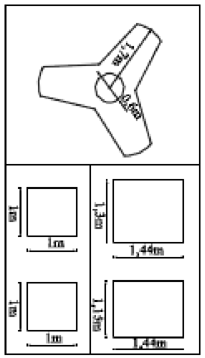
The last step in the process to determine the beach levels in the cross-sections is the actual measuring by means of the theodolite and the levelling rod. Because of the distance between the theodolite and the levelling rod at the cross-section, walkie-talkies were used for the necessary communication. Four persons were necessary in this process of measuring: 2 persons at the cross-section line, and two persons at the theodolite. The list of actions was:

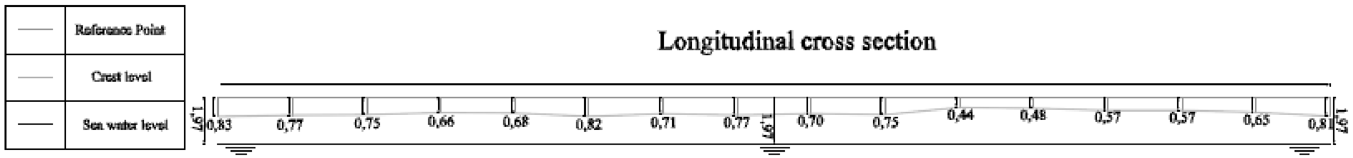
- A person with the levelling rod is positioned at a place on the cross-section line, which is defined by the measuring tape;
- A second person communicates the position of the levelling rod on the measuring tape by means of the walkie-talkie to a third person at the theodolite.
- A fourth person at the theodolite denotes the height, which can be read through the theodolite with the help of the levelling rod.
- When the height is denoted, the first person repositions the levelling rod to another position down the cross-section line. Important is to stay exactly on the cross-section line and to keep the measuring tape as horizontal as possible. This is continued till sufficient points at the cross-section line are denoted.

C. Breakwater cross-section



Types of armour layers	Shape
Sand	
Natural Rocks	
Mix of natural rocks, cubic concrete blocks and tetrapods	
Tetrapods	





D. Wave observations

Observation 1 (at end of pier) (by Christiaan)

H	$H_{1/3}$	$H_{1/10}$	$H_{2/100}$	$H_{1/100}$	H^2	H_{rms}	Wave amplitude			Measured data		Theoretical Rayleigh	
[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]					$P(H_{gem}<H)$	
1.11	1.51	1.74	2.10	2.10	1.38	1.18	-0.847				Rayleigh		Rayleigh
0.15					0.02		0.547	0.397	1	0.02	0.14	0.02	0.128
0.30					0.09		0.847	0.547	2	0.04	0.20	0.06	0.255
0.45					0.20		0.697	0.247	3	0.06	0.25	0.14	0.383
0.60					0.36		0.697	0.097	4	0.08	0.29	0.23	0.510
0.60					0.36		0.697	0.097	5	0.10	0.33	0.23	0.510
0.60					0.36		0.697	0.097	6	0.12	0.36	0.23	0.510
0.60					0.36		0.847	0.247	7	0.14	0.39	0.23	0.510
0.75					0.56		0.847	0.097	8	0.16	0.42	0.33	0.638
0.75					0.56		0.847	0.097	9	0.18	0.45	0.33	0.638
0.75					0.56		0.697	0.053	10	0.20	0.48	0.33	0.638
0.90					0.81		0.997	0.097	11	0.22	0.50	0.44	0.765
0.90					0.81		0.997	0.097	12	0.24	0.53	0.44	0.765
0.90					0.81		0.997	0.097	13	0.27	0.56	0.44	0.765
0.90					0.81		0.997	0.097	14	0.29	0.58	0.44	0.765
0.90					0.81		0.997	0.097	15	0.31	0.60	0.44	0.765
1.05					1.10		0.997	0.053	16	0.33	0.63	0.55	0.893
1.05					1.10		0.847	0.203	17	0.35	0.65	0.55	0.893
1.05					1.10		0.997	0.053	18	0.37	0.68	0.55	0.893
1.05					1.10		0.997	0.053	19	0.39	0.70	0.55	0.893
1.05					1.10		0.997	0.053	20	0.41	0.72	0.55	0.893
1.05					1.10		0.997	0.053	21	0.43	0.75	0.55	0.893
1.05					1.10		0.997	0.053	22	0.45	0.77	0.55	0.893
1.05					1.10		1.147	0.097	23	0.47	0.80	0.55	0.893
1.20					1.44		0.997	0.203	24	0.49	0.82	0.65	1.020
1.20					1.44		1.297	0.097	25	0.51	0.84	0.65	1.020
1.20					1.44		1.147	0.053	26	0.53	0.87	0.65	1.020
1.20					1.44		0.997	0.203	27	0.55	0.89	0.65	1.020
1.20					1.44		1.147	0.053	28	0.57	0.92	0.65	1.020
1.20					1.44		1.297	0.097	29	0.59	0.95	0.65	1.020
1.20					1.44		1.147	0.053	30	0.61	0.97	0.65	1.020
1.20					1.44		1.147	0.053	31	0.63	1.00	0.65	1.020
1.20					1.44		1.147	0.053	32	0.65	1.03	0.65	1.020
1.35	1.35				1.82		1.447	0.097	33	0.67	1.06	0.73	1.148
1.35	1.35				1.82		1.447	0.097	34	0.69	1.09	0.73	1.148
1.35	1.35				1.82		1.447	0.097	35	0.71	1.12	0.73	1.148
1.35	1.35				1.82		1.297	0.053	36	0.73	1.15	0.73	1.148

1.35	1.35				1.82		1.147	0.203	37	0.76	1.19	0.73	1.148
1.35	1.35				1.82		1.297	0.053	38	0.78	1.22	0.73	1.148
1.35	1.35				1.82		1.297	0.053	39	0.80	1.26	0.73	1.148
1.50	1.50				2.25		1.447	0.053	40	0.82	1.30	0.80	1.276
1.50	1.50				2.25		1.447	0.053	41	0.84	1.35	0.80	1.276
1.50	1.50				2.25		1.297	0.203	42	0.86	1.39	0.80	1.276
1.50	1.50				2.25		1.297	0.203	43	0.88	1.45	0.80	1.276
1.50	1.50	1.50			2.25		1.447	0.053	44	0.90	1.51	0.80	1.276
1.65	1.65	1.65			2.72		1.447	0.203	45	0.92	1.58	0.86	1.403
1.65	1.65	1.65			2.72		1.447	0.203	46	0.94	1.67	0.86	1.403
1.80	1.80	1.80			3.24		1.447	0.353	47	0.96	1.79	0.90	1.531
2.10	2.10	2.10	2.10	2.10	4.41		2.047	0.053	48	0.98	1.97	0.96	1.786

Observation 2 (at end of pier) (by Erwin)

H	$H_{1/3}$	$H_{1/10}$	$H_{2/100}$	$H_{1/100}$	H^2	H_{rms}	Wave amplitude			Measured data		Theoretical Rayleigh	
[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]					$P(H_{gem}<H)$	
1.15	1.74	2.03	2.25	2.40	1.59	1.26	-0.766				Rayleigh		Rayleigh
0.15					0.02		0.466	0.316	1	0.01	0.11	0.01	0.119
0.30					0.09		0.316	0.016	2	0.02	0.16	0.06	0.238
0.30					0.09		0.616	0.316	3	0.04	0.19	0.06	0.238
0.45					0.20		0.916	0.466	4	0.05	0.22	0.12	0.357
0.45					0.20		0.916	0.466	5	0.06	0.25	0.12	0.357
0.45					0.20		0.466	0.016	6	0.07	0.27	0.12	0.357
0.45					0.20		0.466	0.016	7	0.08	0.30	0.12	0.357
0.45					0.20		0.466	0.016	8	0.10	0.32	0.12	0.357
0.45					0.20		0.616	0.166	9	0.11	0.34	0.12	0.357
0.60					0.36		0.766	0.166	10	0.12	0.36	0.20	0.477
0.60					0.36		0.616	0.016	11	0.13	0.38	0.20	0.477
0.60					0.36		0.466	0.134	12	0.14	0.40	0.20	0.477
0.60					0.36		0.766	0.166	13	0.16	0.41	0.20	0.477
0.60					0.36		0.316	0.284	14	0.17	0.43	0.20	0.477
0.60					0.36		0.616	0.016	15	0.18	0.45	0.20	0.477
0.60					0.36		0.616	0.016	16	0.19	0.46	0.20	0.477
0.75					0.56		0.916	0.166	17	0.20	0.48	0.30	0.596
0.75					0.56		0.616	0.134	18	0.22	0.49	0.30	0.596
0.75					0.56		0.766	0.016	19	0.23	0.51	0.30	0.596
0.75					0.56		0.766	0.016	20	0.24	0.53	0.30	0.596
0.75					0.56		0.766	0.016	21	0.25	0.54	0.30	0.596
0.75					0.56		0.766	0.016	22	0.27	0.55	0.30	0.596
0.75					0.56		0.766	0.016	23	0.28	0.57	0.30	0.596
0.75					0.56		1.066	0.316	24	0.29	0.58	0.30	0.596
0.75					0.56		0.616	0.134	25	0.30	0.60	0.30	0.596

0.75					0.56		0.766	0.016	26	0.31	0.61	0.30	0.596
0.75					0.56		0.766	0.016	27	0.33	0.63	0.30	0.596
0.75					0.56		0.766	0.016	28	0.34	0.64	0.30	0.596
0.90					0.81		0.916	0.016	29	0.35	0.66	0.40	0.715
0.90					0.81		0.916	0.016	30	0.36	0.67	0.40	0.715
0.90					0.81		1.066	0.166	31	0.37	0.68	0.40	0.715
0.90					0.81		1.066	0.166	32	0.39	0.70	0.40	0.715
0.90					0.81		0.766	0.134	33	0.40	0.71	0.40	0.715
0.90					0.81		0.766	0.134	34	0.41	0.73	0.40	0.715
1.05					1.10		1.366	0.316	35	0.42	0.74	0.50	0.834
1.05					1.10		1.216	0.166	36	0.43	0.75	0.50	0.834
1.05					1.10		1.066	0.016	37	0.45	0.77	0.50	0.834
1.05					1.10		1.216	0.166	38	0.46	0.78	0.50	0.834
1.05					1.10		1.066	0.016	39	0.47	0.80	0.50	0.834
1.05					1.10		1.216	0.166	40	0.48	0.81	0.50	0.834
1.05					1.10		1.066	0.016	41	0.49	0.83	0.50	0.834
1.05					1.10		1.216	0.166	42	0.51	0.84	0.50	0.834
1.05					1.10		1.216	0.166	43	0.52	0.85	0.50	0.834
1.05					1.10		0.916	0.134	44	0.53	0.87	0.50	0.834
1.20					1.44		1.216	0.016	45	0.54	0.88	0.60	0.953
1.20					1.44		1.216	0.016	46	0.55	0.90	0.60	0.953
1.20					1.44		1.066	0.134	47	0.57	0.91	0.60	0.953
1.35					1.82		1.216	0.134	48	0.58	0.93	0.68	1.072
1.35					1.82		1.216	0.134	49	0.59	0.94	0.68	1.072
1.35					1.82		1.366	0.016	50	0.60	0.96	0.68	1.072
1.35					1.82		1.366	0.016	51	0.61	0.98	0.68	1.072
1.35					1.82		1.066	0.284	52	0.63	0.99	0.68	1.072
1.35					1.82		1.066	0.284	53	0.64	1.01	0.68	1.072
1.50					2.25		1.216	0.284	54	0.65	1.03	0.76	1.191
1.50	1.50				2.25		1.516	0.016	55	0.66	1.04	0.76	1.191
1.50	1.50				2.25		1.516	0.016	56	0.67	1.06	0.76	1.191
1.50	1.50				2.25		1.516	0.016	57	0.69	1.08	0.76	1.191
1.50	1.50				2.25		1.366	0.134	58	0.70	1.10	0.76	1.191
1.50	1.50				2.25		1.516	0.016	59	0.71	1.11	0.76	1.191
1.50	1.50				2.25		1.366	0.134	60	0.72	1.13	0.76	1.191
1.50	1.50				2.25		1.366	0.134	61	0.73	1.15	0.76	1.191
1.50	1.50				2.25		1.516	0.016	62	0.75	1.17	0.76	1.191
1.65	1.65				2.72		1.516	0.134	63	0.76	1.19	0.82	1.311
1.65	1.65				2.72		1.666	0.016	64	0.77	1.21	0.82	1.311
1.65	1.65				2.72		1.816	0.166	65	0.78	1.24	0.82	1.311
1.65	1.65				2.72		1.366	0.284	66	0.80	1.26	0.82	1.311
1.65	1.65				2.72		1.666	0.016	67	0.81	1.28	0.82	1.311
1.65	1.65				2.72		1.366	0.284	68	0.82	1.31	0.82	1.311
1.65	1.65				2.72		1.666	0.016	69	0.83	1.33	0.82	1.311
1.65	1.65				2.72		1.666	0.016	70	0.84	1.36	0.82	1.311

1.65	1.65				2.72		1.666	0.016	71	0.86	1.39	0.82	1.311
1.65	1.65				2.72		1.366	0.284	72	0.87	1.42	0.82	1.311
1.80	1.80				3.24		1.816	0.016	73	0.88	1.45	0.87	1.430
1.80	1.80	1.80			3.24		1.666	0.134	74	0.89	1.49	0.87	1.430
1.95	1.95	1.95			3.80		1.666	0.284	75	0.90	1.53	0.91	1.549
1.95	1.95	1.95			3.80		1.966	0.016	76	0.92	1.57	0.91	1.549
1.95	1.95	1.95			3.80		1.816	0.134	77	0.93	1.62	0.91	1.549
1.95	1.95	1.95			3.80		1.816	0.134	78	0.94	1.68	0.91	1.549
2.10	2.10	2.10			4.41		1.966	0.134	79	0.95	1.74	0.94	1.668
2.10	2.10	2.10			4.41		1.966	0.134	80	0.96	1.82	0.94	1.668
2.10	2.10	2.10	2.10		4.41		2.116	0.016	81	0.98	1.93	0.94	1.668
2.40	2.40	2.40	2.40	2.40	5.76		2.266	0.134	82	0.99	2.10	0.97	1.906

Observation 3 (at end of pier) (by Remon)													
H	**$H_{1/3}$**	**$H_{1/10}$**	**$H_{2/100}$**	**$H_{1/100}$**	**H^2**	**H_{rms}**	**Wave amplitude**			**Measured data**		**Theoretical Rayleigh**	
[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]					**$P(H_{gem}<H)$**	
1.29	1.88	2.19	2.33	2.40	1.95	1.40	-0.846				Rayleigh		Rayleigh
0.30					0.09		0.846	0.546	1	0.01	0.10	0.05	0.215
0.30					0.09		0.846	0.546	2	0.02	0.14	0.05	0.215
0.30					0.09		0.546	0.246	3	0.03	0.17	0.05	0.215
0.30					0.09		0.396	0.096	4	0.04	0.20	0.05	0.215
0.30					0.09		0.396	0.096	5	0.05	0.23	0.05	0.215
0.45					0.20		0.546	0.096	6	0.06	0.25	0.10	0.322
0.45					0.20		0.546	0.096	7	0.07	0.27	0.10	0.322
0.45					0.20		0.546	0.096	8	0.08	0.29	0.10	0.322
0.45					0.20		0.396	0.054	9	0.09	0.31	0.10	0.322
0.60					0.36		0.846	0.246	10	0.10	0.32	0.17	0.430
0.60					0.36		0.846	0.246	11	0.11	0.34	0.17	0.430
0.60					0.36		0.846	0.246	12	0.12	0.36	0.17	0.430
0.60					0.36		0.696	0.096	13	0.13	0.37	0.17	0.430
0.60					0.36		0.546	0.054	14	0.14	0.39	0.17	0.430
0.75					0.56		1.146	0.396	15	0.15	0.40	0.25	0.537
0.75					0.56		0.996	0.246	16	0.16	0.42	0.25	0.537
0.75					0.56		0.996	0.246	17	0.17	0.43	0.25	0.537
0.75					0.56		0.846	0.096	18	0.18	0.44	0.25	0.537
0.75					0.56		0.846	0.096	19	0.19	0.46	0.25	0.537
0.75					0.56		0.546	0.204	20	0.20	0.47	0.25	0.537
0.75					0.56		0.546	0.204	21	0.21	0.48	0.25	0.537
0.90					0.81		1.146	0.246	22	0.22	0.50	0.34	0.644
0.90					0.81		1.146	0.246	23	0.23	0.51	0.34	0.644
0.90					0.81		0.996	0.096	24	0.24	0.52	0.34	0.644
0.90					0.81		0.996	0.096	25	0.25	0.53	0.34	0.644

0.90					0.81		0.996	0.096	26	0.26	0.55	0.34	0.644
0.90					0.81		0.996	0.096	27	0.27	0.56	0.34	0.644
0.90					0.81		0.846	0.054	28	0.28	0.57	0.34	0.644
0.90					0.81		0.846	0.054	29	0.29	0.58	0.34	0.644
0.90					0.81		0.846	0.054	30	0.30	0.59	0.34	0.644
0.90					0.81		0.696	0.204	31	0.31	0.61	0.34	0.644
1.05					1.10		1.146	0.096	32	0.32	0.62	0.43	0.752
1.05					1.10		1.146	0.096	33	0.33	0.63	0.43	0.752
1.05					1.10		1.146	0.096	34	0.34	0.64	0.43	0.752
1.05					1.10		1.146	0.096	35	0.35	0.65	0.43	0.752
1.05					1.10		1.146	0.096	36	0.36	0.66	0.43	0.752
1.05					1.10		1.146	0.096	37	0.37	0.68	0.43	0.752
1.05					1.10		0.996	0.054	38	0.38	0.69	0.43	0.752
1.05					1.10		0.996	0.054	39	0.39	0.70	0.43	0.752
1.05					1.10		0.846	0.204	40	0.40	0.71	0.43	0.752
1.05					1.10		0.696	0.354	41	0.41	0.72	0.43	0.752
1.20					1.44		1.446	0.246	42	0.42	0.73	0.52	0.859
1.20					1.44		1.296	0.096	43	0.43	0.74	0.52	0.859
1.20					1.44		1.296	0.096	44	0.44	0.76	0.52	0.859
1.20					1.44		1.296	0.096	45	0.45	0.77	0.52	0.859
1.20					1.44		1.146	0.054	46	0.46	0.78	0.52	0.859
1.20					1.44		1.146	0.054	47	0.47	0.79	0.52	0.859
1.20					1.44		1.146	0.054	48	0.48	0.80	0.52	0.859
1.20					1.44		1.146	0.054	49	0.49	0.81	0.52	0.859
1.35					1.82		1.446	0.096	50	0.50	0.83	0.61	0.967
1.35					1.82		1.296	0.054	51	0.50	0.84	0.61	0.967
1.35					1.82		1.296	0.054	52	0.51	0.85	0.61	0.967
1.35					1.82		1.296	0.054	53	0.52	0.86	0.61	0.967
1.35					1.82		1.296	0.054	54	0.53	0.87	0.61	0.967
1.35					1.82		1.296	0.054	55	0.54	0.89	0.61	0.967
1.35					1.82		1.146	0.204	56	0.55	0.90	0.61	0.967
1.50					2.25		1.596	0.096	57	0.56	0.91	0.68	1.074
1.50					2.25		1.596	0.096	58	0.57	0.92	0.68	1.074
1.50					2.25		1.596	0.096	59	0.58	0.94	0.68	1.074
1.50					2.25		1.596	0.096	60	0.59	0.95	0.68	1.074
1.50					2.25		1.596	0.096	61	0.60	0.96	0.68	1.074
1.50					2.25		1.446	0.054	62	0.61	0.98	0.68	1.074
1.50					2.25		1.446	0.054	63	0.62	0.99	0.68	1.074
1.50					2.25		1.446	0.054	64	0.63	1.00	0.68	1.074
1.50					2.25		1.446	0.054	65	0.64	1.02	0.68	1.074
1.50					2.25		1.296	0.204	66	0.65	1.03	0.68	1.074
1.50	1.50				2.25		1.296	0.204	67	0.66	1.04	0.68	1.074
1.50	1.50				2.25		1.296	0.204	68	0.67	1.06	0.68	1.074
1.50	1.50				2.25		1.296	0.204	69	0.68	1.07	0.68	1.074
1.50	1.50				2.25		1.146	0.354	70	0.69	1.09	0.68	1.074

1.65	1.65				2.72		1.746	0.096	71	0.70	1.10	0.75	1.181
1.65	1.65				2.72		1.746	0.096	72	0.71	1.12	0.75	1.181
1.65	1.65				2.72		1.596	0.054	73	0.72	1.13	0.75	1.181
1.65	1.65				2.72		1.596	0.054	74	0.73	1.15	0.75	1.181
1.65	1.65				2.72		1.446	0.204	75	0.74	1.16	0.75	1.181
1.65	1.65				2.72		1.446	0.204	76	0.75	1.18	0.75	1.181
1.65	1.65				2.72		1.446	0.204	77	0.76	1.20	0.75	1.181
1.80	1.80				3.24		2.046	0.246	78	0.77	1.22	0.81	1.289
1.80	1.80				3.24		1.896	0.096	79	0.78	1.23	0.81	1.289
1.80	1.80				3.24		1.746	0.054	80	0.79	1.25	0.81	1.289
1.80	1.80				3.24		1.746	0.054	81	0.80	1.27	0.81	1.289
1.80	1.80				3.24		1.746	0.054	82	0.81	1.29	0.81	1.289
1.80	1.80				3.24		1.596	0.204	83	0.82	1.31	0.81	1.289
1.95	1.95				3.80		2.046	0.096	84	0.83	1.33	0.86	1.396
1.95	1.95				3.80		2.046	0.096	85	0.84	1.36	0.86	1.396
1.95	1.95				3.80		1.896	0.054	86	0.85	1.38	0.86	1.396
1.95	1.95				3.80		1.746	0.204	87	0.86	1.41	0.86	1.396
1.95	1.95				3.80		1.746	0.204	88	0.87	1.43	0.86	1.396
1.95	1.95				3.80		1.746	0.204	89	0.88	1.46	0.86	1.396
1.95	1.95				3.80		1.746	0.204	90	0.89	1.49	0.86	1.396
2.10	2.10	2.10			4.41		2.046	0.054	91	0.90	1.52	0.90	1.504
2.10	2.10	2.10			4.41		2.046	0.054	92	0.91	1.55	0.90	1.504
2.10	2.10	2.10			4.41		1.896	0.204	93	0.92	1.59	0.90	1.504
2.10	2.10	2.10			4.41		1.896	0.204	94	0.93	1.63	0.90	1.504
2.10	2.10	2.10			4.41		1.896	0.204	95	0.94	1.68	0.90	1.504
2.25	2.25	2.25			5.06		2.346	0.096	96	0.95	1.73	0.93	1.611
2.25	2.25	2.25			5.06		2.196	0.054	97	0.96	1.80	0.93	1.611
2.25	2.25	2.25			5.06		2.046	0.204	98	0.97	1.88	0.93	1.611
2.25	2.25	2.25	2.25		5.06		1.896	0.354	99	0.98	1.98	0.93	1.611
2.40	2.40	2.40	2.40	2.40	5.76		2.196	0.204	100	0.99	2.15	0.95	1.718

Observation 4 (at middle of pier) (by Erwin & Remon)

H	$H_{1/3}$	$H_{1/10}$	$H_{2/100}$	$H_{1/100}$	H^2	H_{rms}	Wave amplitude			Measured data		Theoretical Rayleigh	
[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]					$P(H_{gem} < H)$	
0.70	0.96	1.11	1.14	1.17	0.55	0.74	-0.531				Rayleigh		Rayleigh
0.22					0.05		0.531	0.311	1	0.00	0.07	0.08	0.298
0.22					0.05		0.531	0.311	2	0.01	0.10	0.08	0.298
0.22					0.05		0.531	0.311	3	0.01	0.12	0.08	0.298
0.22					0.05		0.311	0.091	4	0.02	0.14	0.08	0.298
0.22					0.05		0.311	0.091	5	0.02	0.16	0.08	0.298
0.22					0.05		0.311	0.091	6	0.03	0.17	0.08	0.298
0.22					0.05		0.311	0.091	7	0.03	0.19	0.08	0.298

0.22					0.05		0.311	0.091	8	0.04	0.20	0.08	0.298
0.22					0.05		0.311	0.091	9	0.04	0.21	0.08	0.298
0.22					0.05		0.311	0.091	10	0.05	0.23	0.08	0.298
0.44					0.19		0.531	0.091	11	0.05	0.24	0.30	0.596
0.44					0.19		0.531	0.091	12	0.06	0.25	0.30	0.596
0.44					0.19		0.531	0.091	13	0.06	0.26	0.30	0.596
0.44					0.19		0.531	0.091	14	0.07	0.27	0.30	0.596
0.44					0.19		0.531	0.091	15	0.07	0.28	0.30	0.596
0.44					0.19		0.751	0.311	16	0.08	0.29	0.30	0.596
0.44					0.19		0.531	0.091	17	0.08	0.30	0.30	0.596
0.44					0.19		0.531	0.091	18	0.09	0.31	0.30	0.596
0.44					0.19		0.751	0.311	19	0.09	0.31	0.30	0.596
0.44					0.19		0.531	0.091	20	0.10	0.32	0.30	0.596
0.44					0.19		0.531	0.091	21	0.10	0.33	0.30	0.596
0.44					0.19		0.531	0.091	22	0.11	0.34	0.30	0.596
0.44					0.19		0.531	0.091	23	0.11	0.35	0.30	0.596
0.44					0.19		0.531	0.091	24	0.12	0.36	0.30	0.596
0.44					0.19		0.531	0.091	25	0.12	0.36	0.30	0.596
0.44					0.19		0.751	0.311	26	0.13	0.37	0.30	0.596
0.44					0.19		0.311	0.129	27	0.13	0.38	0.30	0.596
0.44					0.19		0.531	0.091	28	0.14	0.39	0.30	0.596
0.44					0.19		0.531	0.091	29	0.14	0.39	0.30	0.596
0.44					0.19		0.531	0.091	30	0.15	0.40	0.30	0.596
0.44					0.19		0.531	0.091	31	0.15	0.41	0.30	0.596
0.44					0.19		0.531	0.091	32	0.16	0.42	0.30	0.596
0.44					0.19		0.531	0.091	33	0.16	0.42	0.30	0.596
0.44					0.19		0.531	0.091	34	0.17	0.43	0.30	0.596
0.44					0.19		0.531	0.091	35	0.17	0.44	0.30	0.596
0.44					0.19		0.531	0.091	36	0.18	0.44	0.30	0.596
0.44					0.19		0.531	0.091	37	0.18	0.45	0.30	0.596
0.44					0.19		0.531	0.091	38	0.19	0.46	0.30	0.596
0.44					0.19		0.311	0.129	39	0.19	0.46	0.30	0.596
0.44					0.19		0.531	0.091	40	0.20	0.47	0.30	0.596
0.44					0.19		0.531	0.091	41	0.20	0.48	0.30	0.596
0.44					0.19		0.531	0.091	42	0.21	0.48	0.30	0.596
0.44					0.19		0.531	0.091	43	0.21	0.49	0.30	0.596
0.44					0.19		0.311	0.129	44	0.22	0.50	0.30	0.596
0.44					0.19		0.311	0.129	45	0.22	0.50	0.30	0.596
0.44					0.19		0.531	0.091	46	0.23	0.51	0.30	0.596
0.44					0.19		0.531	0.091	47	0.23	0.51	0.30	0.596
0.44					0.19		0.531	0.091	48	0.24	0.52	0.30	0.596
0.66					0.44		0.531	0.129	49	0.24	0.53	0.55	0.893
0.66					0.44		0.751	0.091	50	0.25	0.53	0.55	0.893
0.66					0.44		0.751	0.091	51	0.25	0.54	0.55	0.893
0.66					0.44		0.531	0.129	52	0.26	0.55	0.55	0.893

0.66					0.44		0.531	0.129	53	0.26	0.55	0.55	0.893
0.66					0.44		0.751	0.091	54	0.27	0.56	0.55	0.893
0.66					0.44		0.971	0.311	55	0.27	0.56	0.55	0.893
0.66					0.44		0.751	0.091	56	0.28	0.57	0.55	0.893
0.66					0.44		0.751	0.091	57	0.28	0.58	0.55	0.893
0.66					0.44		0.751	0.091	58	0.29	0.58	0.55	0.893
0.66					0.44		0.751	0.091	59	0.29	0.59	0.55	0.893
0.66					0.44		0.751	0.091	60	0.30	0.59	0.55	0.893
0.66					0.44		0.751	0.091	61	0.30	0.60	0.55	0.893
0.66					0.44		0.531	0.129	62	0.31	0.61	0.55	0.893
0.66					0.44		0.751	0.091	63	0.31	0.61	0.55	0.893
0.66					0.44		0.531	0.129	64	0.32	0.62	0.55	0.893
0.66					0.44		0.751	0.091	65	0.32	0.62	0.55	0.893
0.66					0.44		0.751	0.091	66	0.33	0.63	0.55	0.893
0.66					0.44		0.531	0.129	67	0.33	0.63	0.55	0.893
0.66					0.44		0.751	0.091	68	0.34	0.64	0.55	0.893
0.66					0.44		0.751	0.091	69	0.34	0.65	0.55	0.893
0.66					0.44		0.531	0.129	70	0.35	0.65	0.55	0.893
0.66					0.44		0.531	0.129	71	0.35	0.66	0.55	0.893
0.66					0.44		0.751	0.091	72	0.36	0.66	0.55	0.893
0.66					0.44		0.751	0.091	73	0.36	0.67	0.55	0.893
0.66					0.44		0.751	0.091	74	0.37	0.68	0.55	0.893
0.66					0.44		0.531	0.129	75	0.37	0.68	0.55	0.893
0.66					0.44		0.751	0.091	76	0.38	0.69	0.55	0.893
0.66					0.44		0.531	0.129	77	0.38	0.69	0.55	0.893
0.66					0.44		0.751	0.091	78	0.39	0.70	0.55	0.893
0.66					0.44		0.751	0.091	79	0.39	0.70	0.55	0.893
0.66					0.44		0.751	0.091	80	0.40	0.71	0.55	0.893
0.66					0.44		0.751	0.091	81	0.40	0.72	0.55	0.893
0.66					0.44		0.751	0.091	82	0.41	0.72	0.55	0.893
0.66					0.44		0.751	0.091	83	0.41	0.73	0.55	0.893
0.66					0.44		0.531	0.129	84	0.42	0.73	0.55	0.893
0.66					0.44		0.531	0.129	85	0.42	0.74	0.55	0.893
0.66					0.44		0.751	0.091	86	0.43	0.74	0.55	0.893
0.66					0.44		0.751	0.091	87	0.43	0.75	0.55	0.893
0.66					0.44		0.751	0.091	88	0.44	0.76	0.55	0.893
0.66					0.44		0.751	0.091	89	0.44	0.76	0.55	0.893
0.66					0.44		0.531	0.129	90	0.45	0.77	0.55	0.893
0.66					0.44		0.751	0.091	91	0.45	0.77	0.55	0.893
0.66					0.44		0.751	0.091	92	0.46	0.78	0.55	0.893
0.66					0.44		0.751	0.091	93	0.46	0.79	0.55	0.893
0.66					0.44		0.751	0.091	94	0.47	0.79	0.55	0.893
0.66					0.44		0.971	0.311	95	0.47	0.80	0.55	0.893
0.66					0.44		0.751	0.091	96	0.48	0.80	0.55	0.893
0.66					0.44		0.971	0.311	97	0.48	0.81	0.55	0.893

0.66					0.44		0.751	0.091	98	0.49	0.81	0.55	0.893
0.66					0.44		0.531	0.129	99	0.49	0.82	0.55	0.893
0.66					0.44		0.531	0.129	100	0.50	0.83	0.55	0.893
0.66					0.44		0.751	0.091	101	0.50	0.83	0.55	0.893
0.66					0.44		0.531	0.129	102	0.50	0.84	0.55	0.893
0.66					0.44		0.531	0.129	103	0.51	0.84	0.55	0.893
0.66					0.44		0.751	0.091	104	0.51	0.85	0.55	0.893
0.66					0.44		0.751	0.091	105	0.52	0.86	0.55	0.893
0.66					0.44		0.531	0.129	106	0.52	0.86	0.55	0.893
0.66					0.44		0.751	0.091	107	0.53	0.87	0.55	0.893
0.66					0.44		0.751	0.091	108	0.53	0.87	0.55	0.893
0.66					0.44		0.531	0.129	109	0.54	0.88	0.55	0.893
0.66					0.44		0.751	0.091	110	0.54	0.89	0.55	0.893
0.66					0.44		0.531	0.129	111	0.55	0.89	0.55	0.893
0.66					0.44		0.751	0.091	112	0.55	0.90	0.55	0.893
0.66					0.44		0.751	0.091	113	0.56	0.91	0.55	0.893
0.66					0.44		0.751	0.091	114	0.56	0.91	0.55	0.893
0.66					0.44		0.751	0.091	115	0.57	0.92	0.55	0.893
0.66					0.44		0.751	0.091	116	0.57	0.92	0.55	0.893
0.66					0.44		0.531	0.129	117	0.58	0.93	0.55	0.893
0.66					0.44		0.531	0.129	118	0.58	0.94	0.55	0.893
0.66					0.44		0.531	0.129	119	0.59	0.94	0.55	0.893
0.66					0.44		0.531	0.129	120	0.59	0.95	0.55	0.893
0.66					0.44		0.751	0.091	121	0.60	0.96	0.55	0.893
0.66					0.44		0.531	0.129	122	0.60	0.96	0.55	0.893
0.66					0.44		0.751	0.091	123	0.61	0.97	0.55	0.893
0.66					0.44		0.531	0.129	124	0.61	0.98	0.55	0.893
0.66					0.44		0.751	0.091	125	0.62	0.98	0.55	0.893
0.66					0.44		0.531	0.129	126	0.62	0.99	0.55	0.893
0.66					0.44		0.751	0.091	127	0.63	1.00	0.55	0.893
0.66					0.44		0.751	0.091	128	0.63	1.00	0.55	0.893
0.66					0.44		0.531	0.129	129	0.64	1.01	0.55	0.893
0.77					0.59		0.641	0.129	130	0.64	1.02	0.66	1.042
0.88					0.77		0.751	0.129	131	0.65	1.02	0.76	1.191
0.88					0.77		0.751	0.129	132	0.65	1.03	0.76	1.191
0.88					0.77		0.531	0.349	133	0.66	1.04	0.76	1.191
0.88					0.77		0.751	0.129	134	0.66	1.04	0.76	1.191
0.88	0.88				0.77		0.751	0.129	135	0.67	1.05	0.76	1.191
0.88	0.88				0.77		0.971	0.091	136	0.67	1.06	0.76	1.191
0.88	0.88				0.77		0.751	0.129	137	0.68	1.06	0.76	1.191
0.88	0.88				0.77		0.751	0.129	138	0.68	1.07	0.76	1.191
0.88	0.88				0.77		0.971	0.091	139	0.69	1.08	0.76	1.191
0.88	0.88				0.77		0.971	0.091	140	0.69	1.09	0.76	1.191
0.88	0.88				0.77		0.971	0.091	141	0.70	1.09	0.76	1.191
0.88	0.88				0.77		0.971	0.091	142	0.70	1.10	0.76	1.191

0.88	0.88				0.77		0.971	0.091	143	0.71	1.11	0.76	1.191
0.88	0.88				0.77		0.971	0.091	144	0.71	1.12	0.76	1.191
0.88	0.88				0.77		0.971	0.091	145	0.72	1.12	0.76	1.191
0.88	0.88				0.77		0.751	0.129	146	0.72	1.13	0.76	1.191
0.88	0.88				0.77		0.751	0.129	147	0.73	1.14	0.76	1.191
0.88	0.88				0.77		0.751	0.129	148	0.73	1.15	0.76	1.191
0.88	0.88				0.77		0.971	0.091	149	0.74	1.16	0.76	1.191
0.88	0.88				0.77		0.751	0.129	150	0.74	1.16	0.76	1.191
0.88	0.88				0.77		0.751	0.129	151	0.75	1.17	0.76	1.191
0.88	0.88				0.77		0.751	0.129	152	0.75	1.18	0.76	1.191
0.88	0.88				0.77		0.751	0.129	153	0.76	1.19	0.76	1.191
0.88	0.88				0.77		0.751	0.129	154	0.76	1.20	0.76	1.191
0.88	0.88				0.77		0.751	0.129	155	0.77	1.21	0.76	1.191
0.88	0.88				0.77		0.751	0.129	156	0.77	1.22	0.76	1.191
0.88	0.88				0.77		0.751	0.129	157	0.78	1.23	0.76	1.191
0.88	0.88				0.77		0.751	0.129	158	0.78	1.23	0.76	1.191
0.88	0.88				0.77		0.751	0.129	159	0.79	1.24	0.76	1.191
0.88	0.88				0.77		0.971	0.091	160	0.79	1.25	0.76	1.191
0.88	0.88				0.77		0.751	0.129	161	0.80	1.26	0.76	1.191
0.88	0.88				0.77		0.971	0.091	162	0.80	1.27	0.76	1.191
0.88	0.88				0.77		0.971	0.091	163	0.81	1.28	0.76	1.191
0.88	0.88				0.77		0.751	0.129	164	0.81	1.29	0.76	1.191
0.88	0.88				0.77		0.531	0.349	165	0.82	1.30	0.76	1.191
0.88	0.88				0.77		0.751	0.129	166	0.82	1.31	0.76	1.191
0.88	0.88				0.77		0.971	0.091	167	0.83	1.32	0.76	1.191
0.88	0.88				0.77		0.971	0.091	168	0.83	1.33	0.76	1.191
0.88	0.88				0.77		0.971	0.091	169	0.84	1.35	0.76	1.191
0.88	0.88				0.77		0.751	0.129	170	0.84	1.36	0.76	1.191
0.88	0.88				0.77		0.751	0.129	171	0.85	1.37	0.76	1.191
0.88	0.88				0.77		0.751	0.129	172	0.85	1.38	0.76	1.191
0.88	0.88				0.77		0.971	0.091	173	0.86	1.39	0.76	1.191
0.88	0.88				0.77		0.531	0.349	174	0.86	1.41	0.76	1.191
0.88	0.88				0.77		0.751	0.129	175	0.87	1.42	0.76	1.191
0.88	0.88				0.77		0.971	0.091	176	0.87	1.43	0.76	1.191
0.88	0.88				0.77		0.751	0.129	177	0.88	1.45	0.76	1.191
1.10	1.10				1.21		0.971	0.129	178	0.88	1.46	0.89	1.489
1.10	1.10				1.21		0.971	0.129	179	0.89	1.47	0.89	1.489
1.10	1.10				1.21		0.971	0.129	180	0.89	1.49	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	181	0.90	1.50	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	182	0.90	1.52	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	183	0.91	1.54	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	184	0.91	1.55	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	185	0.92	1.57	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	186	0.92	1.59	0.89	1.489
1.10	1.10	1.10			1.21		1.191	0.091	187	0.93	1.61	0.89	1.489

1.10	1.10	1.10			1.21		0.971	0.129	188	0.93	1.63	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	189	0.94	1.66	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	190	0.94	1.68	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	191	0.95	1.71	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	192	0.95	1.73	0.89	1.489
1.10	1.10	1.10			1.21		0.751	0.349	193	0.96	1.76	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	194	0.96	1.80	0.89	1.489
1.10	1.10	1.10			1.21		0.971	0.129	195	0.97	1.83	0.89	1.489
1.10	1.10	1.10			1.21		0.751	0.349	196	0.97	1.88	0.89	1.489
1.10	1.10	1.10	1.10		1.21		0.971	0.129	197	0.98	1.92	0.89	1.489
1.10	1.10	1.10	1.10		1.21		0.971	0.129	198	0.98	1.98	0.89	1.489
1.10	1.10	1.10	1.10	1.10	1.21		0.971	0.129	199	0.99	2.05	0.89	1.489
1.10	1.10	1.10	1.10	1.10	1.21		0.971	0.129	200	0.99	2.15	0.89	1.489
1.32	1.32	1.32	1.32	1.32	1.74		0.971	0.349	201	1.00	2.30	0.96	1.787

E. Calculations with theory of Battjes & Groenendijk (2000)

Battjes & Groenendijk 2000

		Prob.	Theory 1	Data 1	Theory 2	Data 2	Theory 3	Data 3	Theory 4	Data 4
Slope	tan(α)		0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05
Local water depth	h [m]		2.8	2.8	2.8	2.8	2.8	2.8	2.1	2.1
Transitional wave height	H_{tr}		1.1424	1.1424	1.1424	1.1424	1.1424	1.1424	1.344	1.344
	H_{rms}		1.18	1.18	1.26	1.26	1.40	1.40	0.74	0.74
Non-dimensional H_{tr}	$H_{tr/Hrms}$		0.97		0.91		0.82		1.82	
	H_{33}/H_{rms}		1.32		1.32		1.30		1.42	
	H_{10}/H_{rms}		1.52		1.51		1.50		1.77	
	H_2/H_{rms}		1.61		1.60		1.59		1.91	
	H_1/H_{rms}		1.69		1.68		1.66		2.00	
	$H_{0.1}/H_{rms}$		1.90		1.88		1.87		2.25	
Significant wave height	H_{33}	0.333	1.56	1.51	1.66	1.74	1.82	1.88	1.05	0.96
	H_{10}	0.100	1.79	1.74	1.91	2.03	2.10	2.19	1.31	1.11
	H_2	0.020	1.89	2.10	2.02	2.25	2.22	2.33	1.41	1.14
	H_1	0.010	1.98	2.10	2.11	2.40	2.32	2.40	1.48	1.17
	$H_{0.1}$	0.001	2.23		2.37		2.60		1.66	